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A method for external measurement of toroidal equilibrium parameters

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Abstract

A method has been developed for determining from external magnetic field measurements the horizontal shift, the vertical shift and the poloidal field asymmetry parameter (Λ) of a toroidal plasma in force equilibrium. The magnetic measurements consist of two toroidal differential flux loops, giving the average vertical magnetic field and the average radial magnetic field respectively, together with cosine-coils for obtaining the m=1 cosine harmonic of the external poloidal magnetic field component. The method is used to analyse the evolution of the toroidal equilibrium during reversed-field pinch discharges in the Extrap T1-U device. We find that good equilibrium control is needed for long plasma pulses. For non-optimized externally applied vertical fields, the diagnostic clearly shows a horizontal drift motion of the pinch resulting in earlier discharge termination.

1. Introduction

The importance of controlling the toroidal equilibrium position of reversed-field pinch discharges has been stressed in earlier studies made on the HBTX1A and REPUTE-1 RFP experiments [1, 2]. We have developed an analysis method, described in this paper, which determines essential parameters of the toroidal plasma equilibrium such as the horizontal shift of the outermost closed plasma flux surface relative to the geometrical minor axis (Δ_x), the vertical shift of the outermost flux surface (Δ_y) and the poloidal field asymmetry parameter (Λ), which is related to the sum of the poloidal beta value (β_θ) and the normalised internal inductance (l_i) of the plasma. The method is applied to the Extrap T1-U reversed-field pinch experiment [3, 4].

We prefer a non-perturbative method, which therefore must rely upon external magnetic diagnostics, and ideally the measurement should need as few diagnostic channels as possible in order to be feasible for implementation as a routine diagnostic tool on the experiment. In order to fulfil these requirements, we have developed a method which uses (in the minimal version) only three magnetic signals in addition to standard measurements such as total plasma current and loop voltage. We use two toroidal differential flux loops, giving the average vertical magnetic field and the average radial magnetic field respectively, together with one or several cosine-coils for measurement of the m=1 cosine harmonic of the external poloidal magnetic field component. Our analysis method relies on the use of asymptotic analytical solutions to the Grad-Shafranov equilibrium equation in the large aspect ratio limit ($R / a >> 1$) [5, 6]. We thus assume an axisymmetric plasma with a circular cross section, bounded at one point by a material limiter. In addition we take the approximation of small equilibrium displacements ($\Delta / a << 1$).

The basis for the measurement of the toroidal equilibrium is described in the review article by Mukhovatov and Shafranov [5]. In the case of an ideally conducting shell surrounding the plasma, and with an optional time-constant bias vertical field, the measurement is quite simple and requires only a cosine-coil. This method has previously been utilized in HBTX1A [1]. In the opposite limiting case, without shell as in a Tokamak, the externally applied vertical field is produced exclusively in external discrete conductors and may thus be computed directly, which also reduces the problem significantly [7]. However, in reversed-field pinches with a resistive shell such as the Extrap T1-U device, there are time dependent eddy currents in the shell which contributes significantly to the external vertical field. The spatial distribution of these currents is difficult to compute, and therefore we must use a method which does not require an explicit calculation of the external field. A method has been developed for the resistive shell reversed-field pinch REPUTE-1 by H. Ji, et al., which solves this problem by measuring the poloidal and radial magnetic field components outside the plasma boundary with arrays of discrete coils [2]. However, since discrete coils are used, a larger number of data channels are required.

The equilibrium measurement method presented in the paper has been developed for the Extrap T1-U experiment which is described in detail elsewhere [3, 4]. We note some important changes to the Extrap T1-U device which have done recently: The vacuum vessel has been replaced giving much improved vacuum conditions and reduced impurity content in the plasma. The previous stainless shell has been replaced with a brass shell having a longer vertical field penetration time. In addition, copper shielding plates have been placed over the poloidal gaps in order to reduce the gap error fields.

For the purpose of illustrating the analysis method developed, we present the results of a systematic study of the effect of the applied vertical field on the toroidal equilibrium. We find that good equilibrium control is needed for long plasma pulses. For non-optimized vertical fields, the equilibrium diagnostic clearly shows a horizontal drift motion of the pinch resulting in earlier discharge termination.

This paper is organized as follows: In section 2, we outline the theory needed for the analysis of the external equilibrium diagnostics. The method for computing the equilibrium parameters is described in section 3. Experimental results are discussed in section 4. Finally, we give some practical details on the use of our equilibrium analysis computer code in an appendix.

2. Calculation of the external magnetic field

The purpose of this section is to derive analytical expressions for the poloidal flux function and the poloidal magnetic field components outside the liner where the external magnetic diagnostics are situated.

We assume an axisymmetric toroidal plasma in force equilibrium. The poloidal flux function Ψ ($\Psi=\psi_{pol}/2\pi$), which describes the poloidal magnetic fields, satisfies the Grad-Shafranov equation. We will start our analysis from the G-S solution in the vacuum region outside the plasma. Taking the approximation of a circular cross-section plasma column and a large aspect ratio (R/a>>1) we have the well known expression [5, 6];

$$\Psi(\rho,\omega) = \frac{\mu_0 I_p R_p}{2\pi}\left(\ln\frac{8R_p}{\rho} - 2 - \frac{\rho}{2R_p}\left(\ln\frac{\rho}{a} + \left(\Lambda + \frac{1}{2}\right)\left(1 - \left(\frac{a}{\rho}\right)^2\right)\right)\cos\omega\right) \quad (1)$$

The flux function Ψ is expressed in a polar coordinate system (ρ,ω) centred on the plasma minor axis, which here is defined by *the centre of the outermost closed plasma flux surface* ($\rho=a$), see Fig. 2. Here I_p is the total plasma current in the positive ϕ-direction and R_p is the plasma major radius. The poloidal field asymmetry factor Λ can be expressed as;

$$\Lambda = \beta_p + \frac{l_i}{2} - 1 \quad (2)$$

Here β_p is the poloidal beta value, defined as;

$$\beta_p = \frac{2\mu_0}{\pi a^2 B_a^2}\int_0^{2\pi}\int_0^a p\,\rho d\rho d\omega \quad (3)$$

where p is the plasma pressure and $B_a=\mu_0 I_p/2\pi a$ is the poloidal magnetic field at the plasma boundary. The normalised internal inductance l_i is defined as;

$$l_i = \frac{1}{\pi a^2 B_a^2}\int_0^{2\pi}\int_0^a B_\omega^2\,\rho d\rho d\omega. \quad (4)$$

We assume that the plasma boundary is shifted by a small amount horizontally (Δ_x) and vertically (Δ_y); $\Delta_x/a<<1$ and $\Delta_y/a<<1$ (see Fig. 2). Our object is to transform the expression for $\Psi(\rho,\omega)$ (Eq. (1)) to an expression $\Psi(r,\theta)$ which is defined in a polar coordinate system (r,θ) centred on *the geometrical minor axis of the vacuum vessel.* To first order in the small parameters Δ_x/r and Δ_y/r we obtain the following coordinate transformation formulas:

$$\rho \approx r\left(1 - \frac{\Delta_x}{r}\cos\theta - \frac{\Delta_y}{r}\sin\theta\right) \tag{5}$$

$$\omega \approx \theta \tag{6}$$

$$R_p \approx R_0 \tag{7}$$

We also use R/a>>1 to obtain the expression for $\Psi(r,\theta)$:

$$\Psi(r,\theta) = \frac{\mu_0 I_p R_0}{2\pi}\left(\ln\frac{8R_0}{r} - 2\right) +$$

$$\frac{\mu_0 I_p R_0}{2\pi}\left(\left(\frac{\Delta_x}{r} - \frac{r}{2R_0}\left(\ln\frac{r}{a} + \left(\Lambda + \frac{1}{2}\right)\left(1 - \left(\frac{a}{r}\right)^2\right)\right)\right)\cos\theta + \frac{\Delta_y}{r}\sin\theta\right) \tag{8}$$

The magnetic field components are computed from the relations:

$$B_r = -\frac{1}{rR}\frac{\partial\Psi}{\partial\theta} \tag{9}$$

$$B_\theta = \frac{1}{R}\frac{\partial\Psi}{\partial r} \tag{10}$$

We thus obtain

$$B_r(r,\theta) = \frac{\mu_0 I_p}{2\pi r}\left(\left(\frac{\Delta_x}{r} - \frac{r}{2R_0}\left(\ln\frac{r}{a} + \left(\Lambda + \frac{1}{2}\right)\left(1 - \left(\frac{a}{r}\right)^2\right)\right)\right)\sin\theta - \frac{\Delta_y}{r}\cos\theta\right) \tag{11}$$

$$B_\theta(r,\theta) = -\frac{\mu_0 I_p}{2\pi r} -$$

$$\frac{\mu_0 I_p}{2\pi r}\left(\left(\frac{\Delta_x}{r} + \frac{r}{2R_0}\left(\ln\frac{r}{a} - 1 + \left(\Lambda + \frac{1}{2}\right)\left(1 + \left(\frac{a}{r}\right)^2\right)\right)\right)\cos\theta + \frac{\Delta_y}{r}\sin\theta\right) \tag{12}$$

The effect of a toroidal current driven by the applied loop voltage in the vacuum vessel (which is closed electrically in the toroidal direction) need to be included in the analysis. We model the toroidal current in the liner by a surface current $j_s(\theta)$ at r=b (see Fig. 2):

$$j_s = \frac{I_L}{2\pi b}\left(1 + \frac{b}{R_0}\Gamma \cos\theta + \frac{b}{R_0}\Omega \sin\theta\right) \tag{13}$$

The total toroidal current in the liner which flows in the positive ϕ–direction is denoted I_L. We assume a small poloidal asymmetry which is expressed by the factors Γ and Ω which thus are taken to be of the order one or less. For time scales long compared to the transverse field penetration time of the liner, the factors Γ and Ω may be set to zero, thus taking a poloidally symmetric current distribution. We divide space into two regions:

I) $r<b$

II) $r>b$.

