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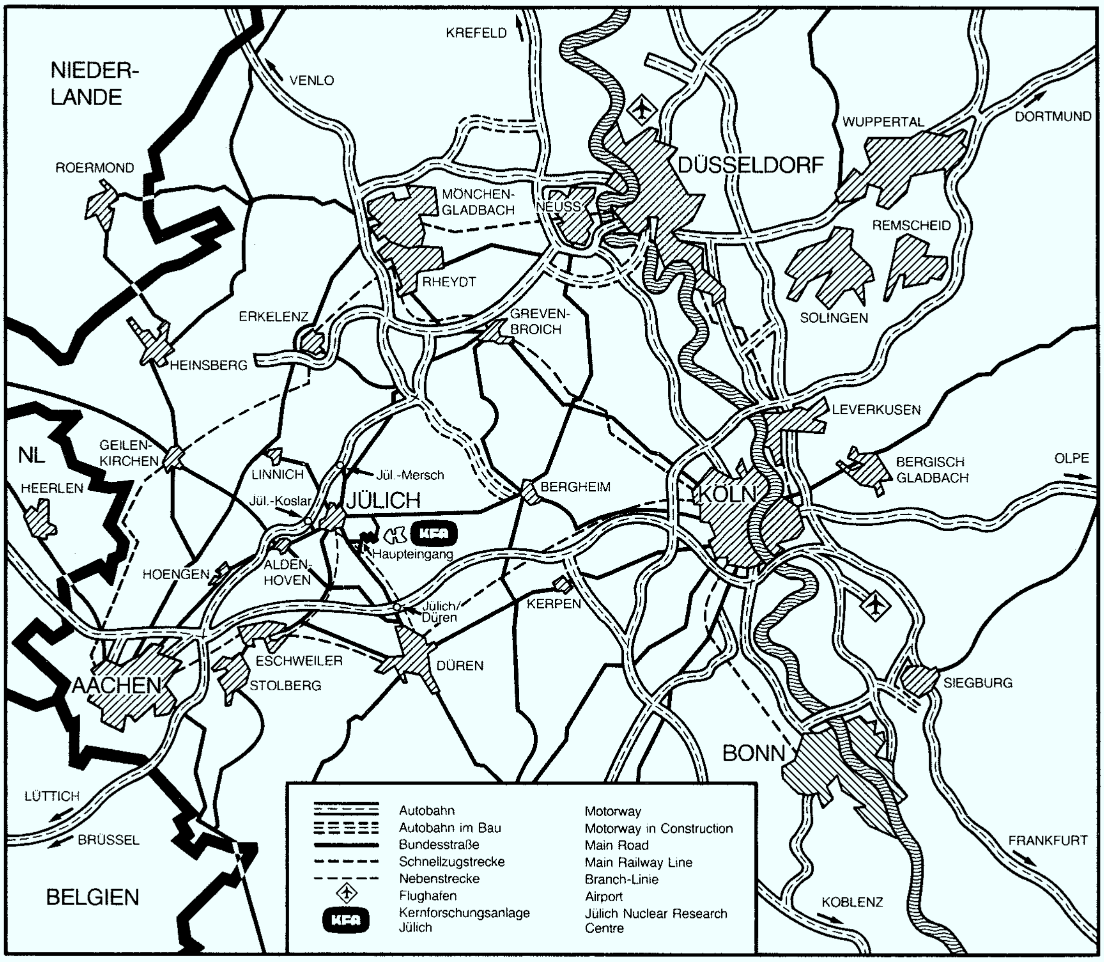

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Abstract

On the basis of a method developed by Zakharov and Shafranov [1] for the determination of the plasma cross section in toroidal geometry two special pick-up coils for the two components of the poloidal magnetic field were built. A cosine coil of higher order and a saddle coil were designed and installed outside the plasma column. The proper sum of these two signals permits the evaluation of the first momentum of the plasma current which is the equilibrium plasma displacement. The horizontal position of the plasma column was controlled on-line by the TEXTOR feedback system using this analog sum signal.