Region (I): The magnetic field components in the vacuum region outside the plasma boundary; B_r^I and B_θ^I, are given by equations (11) and (12) respectively.

Region (II): We use a general expression for the poloidal flux function Ψ^{II} (valid for the circular-plasma boundary, large aspect ratio approximation) [6]:

$$\Psi^{II}(r,\theta) = \frac{\mu_0(I_p+I_L)R_0}{2\pi}\left(\ln\frac{8R_0}{r} - 2 + \frac{r}{2R_0}\left(\ln\frac{8R_0}{r} - 1\right)\right)\cos\theta +$$

$$\left(\frac{C_1}{r} + C_2 r\right)\cos\theta + \frac{C_3}{r}\sin\theta \tag{14}$$

The expressions for the magnetic field components outside the liner; B_r^{II} and B_θ^{II}, are obtained using Eq.(14) and the relations (9) and (10). The three constants C_1, C_2 and C_3 are determined by matching the general solutions in region (II) to the solution found for region (I) through the magnetic field boundary conditions at the surface r=b:

$$B_r^{II}(b,\theta) - B_r^{I}(b,\theta) = 0 \tag{15}$$

$$B_\theta^{II}(b,\theta) - B_\theta^{I}(b,\theta) = -\mu_0 j_s(\theta) \tag{16}$$

We thus find:

$$C_1 = \frac{\mu_0 I_p b^2}{2\pi}\left(\frac{R_0\Delta_x}{b^2} + \frac{1}{2}\left(\left(\Lambda + \frac{1}{2}\right)\left(\frac{a}{b}\right)^2\right) \right) + \frac{\mu_0 I_L b^2}{2\pi}\frac{1}{2}\left(\Gamma + \frac{1}{2}\right) \tag{17}$$

$$C_2 = -\frac{\mu_0 I_p}{2\pi}\frac{1}{2}\left(\ln\frac{8R_0}{a} + \Lambda - \frac{1}{2}\right) - \frac{\mu_0 I_L}{2\pi}\frac{1}{2}\left(\ln\frac{8R_0}{b} + \Gamma - \frac{1}{2}\right) \tag{18}$$

$$C_3 = \frac{\mu_0 I_p}{2\pi} R_0 \Delta_y - \frac{\mu_0 I_L}{2\pi} b^2 \Omega \tag{19}$$

Inserting expressions (17), (18) and (19) into Eq. (14) we obtain:

$$\begin{aligned}
\Psi^{II}(r,\theta) = {} & \frac{\mu_0 (I_p + I_L) R_0}{2\pi}\left(\ln\frac{8R_0}{r} - 2\right) + \\
& \frac{\mu_0 I_p R_0}{4\pi}\left(2\frac{\Delta_x}{r} + \frac{r}{R_0}\left(\ln\frac{a}{r} - \left(\Lambda + \frac{1}{2}\right)\left(1 - \left(\frac{a}{r}\right)^2\right)\right)\right)\cos\theta + \\
& \frac{\mu_0 I_L R_0}{4\pi}\frac{r}{R_0}\left(\ln\frac{b}{r} - \left(\Gamma + \frac{1}{2}\right)\left(1 - \left(\frac{b}{r}\right)^2\right)\right)\cos\theta + \\
& \frac{\mu_0 I_p R_0}{4\pi} 2\frac{\Delta_y}{r}\sin\theta - \frac{\mu_0 I_L R_0}{4\pi} 2\frac{r}{R_0}\Omega\left(\frac{b}{r}\right)^2\sin\theta
\end{aligned} \tag{20}$$

Finally, by using Eqs (9) and (10), we obtain the expressions for the magnetic field components in the region outside the liner due to a toroidal plasma current with a small displacement and a toroidal current in the liner:

$$B_r^{II}(r,\theta) = \frac{\mu_0 I_p}{4\pi R_0}\left(2\frac{R_0\Delta_x}{r^2} + \ln\frac{a}{r} - \left(\Lambda + \frac{1}{2}\right)\left(1 - (\frac{a}{r})^2\right)\right)\sin\theta +$$

$$\frac{\mu_0 I_L}{4\pi R_0}\left(\ln\frac{b}{r} - \left(\Gamma + \frac{1}{2}\right)\left(1 - (\frac{b}{r})^2\right)\right)\sin\theta -$$

$$\frac{\mu_0 I_p}{4\pi R_0} 2\frac{R_0\Delta_y}{r^2}\cos\theta + \frac{\mu_0 I_L}{4\pi R_0} 2\,\Omega\,(\frac{b}{r})^2\cos\theta \qquad (21)$$

$$B_\theta^{II}(r,\theta) = -\frac{\mu_0(I_p+I_L)}{2\pi r} +$$

$$\frac{\mu_0 I_p}{4\pi R_0}\left(-2\frac{R_0\Delta_x}{r^2} + \ln\frac{a}{r} + 1 - \left(\Lambda + \frac{1}{2}\right)\left(1 + (\frac{a}{r})^2\right)\right)\cos\theta +$$

$$\frac{\mu_0 I_L}{4\pi R_0}\left(\ln\frac{b}{r} + 1 - \left(\Gamma + \frac{1}{2}\right)\left(1 + (\frac{b}{r})^2\right)\right)\cos\theta -$$

$$\frac{\mu_0 I_p}{4\pi R_0} 2\frac{R_0\Delta_y}{r^2}\sin\theta + \frac{\mu_0 I_L}{4\pi R_0} 2\,\Omega\,(\frac{b}{r})^2\sin\theta \qquad (22)$$

For clarity we repeat the notation: I_p and I_L are total current in plasma and liner respectively, R_0 is major radius, a is minor radius of outermost closed plasma flux surface, b is liner radius and Δ_x and Δ_y are horizontal and vertical displacement of the outermost closed plasma flux surface respectively, Λ is the plasma field poloidal asymmetry factor and Γ and Ω are the liner field poloidal asymmetry factors.

3. Method of determining Δ_x, Δ_y and Λ from measurements

The poloidal magnetic field components $B_\theta(r,\theta)$ and $B_r(r,\theta)$ are not obtained directly from the measurements. In this section, we first describe the magnetic diagnostics which are used. Second, we derive expressions for the equilibrium parameters in terms of the measured magnetic field quantities which then are used for determining the horizontal shift Δ_x, the vertical shift Δ_y and the asymmetry parameter Λ.

3.1. Magnetic diagnostics

The magnetic diagnostic needed for the analysis are:

1) Rogowski coil for total secondary current
2) Toroidal loop for liner current (loop voltage)
3) Cosine coil for B-cos poloidal magnetic field
4) Differential flux loops for average B-vertical and B-radial

Total plasma and liner toroidal current

The total secondary toroidal current is measured with a Rogowski coil encircling the vacuum vessel. The totol toroidal current which flows through the resistive stainless steel liner is obtained from the loop voltage measured with a single toroidal loop positioned close to the liner, using the known toroidal resistance of the liner. This liner current is then subtracted from the total current in order to obtain the plasma current. For convenience we define the following quantities:

$$B_P = \frac{\mu_0 I_p}{4\pi R_0} \tag{23}$$

$$B_L = \frac{\mu_0 I_L}{4\pi R_0} \tag{24}$$

Cosine poloidal magnetic field

We use one or several cosine coils (up to three) to obtain a measurement of the 1:st cosine Fourier harmonic of the poloidal magnetic field component outside the liner. By using several coils and averaging the signals, we obtain a coarse toroidal averaging which is consistent with the toroidal asymmetry assumption used in the analysis. The minor radius of the cos-coils is denoted r=c (see Fig. 2). Fourier decomposing the poloidal field at the position of the coil, we have:

$$B_\theta(c,\theta) = B_0 + B_C \cos\theta + B_S \sin\theta \tag{25}$$

The cosine-coil signal is proportional to B_C. The cosine coil was calibrated in a specially-built setup. The device had a cylindrical geometry with radius c. The cosine coil was placed on the cylindrical surface encircling two linear conductors, displaced a distance Δ from the cylinder axis (both conductors were placed on the same diameter a distance 2Δ apart). A sinusoidal current with amplitude I and frequency f was run in opposite directions through the conductors and the cosine-coil calibration constant k was determined as:

$$V_{cos} = k\, 2\pi f\, 2I\Delta \tag{26}$$

Calibration data for the coils used are collected in Table II. The scale constant for the cosine magnetic field is computed using the following exact relation for the field from *one* displaced, straight conductor;

$$B_C = \frac{\mu_0 I\Delta}{2\pi c^2} \tag{27}$$

where c is the radius of the cosine coil.