Introduction

The different operating modes of TEXTOR tokamak require a redundant offer of the actual values of plasma position signals for feedback control. This paper describes a magnetic method of plasma position detection. The diagnostic components involved allowed a position control up to pulse durations of 4 sec.

The equilibrium displacement of a tokamak plasma is often studied by measuring the poloidal magnetic field components outside the plasma using magnetic sensors. The difference signal of the poloidal field on the high and low field side in the aequatorial plane gives basic information about the plasma position. This method is based on the theory of macroscopic equilibrium of the plasma column [2] . Relating to this theory a set of formula is given in [3] for the determiniation of the position of the plasma.

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Two alternative methods were developed on TEXTOR. They rely on interferometric [4] or polarimetric [5] IR-laser measurements, from which an actual value signal was derived which permitted a good position control. Still an other way to determine the horizontal plasma position is based on Maxwell's equations. This method was suggested by Zakharov and Shafranov [1] . The current density multipole moments derived represent integral relations of the magnetic field components measured outside of the plasma. Adopting the result of Zakharov and Shafranov special coils were made for the determination of the plasma position. The task was not only to determine the plasma position, but to control it using the existing active feedback control system [6] . A schematic diagram is given in Fig. 1. Plasma current and plasma position are controlled by the feedback system of TEXTOR which employs decoupling controllers.

Design of the coils

According to [1] in a cylindrical coordinate system (R,φ,z) the m-th toroidal multipole moment is

$$Y_m = \frac{1}{I_p}\int j_\varphi f_m \, dS = \frac{1}{\mu_0 I_p}\oint (f_m B_\omega + R g_m B_n)\, dl\,, \qquad (1)$$

where I_p is the plasma current, j_φ is the current density, S is the cross sectional area of the plasma, l is a contour close to the cross-sectional area, B_ω and B_n are the tangential and normal magnetic field components, f_m and g_m are polynomials satisfying the differential equation of the problem.

The zeroth moment, Y_0, is the plasma current itself, Y_1 defines the plasma current centre from the origin of the contour l, and the higher order moments determine the plasma shape.

Let us assume a symmetry with regard to the z = 0 plane. If the displacement, Δ_H, is much smaller than the plasma major radius R_0, then

$$Y_1 \equiv \Delta_H = \frac{1}{\mu_0 I_p}\oint \left[\left(x + \frac{x^2}{2R_0}\right)B_\omega + z\left(1 + \frac{x}{R_0}\right)B_n\right] dl\,, \qquad (2)$$

where $X = R - R_0$ or $X = b\cos\omega$and b is the radius of contour 1.

According to the integral (2) for the first part a higher order cosine-coil with turn number of

$$n(\omega) \propto \frac{b}{4R_0} + \cos\omega + \frac{b}{4R_0}\cos 2\omega$$

and for the second part of (2) a saddle coil of width

$$\Delta(\omega) \propto \sin\omega \left(1 + \frac{b}{R_0}\cos\omega\right)$$

were built. The number of turns for the modified cosine-coil is 1854, and the effective cross section area of this is 3.63 cm². The principle of the coil design with a variable winding density is shown in Fig. 2. The total area of the saddle coil is 1.7×10^4cm². The radius of the coil is b = 55,1 cm, the major radius of the plasma is R_0 = 175 cm. The plasma current I_p playing a role in the denominator of (2) was measured with a Rogowsky coil.

Results

For the real time evaluation of Δ_H the signals from the coils were integrated frist, normalized to the plasma current I_p and finally added with their proper coefficients. The final signal then is proportional to the plasma current displacement. Plasma position control was examined for various plasma operational programs. The parameter range is listed below.