Average B-vertical and B-radial magnetic field

The spatially averaged vertical and horizontal fields are measured by a pair of toroidal flux loops respectively. In our case we have fully toroidal flux loops. Alternatively one or several local saddle coils (giving a coarse toroidal averaging analogous as for the cosine-coils) would function equally well, although this scheme may require recording of a larger number of signals. The four flux loops are situated at minor radius r=d and at angles $\theta=0$, $\pi/2$, π and $3\pi/2$ as shown in Fig. 2. The loops at $\theta=0$ and $\theta=\pi$ are interconnected in order to give an output signal proportional to the average vertical field:

$$B_Z = 2\pi \frac{1}{A}\left(\Psi(d,0) - \Psi(d,\pi)\right) \tag{28}$$

Here $A=4\pi R_0 d$ is the area of each differential flux loop. We note that the poloidal flux is 2π times the poloidal flux function Ψ. The horizontally asymmetric part of the toroidal current in the liner, represented by the factor Γ, is determined from the measured data by taking the time derivative of the B_Z signal giving the differential loop voltage at the liner, and using the known resistance of the liner.

Similarly, the loops at $\theta=\pi/2$ and $\theta=3\pi/2$ are interconnected to give a signal proportional to the average radial field:

$$B_R = 2\pi \frac{1}{A}\left(\Psi(d,3\pi/2) - \Psi(d,\pi/2)\right) \tag{29}$$

The vertically asymmetric part of the toroidal current in the liner, represented by the factor Ω is determined by taking the time derivative of the B_R signal, and calculated analogously as Γ.

3.2. Relations for determining Δ_x, Δ_y and Λ

From Eqs (22), (23), (24) and (25) we obtain:

$$B_C = B_P\left(- 2\frac{R_0\Delta_x}{c^2} + \ln \frac{a}{c} + 1 - \left(\Lambda + \frac{1}{2}\right)\left(1 + (\frac{a}{c})^2\right)\right) +$$

$$B_L\left(\ln \frac{b}{c} + 1 - \left(\Gamma + \frac{1}{2}\right)\left(1 + (\frac{b}{c})^2\right)\right) \tag{30}$$

Analogously, we obtain from Eqs (20), (23), (24), (28) and (29);

$$B_Z = B_P\left(2\frac{R_0\Delta_x}{d^2} + \left(\ln \frac{a}{d} - \left(\Lambda + \frac{1}{2}\right)\left(1 - (\frac{a}{d})^2\right)\right)\right) +$$

$$B_L\left(\ln \frac{b}{d} - \left(\Gamma + \frac{1}{2}\right)\left(1 - (\frac{b}{d})^2\right)\right) \tag{31}$$

and

$$B_R = - B_P\, 2\frac{R_0\Delta_y}{d^2} + B_L\, 2\,\Omega\, (\frac{b}{d})^2 \tag{32}$$

We note that the plasma radius (r=a) is a function of the displacements Δ_x and Δ_y;

$$a = a_L - \sqrt{\Delta_x{}^2 + \Delta_y{}^2} \tag{33}$$

where a_L is the plasma limiter minor radius. We solve Eqs. (30) and (31) for Δ_x and Λ obtaining;

$$\begin{aligned}
\Delta_x\ B_P \frac{2R_0}{c^2}\left(1 + (\tfrac{c}{d})^2\right) = {} & B_Z\left(1 + (\tfrac{a}{c})^2\right) + B_C\left(-1 + (\tfrac{a}{d})^2\right) + \\
& B_P\left(1 - (\tfrac{a}{d})^2 - \ln\tfrac{c}{d} - (\tfrac{a}{c})^2\ln\tfrac{a}{d} - (\tfrac{a}{d})^2\ln\tfrac{a}{c}\right) + \\
& B_L\left(1 - (\tfrac{a}{d})^2 - \ln\tfrac{c}{d} - (\tfrac{a}{c})^2\ln\tfrac{b}{d} - (\tfrac{a}{d})^2\ln\tfrac{b}{c}\right) - \\
& B_L\left(\Gamma + \tfrac{1}{2}\right)(\tfrac{b}{c})^2\left(1 - (\tfrac{a}{b})^2\right)\left(1 + (\tfrac{c}{d})^2\right)
\end{aligned} \tag{34}$$

and

$$\begin{aligned}
\Lambda\ B_P\left(1 + (\tfrac{c}{d})^2\right) = {} & -\ B_Z - B_C\,(\tfrac{c}{d})^2 + \\
& B_P\left(\ln\tfrac{a}{d} + (\tfrac{c}{d})^2\ln\tfrac{a}{c} - \tfrac{1}{2}\left(1 - (\tfrac{c}{d})^2\right)\right) + \\
& B_L\left(\ln\tfrac{b}{d} + (\tfrac{c}{d})^2\ln\tfrac{b}{c} + (\tfrac{c}{d})^2 - \left(\Gamma + \tfrac{1}{2}\right)\left(1 + (\tfrac{c}{d})^2\right)\right)
\end{aligned} \tag{35}$$

Since the plasma radius is dependent on the displacement through Eq. (33), we use the following procedure to determine Δ_x, Δ_y and Λ:

1) Determine the vertical displacement Δ_y by insertion into Eq. (32).

2) Determine the horizontal displacement Δ_x by inserting Eq. (33) into Eq. (34) and finding the Δ_x using a numerical equation solver. (Alternatively we could have solved Eq. (33) and (34) simultaneously by iteration) .

3) Determine asymmetry parameter Λ by insertion into Eq. (35)

In the following we will assume Γ=0 and Ω=0. This approximation is justified in our case since we are interested in the plasma behaviour on a time scale which is long compared to the transverse field penetration time of the liner (τ_v of the liner is a few microseconds).

4. Analysis of experimental data

In order to illustrate the analysis method, we present here the results a systematic study of the effect of the external vertical field on the toroidal equilibrium. The Extrap T1-U experiment was run in RFP mode. Operational parameters are summarized in Table I. Time-traces of some plasma parameters for a discharge with optimized applied vertical field are shown in Fig. 3.

The vertical field for equilibrium control in Extrap T1-U is produced by the primary winding. The primary turns are located on the inboard and outboard side of the shell, as shown in Fig.1. The inboard and outboard turns are electrically connected in parallel, and by introducing a small inductance in either the inboard or outboard turns, we control the ratio of the inboard and outboard primary current, thus changing the amplitude of the applied vertical field in the plasma region.

We have inserted small inductances in steps up to a total of about 80 μH in either winding, which resulted in inboard to outboard current ratios ranging from I_{in}/I_{out}=0.13 to I_{in}/I_{out}=1.35. The applied vertical field was thus varied in steps over a quite large range. The resulting time evolution of the horizontal displacement Δ_x, the vertical displacement Δ_y and the poloidal field asymmetry parameter Λ was monitored, using the analysis method described above. The results are shown in Figs 4a to 4f for a series of discharges with primary current ratios I_{in}/I_{out}=1.35, 1.01, 0.68, 0.57, 0.42 and 0.13 respectively. We find that the plasma duration is clearly dependent on the inboard to outboard primary current ratio, i.e. to the applied vertical field strength. The pulse length is increased by a factor of two from t_p=250 μs, which we observe with the extreme ratios I_{in}/I_{out}=1.35 and 0.13 , shown in Figs 4a and 4f respectively, to t_p=500 μs at the optimimum current ratio which seems to be around I_{in}/I_{out}=0.68. The total displacement of the outermost closed plasma flux surface is in this case fairly stationary during the discharge and the displacement is only around Δ=1 mm (see Fig. 4c). By decreasing or increasing the current ratio from this optimum value we obtain plasmas with a non-stationary horizontal position, drifting outward or inward respectively. The horizontal velocity is approximately constant during the discharge. The velocity ranges from v=5 m/s to v=20 m/s depending on the applied vertical field, and is increasing as the current ratio gets further away from the optimum value.

The vertical position is relatively stationary for all primary current ratios. However, it seems as the discharge position generally is about 1 mm below the equatorial plane at the start up and then moves upward during the initial stage of the discharge to a central position. The termination phase of the discharge is in general characterized by a rapid upward movement of the pinch.

For all cases, the poloidal field asymmetry factor Λ is in the range from Λ=0 to Λ=-0.5 and seems not to be simply related to the primary current ratio.

We conclude that good equilibrium control is necessary in order to obtain long pulses and that the shorter discharge durations obtained with a non-optimimized primary current distribution is explained by a horizontal drift motion of the plasma, either inward or outward, depending on the value of the inboard to outboard current ratio.

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Appendix: Computer code for equilibrium analysis

A computer code ('TOREQU') for analysis of the external toroidal equilibrium measurement has been developed. The code computes the time evolution of the horizontal displacement Δ_x, the vertical displacement Δ_y and the poloidal field asymmetry factor Λ for a single discharge. The code runs on a LSI11/73 computer with RSX11M operating system. Input diagnostic data are read from data files created by the CAMAC data acquistion system software DAMP. The computational section of the code is contained in a separate subroutine ('DXDYLA') which optionally can be used in other software. All code is written in FORTRAN77.

The 'TOREQU' code requires the following diagnostic input data, scaled as shown below:

1. Plasma current (kA)
2. Loop voltage (V)
3. Edge toroidal field (T)
4. Average vertical magnetic field B_Z (T)
5. Average horizontal magnetic field B_R (T)
6. Cosine coil 1 (Am)
7. Cosine coil 2 (Am) (optional)
8. Cosine coil 3 (Am) (optional)

It was found that the external equilibrium diagnostics picked up a certain amount of toroidal field and therefore the measured edge toroidal field is used for subtracting this unwanted contribution to the signal prior to the equilibrium computation.

The calculation of Δ_x, Δ_y and Λ, which is done in the subroutine 'DXDYLA', follows the method described in section 3 of this report.

Example use of the code 'TOREQU' (operator input is underlined):

RUN $TOREQU
Enter terminal type (1=Westward, 2=Tektronix, 3=Pericom) 3
Enter shot# (0=last, -1=exit): 24470

....

Enter shot# (0=last, -1=exit): -1

The code requires that a copy of the parameter file 'TOREQU.DAT' exists on the default directory. Parameters in the code, such as machine geometry, diagnostic channel#, calibration factors, plotting parameters and so on, are changed by editing the parameter file on the default directory using the EDT editor:

EDIT TOREQU.DAT
c <ret>
......
<F1><7>
Command: Exit

Listing of the most important parameters in 'TOREQU.DAT':

- Diagnostic channel#
- Toroidal resistance of liner
- Conversion scale factors for the input diagnostics
  (e.g. from [Am] to [T] for B_{cos} signals)
- Scale factors for $B_{\phi a}$ pick-up subtraction
- Machine geometry (R_0, a_L, b)
- Magnetic diagnostic coil radii (c, d)
- Plotting parameters (axis scaling and so on)

Table I Extrap T1-U Operating Parameters

vacuum vessel:

major / minor radii: 0.5 m / 0.057 m

material: stainless steel

bellow sections: inner minor radius 57 mm, 0.25 mm thickness

port sections: inner radius a_L=55 mm, 0.7 mm thickness

$\tau_V \approx 3\ \mu s$

R_{tor}=78 mΩ

shell:

material: brass, 2.5 mm thickness

12 poloidal gaps, 2 toroidal gaps

τ_V=0.5 ms, τ_H=0.3 ms

filling gas:

5 mTorr D_2, continuous gas flow

preionization:

hot filament, biased relative to vessel wall

OHC primary winding:

4 turns in series on inboard and 4 turns in series on outboard side of shell, inboard and outboard windings connected in parallel

OHC capacitor banks:

C_4 (500 μF, t=2500 μs): V_4=6 kV

C_5 (1600 μF, t=2700 μs): V_5=2.5 kV

TF winding:

48 turns

TF capacitor banks:

C_1 (120 μf, t=2280 μs): V_1=4 kV

C_{elyt} (144 mF, t=2750 μs): V_{elyt}=100 V

Table II Magnetic diagnostics data

Cosine coil #1 (ϕ=261°): $k_1=1.0\times10^{-7}$ Vs/Am

Cosine coil #2 (ϕ=141°): $k_2=1.3\times10^{-7}$ Vs/Am

Cosine coil #3 (ϕ=39°): $k_3=1.4\times10^{-7}$ Vs/Am

Cosine coil radius: c=61 mm

Diff. flux loop area (B_Z, B_R): A= 0.421 m^2

Diff. flux loop minor radius: d=67 mm

Figure captions

1. Cross sectional diagram of the Extrap T1-U device showing the bellows vacuum vessel, resistive shell, octupole rings, toroidal field coil and primary coils. The primary winding produces the vertical field for plasma equilibrium control.

2. Diagram showing the notation used in the analysis; R_0 is vacuum vessel major radius, a is minor radius of outermost closed plasma flux surface, R_p is the major radius of the center of the outermost flux surface, Δ_x is the horizontal displacement of the outermost flux surface relative to the geometrical minor axis, Δ_y is the corresponding vertical shift, a_L is the plasma limiter minor radius, b is the liner current sheet minor radius, c is the cosine coil minor radius and d is the minor radius of the toroidal flux loops. The angular positions of the flux loops are indicated in the figure.

3. Time traces of, from top to bottom, plasma+liner current, loop voltage, average toroidal magnetic field, edge toroidal field and line averaged plasma density for a discharge with optimized vertical field. Inboard to outboard primary current ratio I_{in} / I_{out}=0.68. Operational parameters as in Table I.

4a. Time traces of, from top to bottom, plasma+liner current, horizontal displacement Δ_x, vertical displacement Δ_y and poloidal field asymmetry parameter Λ. Operational parameters as in Table I. Inboard to outboard primary current ratio I_{in} / I_{out}=1.35.

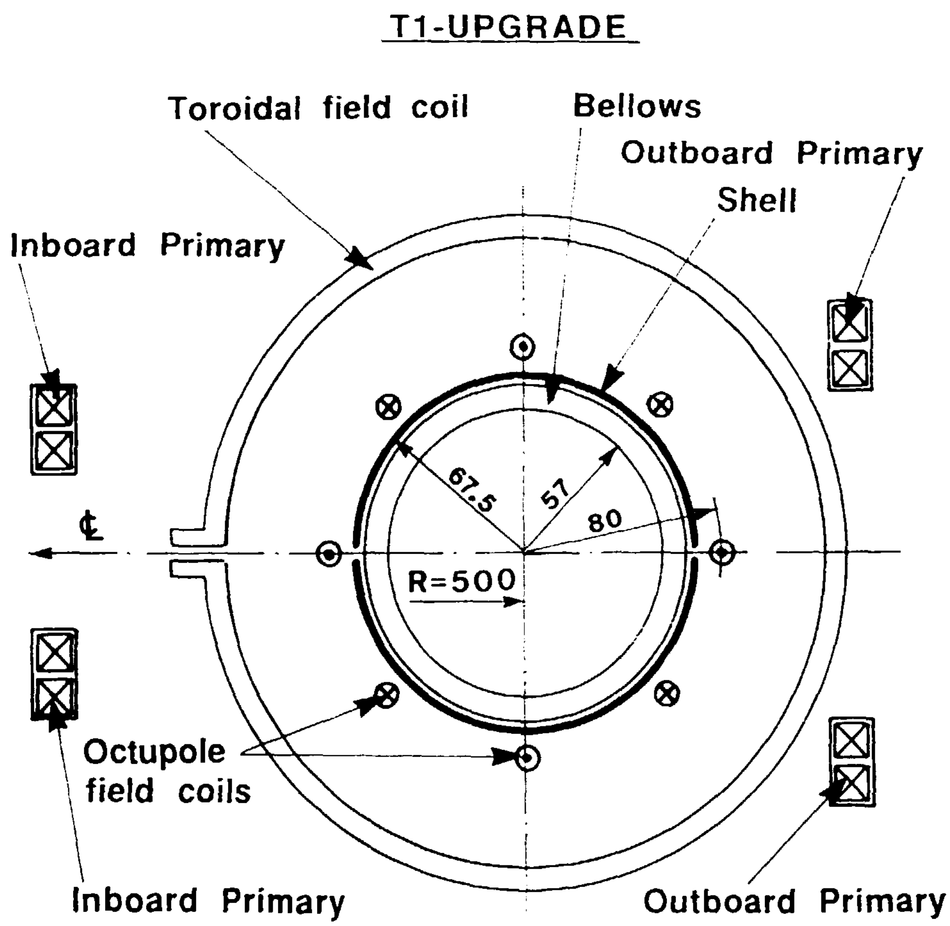
4b. Same as figure 4a, but inboard to outboard primary current ratio I_{in} / I_{out}=1.01.

4c. Same as figure 4a, but inboard to outboard primary current ratio I_{in} / I_{out}=0.68.

4d. Same as figure 4a, but inboard to outboard primary current ratio I_{in} / I_{out}=0.57.

4e. Same as figure 4a, but inboard to outboard primary current ratio I_{in} / I_{out}=0.42.

4f. Same as figure 4a, but inboard to outboard primary current ratio I_{in} / I_{out}=0.13.