Plasma current	[kA]	$190 \leq I_p \leq 600$
Toroidal field	[T]	$1.8 \leq B_T \leq 2.6$
Limiter radius	[cm]	$44 \leq a_L \leq 48$
ICRH heating power	[kW]	max. 1000
Electron density	[10^{13}cm^{-3}]	$1.0 \leq \bar{n}_e \leq 4.5$
Electron temperature	[eV]	$800 \leq Te \leq 1500$

Fig. 3 presents characteristic signals of different discharges. The duration of the current pulse lasted up to 4 sec. The measurements of plasma position were compared with other position signals, e.g. a laser polarimeter and a laser interferometer signal [5]. The time dependence of the signals of the laser polarimeter and the magnetic diagnostics are given in Fig. 4. In this case the plasma column was displaced by program 3 cm towards the machine center for a duration of one second beginning at a time one second after start-up. The shift of the plasma column is demonstrated by the displacement of the electron and current density profiles (see Fig. 5). The linearity of the displacement was checked by comparing it with measured position signals of the laser polarimeter and interferometer as presented in Fig. 6. Fig. 7 shows the loop voltage as a function of plasma position. The loop voltage was measured 0.5 sec after the beginning of the displacement of the plasma column.

Conclusion

We have shown that a plasma displacement can be reliably measured by a method suggested by Zakharov and Shafranov and controlled by the TEXTOR positional feedback system. The results obtained are in good agreement with those measured by laser interferometer or polarimeter. The described method is capable to acquire the plasma position under various experimental conditions in a wide range of machine parameters. The new positional system was integrated into the existing control system adjusting the gain of the control loop.

References

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Figure Captions

Fig. 1 Principle of plasma position control in TEXTOR

Fig. 2 Principle of an induction coil for the measurement of the first current momentum. Minerally insulated coaxial steel cable (Typ: Thermocoax) permitted a working temperature of more than 600°C. The coil was composed out of four different winding elements. The number in brackets represents the winding density used in the coil fabrication.

Fig. 3 Plasma current, loop voltage and horizontal displacement as a function of time for discharges with magnetic position control:

a. Standard discharge;
b. Discharge with high current;
c. Discharge with programmed time evolution of the current;
d. Plasma position 1 sec after start-up of the discharge was displaced 7 cm towards the machine centre.

Fig. 4 Magnetic and polarimetric position signal as a function of time for a discharge with magnetic feedback position control.

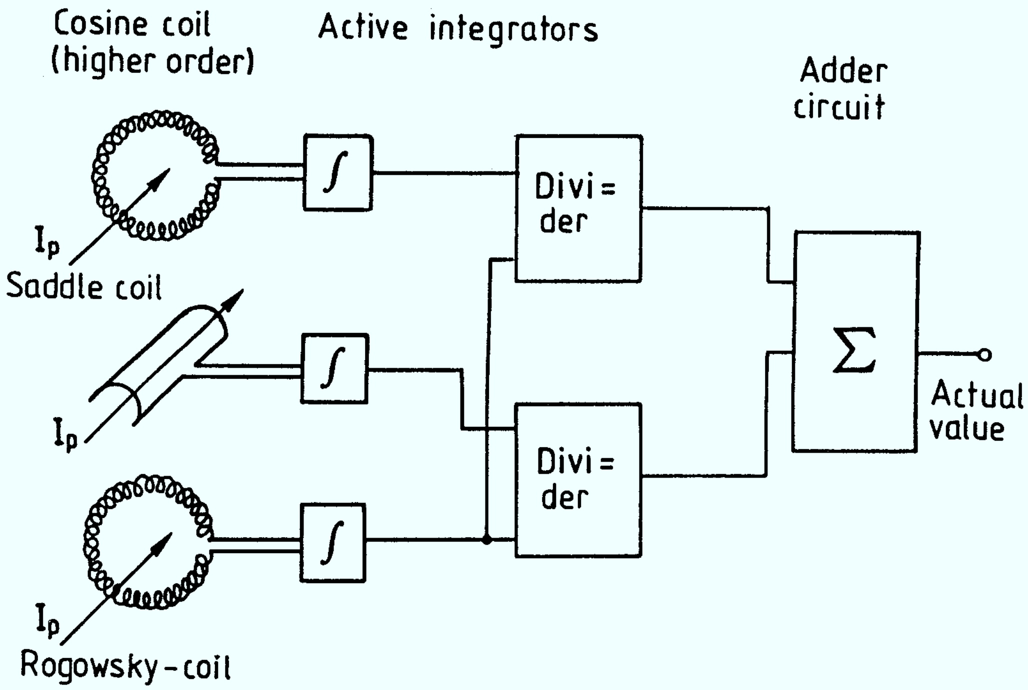
Fig. 5 Electron and plasma current density profiles for a discharge with normal radial position measured at time t = 0.9 sec and intentionally displaced position at t = 1.7 sec. The plasma shift began at t = 1 sec and lasted for one second.