T1-UPGRADE
Toroidal field coil
Bellows
Outboard Primary
Shell
Inboard Primary
67.5
57
80
R=500
Octupole
field coils
Inboard Primary
Outboard Primary

Fig. 1

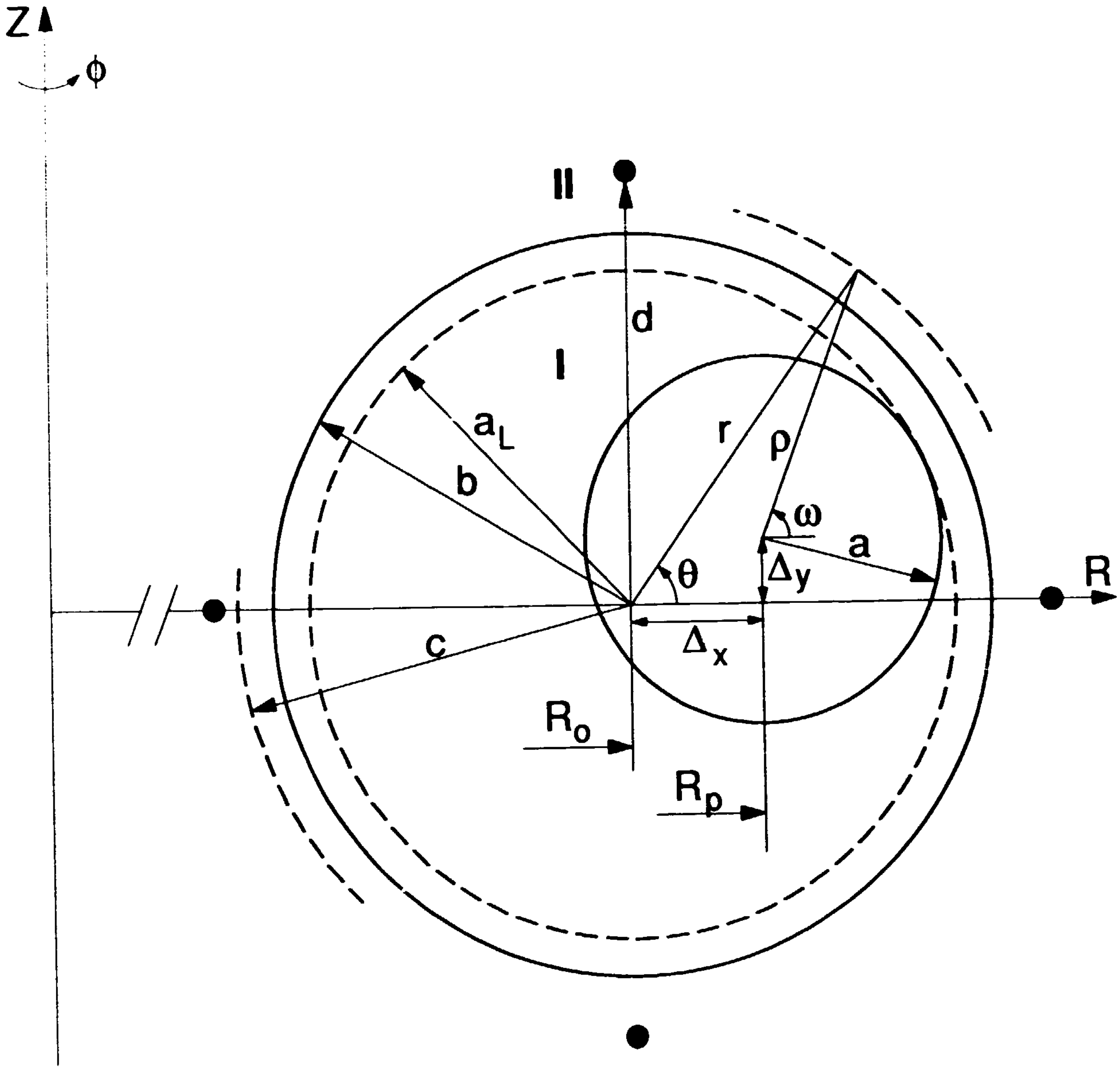
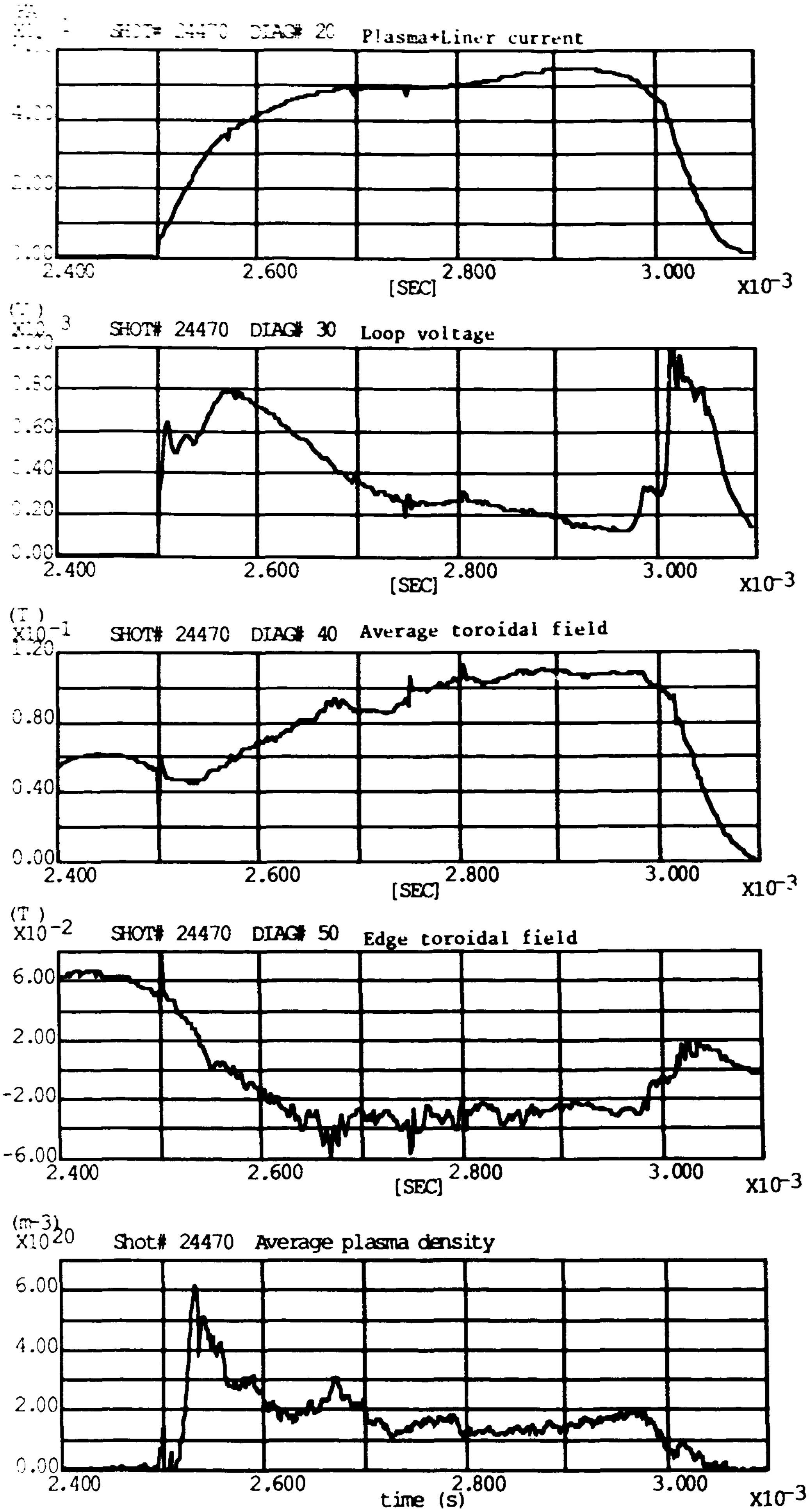
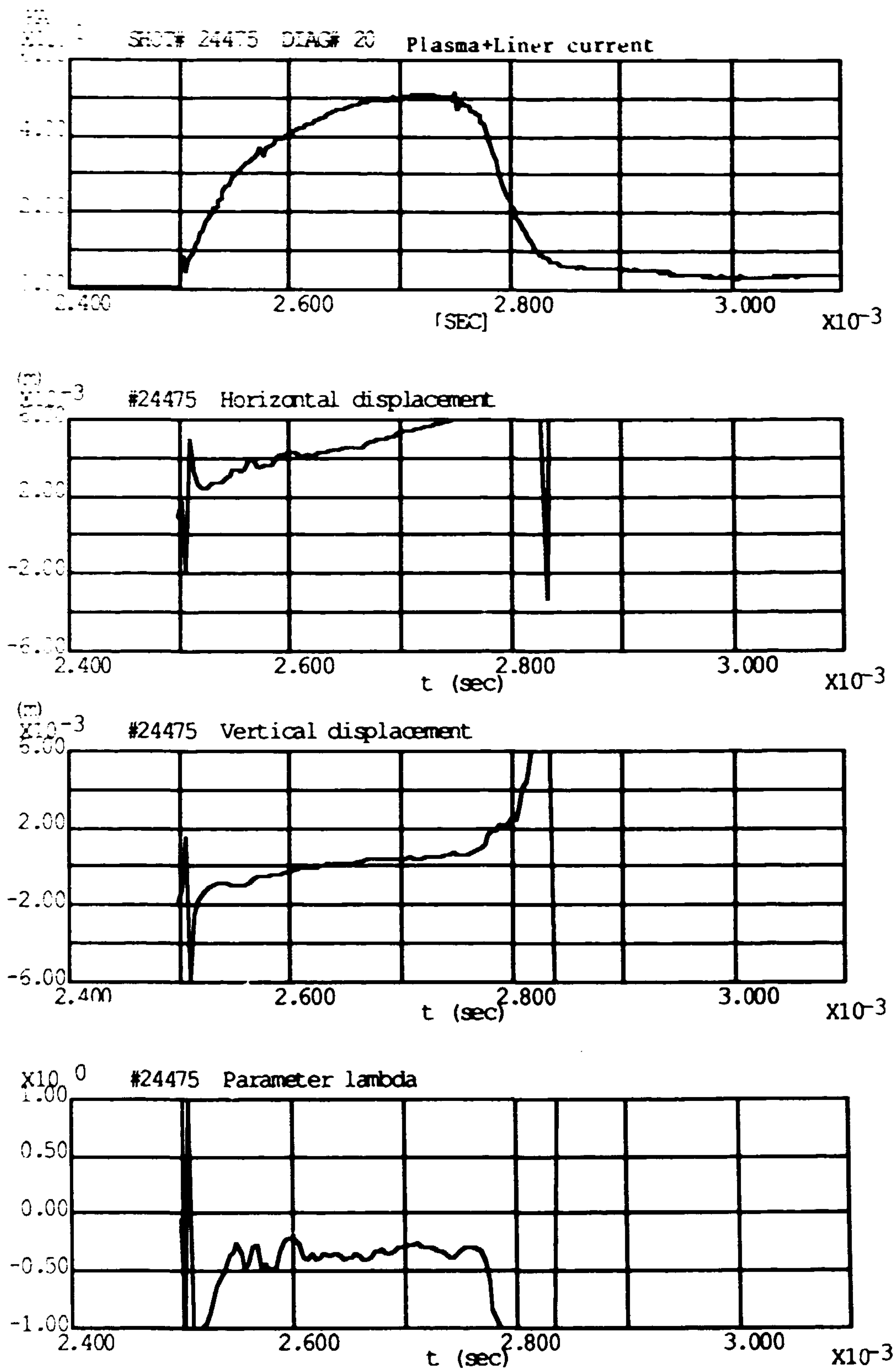


Fig. 2



DIAG# 20
Plasma+Liner current
4.00
0.00
2.400
2.600
2.800
3.000
[SEC]
X10^-3
SHOT# 24470
DIAG# 30
Loop voltage
0.00
2.400
2.600
2.800
3.000
[SEC]
X10^-3
(T)
X10^-1
SHOT# 24470
DIAG# 40
Average toroidal field
0.80
0.40
0.00
2.400
2.600
2.800
3.000
[SEC]
(T)
X10^-2
SHOT# 24470
DIAG# 50
Edge toroidal field
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
[SEC]
X10^-3
(m-3)
X10^20
Shot# 24470
Average plasma density
6.00
4.00
2.00
0.00
2.400
2.600
2.800
3.000
time (s)
X10^-3

Fig. 3



SHOT# 24475 DIAG# 20 Plasma+Liner current
2.400
2.600
[SEC]
2.800
3.000
X10-3
#24475 Horizontal displacement
2.400
2.600
t (sec)
2.800
3.000
X10-3
#24475 Vertical displacement
2.00
-2.00
-6.00
2.600
t (sec)
2.800
3.000
X10-3
X10 0
#24475 Parameter lambda
0.50
0.00
-0.50
-1.00
2.400
2.600
t (sec)
2.800
3.000
X10-3

Fig. 4a

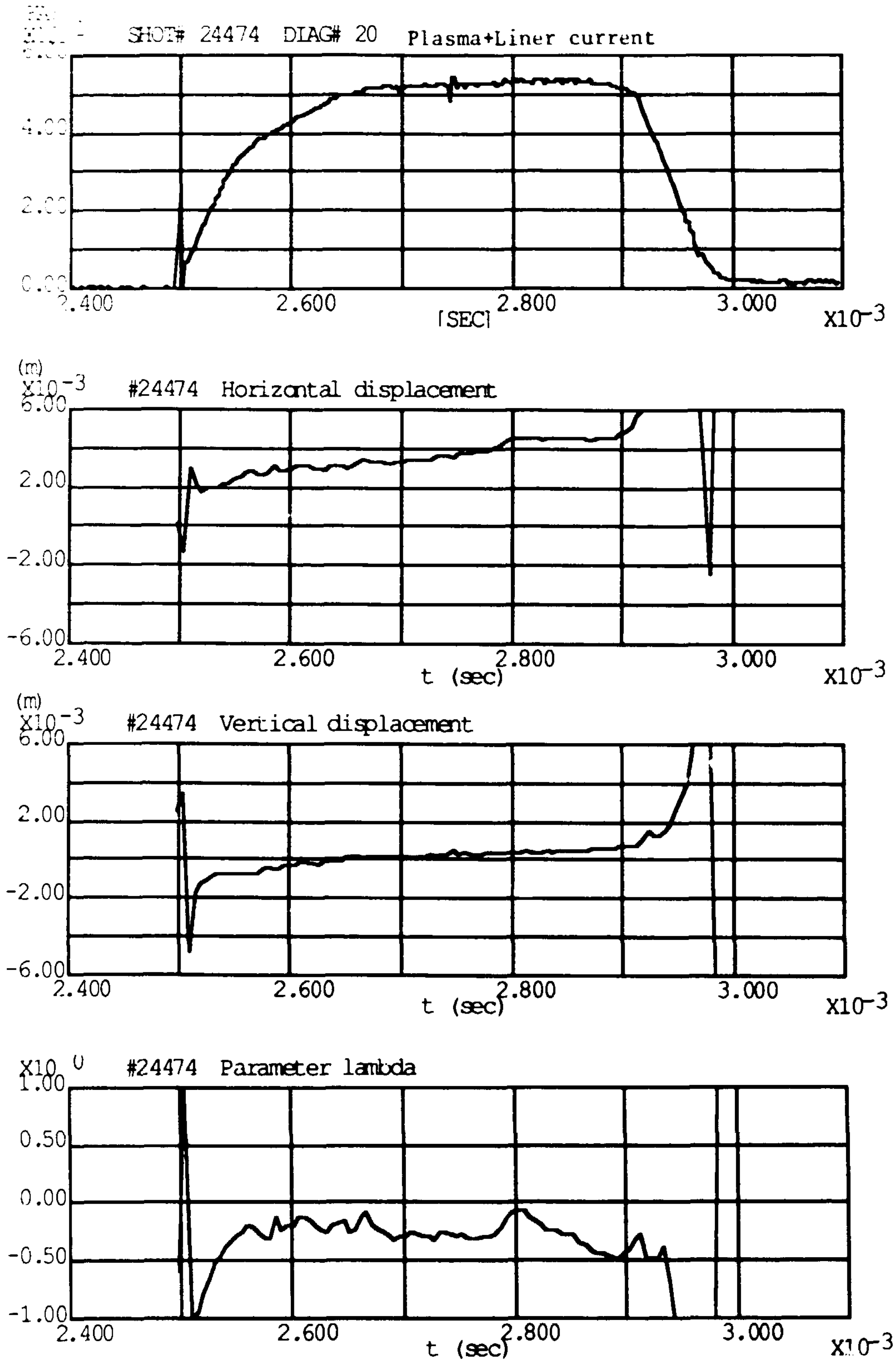

SHOT# 24474 DIAG# 20 Plasma+Liner current
4.00
2.00
0.00
2.400
2.600
2.800
3.000
[SEC]
X10-3
(m)
X10-3
#24474 Horizontal displacement
6.00
2.00
-2.00
-6.00
t (sec)
#24474 Vertical displacement
X10 0
#24474 Parameter lambda
1.00
0.50
0.00
-0.50
-1.00

Fig. 4b

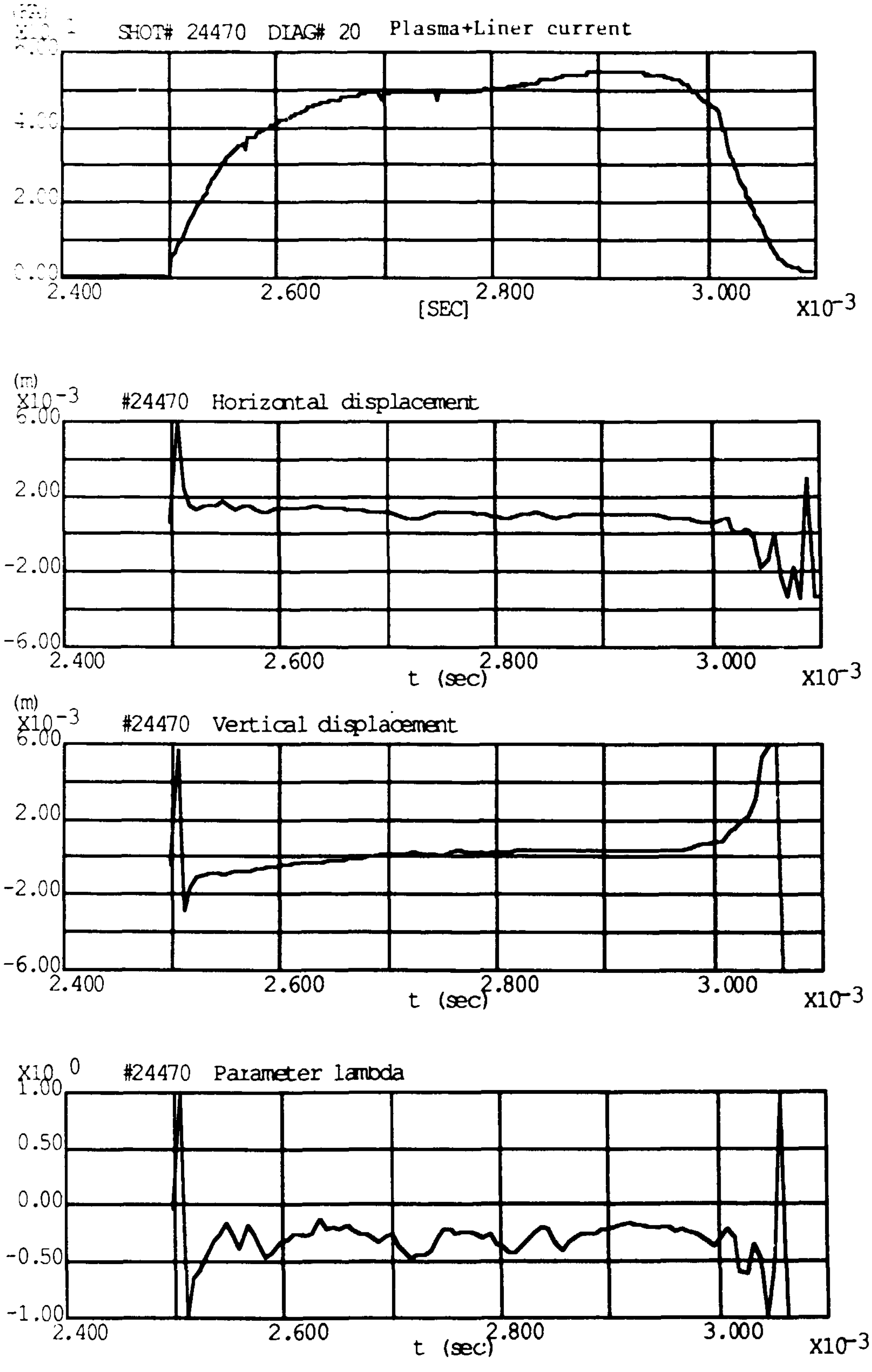

SHOT# 24470 DIAG# 20 Plasma+Liner current
4.00
2.00
2.400
2.600
2.800
3.000
[SEC]
X10-3
(m)
X10-3
#24470 Horizontal displacement
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
(m)
X10-3
#24470 Vertical displacement
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
X10 0
#24470 Parameter lambda
1.00
0.50
0.00
-0.50
-1.00
2.400
2.600
2.800
3.000
t (sec)
X10-3

Fig. 4c

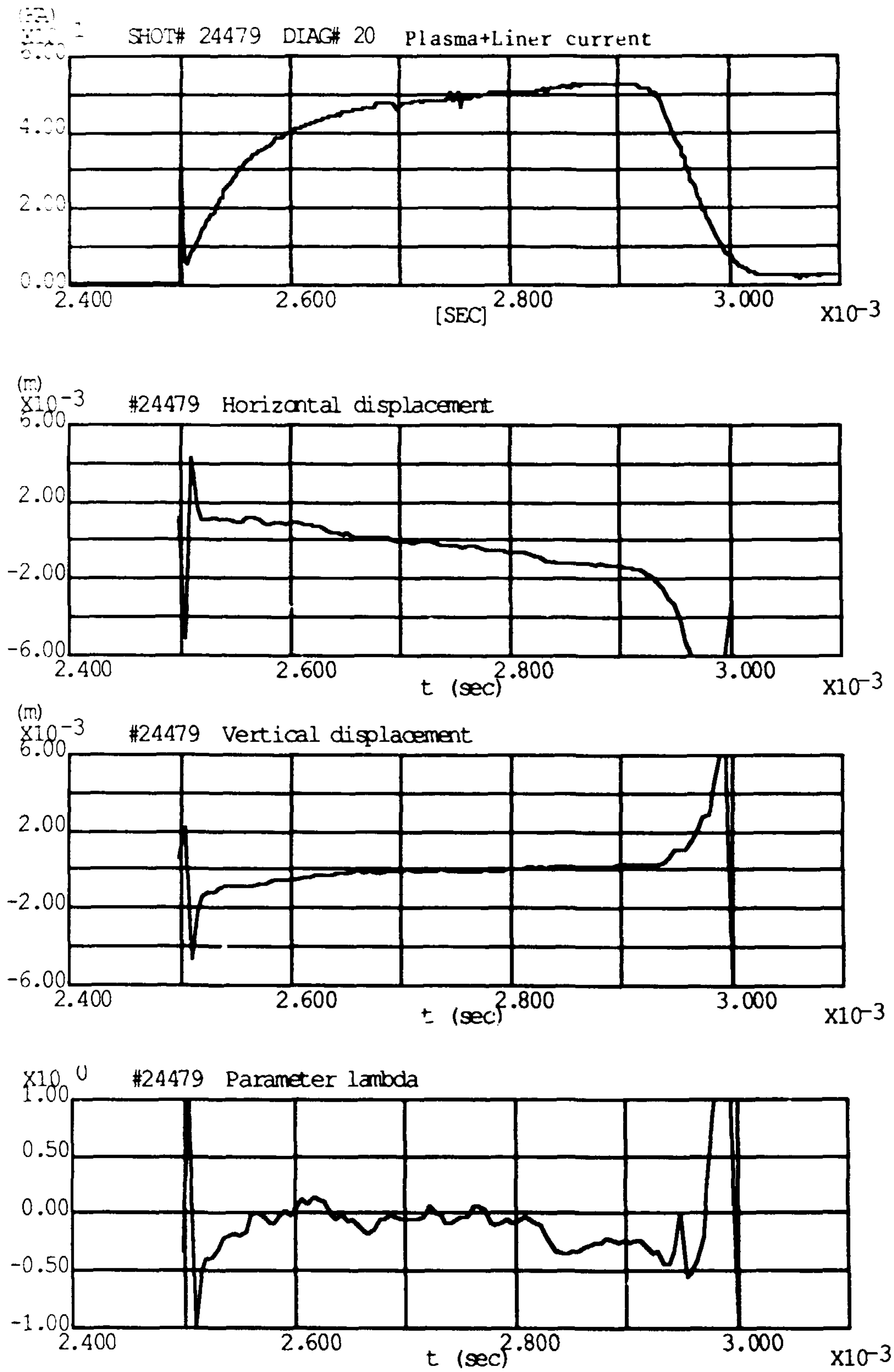

SHOT# 24479 DIAG# 20 Plasma+Liner current
4.00
2.00
0.00
2.400
2.600
2.800
3.000
[SEC]
X10-3
(m)
X10-3
#24479 Horizontal displacement
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
(m)
X10-3
#24479 Vertical displacement
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
X10 0
#24479 Parameter lambda
1.00
0.50
0.00
-0.50
-1.00
2.400
2.600
2.800
3.000
t (sec)
X10-3

Fig. 4d

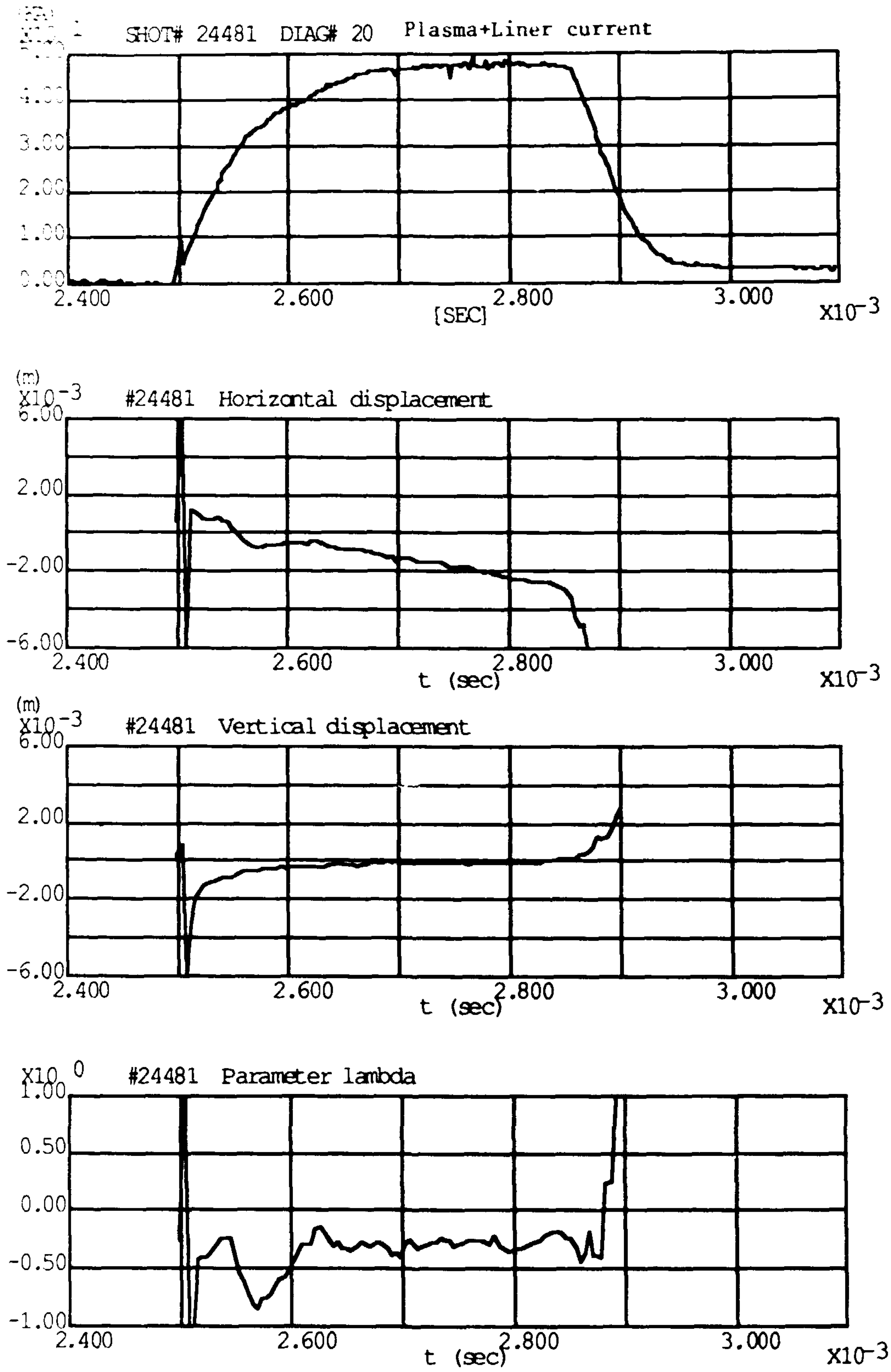

SHOT# 24481 DIAG# 20 Plasma+Liner current
3.00
2.00
1.00
2.400
2.600
2.800
3.000
[SEC]
X10-3
(m)
X10-3
#24481 Horizontal displacement
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
(m)
X10-3
#24481 Vertical displacement
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
X10 0
#24481 Parameter lambda
1.00
0.50
0.00
-0.50
-1.00
2.400
2.600
2.800
3.000
t (sec)
X10-3

Fig. 4e

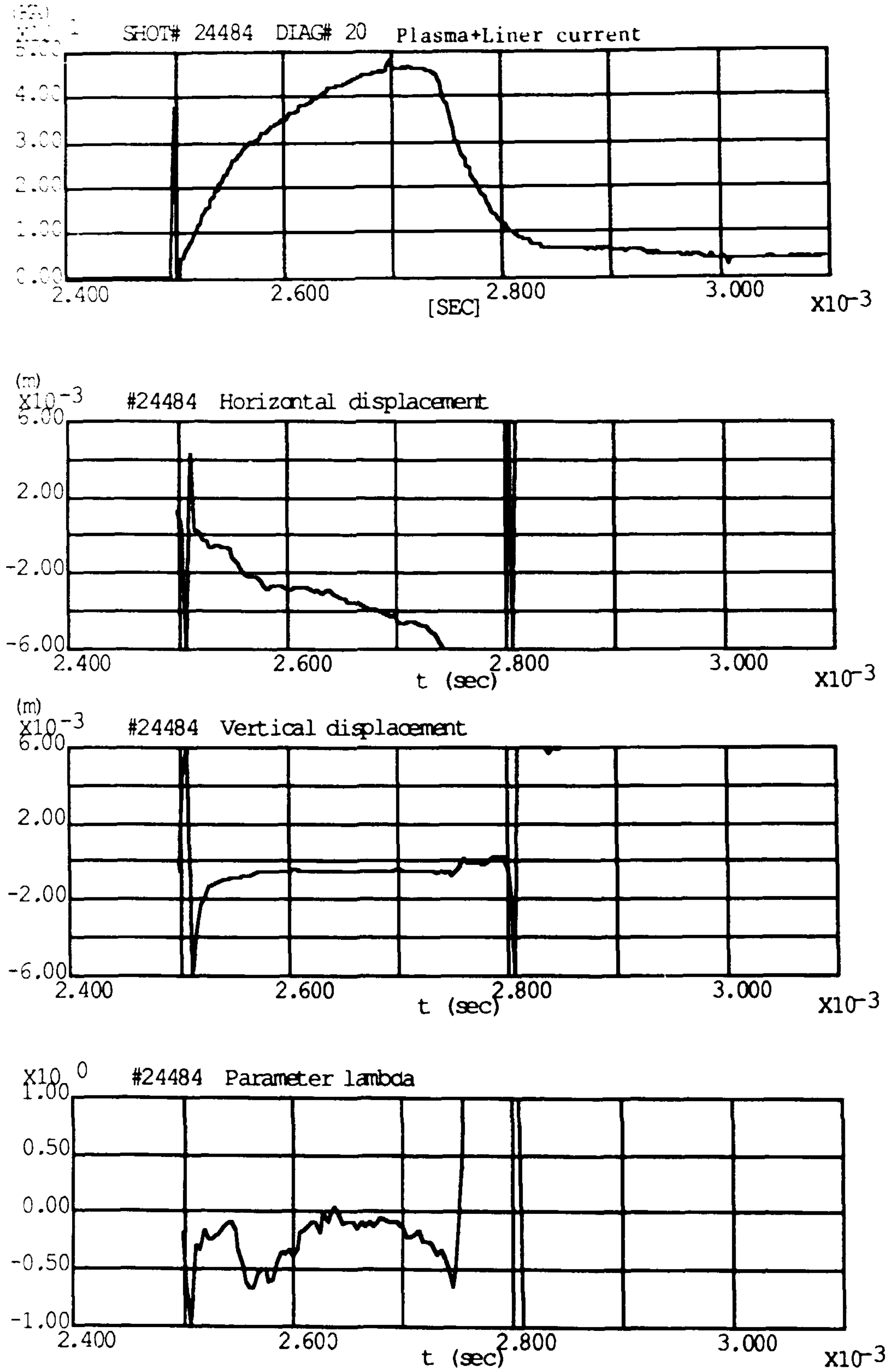

SHOT# 24484 DIAG# 20 Plasma+Liner current
4.00
3.00
2.00
1.00
0.00
2.400
2.600
2.800
3.000
[SEC]
X10-3
(m)
X10-3
#24484 Horizontal displacement
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
(m)
X10-3
#24484 Vertical displacement
6.00
2.00
-2.00
-6.00
2.400
2.600
2.800
3.000
t (sec)
X10-3
X10 0
#24484 Parameter lambda
1.00
0.50
0.00
-0.50
-1.00
2.400
2.600
2.800
3.000
t (sec)
X10-3

Fig. 4f

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A method for external measurement of toroidal equilibrium parameters

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Abstract

A method has been developed for determining from external magnetic field measurements the horizontal shift, the vertical shift and the poloidal field asymmetry parameter (Λ) of a toroidal plasma in force equilibrium. The magnetic measurements consist of two toroidal differential flux loops, giving the average vertical magnetic field and the average radial magnetic field respectively, together with cosine-coils for obtaining the m=1 cosine harmonic of the external poloidal magnetic field component. The method is used to analyse the evolution of the toroidal equilibrium during reversed-field pinch discharges in the Extrap T1-U device. We find that good equilibrium control is needed for long plasma pulses. For non-optimized externally applied vertical fields, the diagnostic clearly shows a horizontal drift motion of the pinch resulting in earlier discharge termination.

Key words

toroidal equilibrium, reversed field pinch, RFP, Extrap, cosine coil