Fig. 6 Plasma column displacement measured by a laser polarimeter and a laser interferometer versus magnetic method for a discharge with magnetic position control.

Fig. 7 Loop voltage as a function of horizontal plasma position.

Fig. 1

$$\Delta_H = \frac{1}{\underset{\substack{\downarrow \\ \text{Rogowsky - coil}}}{\mu_0 \, I_p}} \oint \left[\left(x + \underset{\substack{\downarrow \\ \text{Cosine coil} \\ \text{(higher order)}}}{\frac{x^2}{2R_0}} \right) B_\omega + z \left(1 + \underset{\substack{\downarrow \\ \text{Saddle coil}}}{\frac{x}{R_0}} \right) B_n \right] dl$$



Scheme of TEXTOR on-line control system

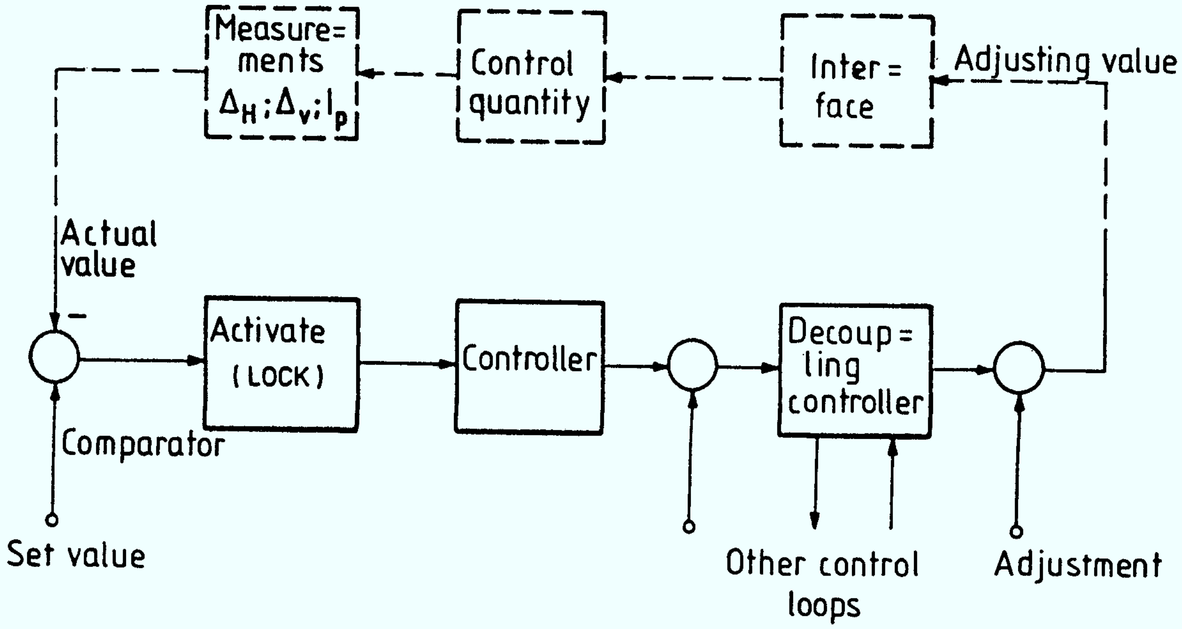
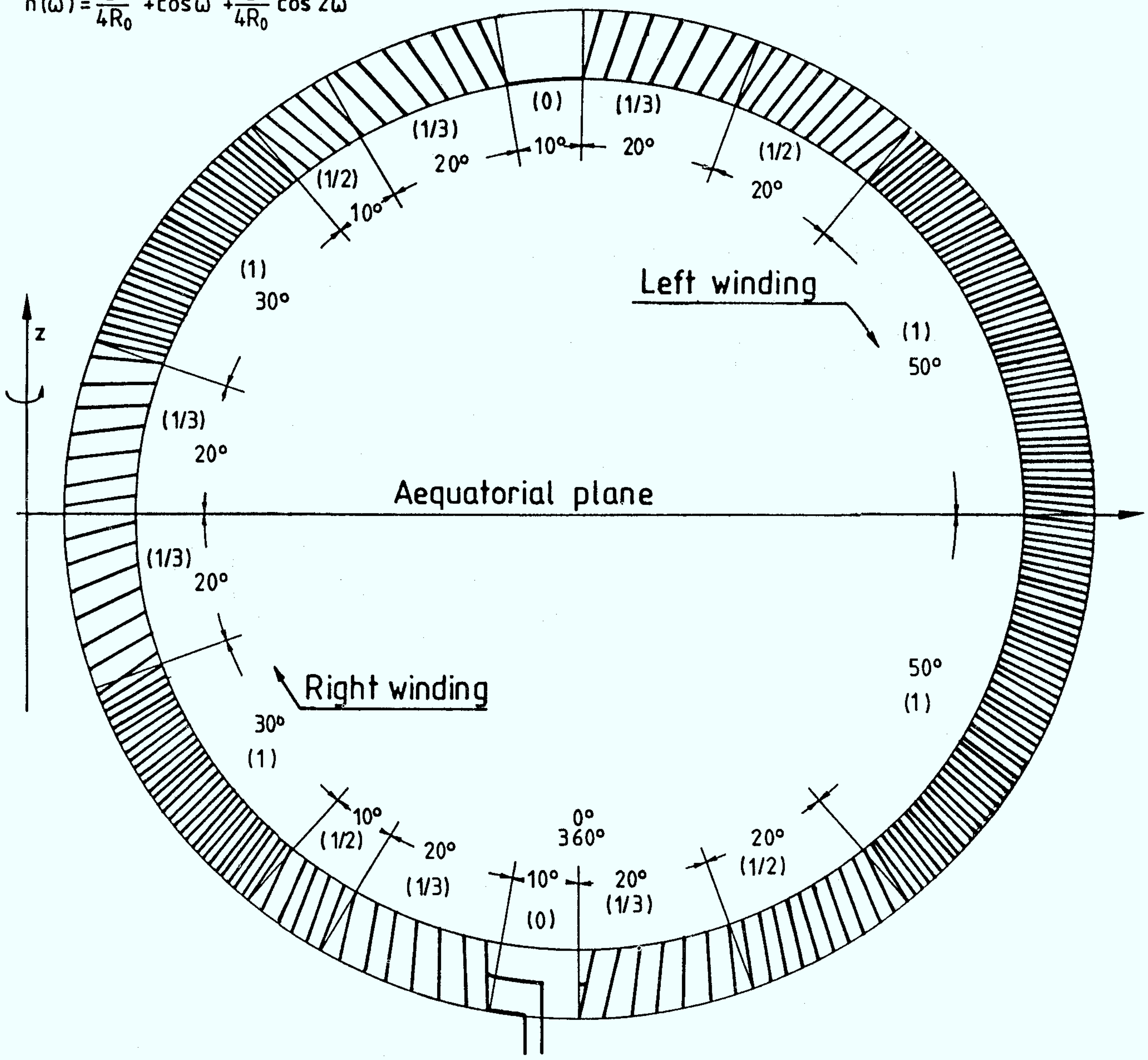


Fig. 2

$$n(\omega) = \frac{b}{4R_0} + \cos\omega + \frac{b}{4R_0}\cos 2\omega$$



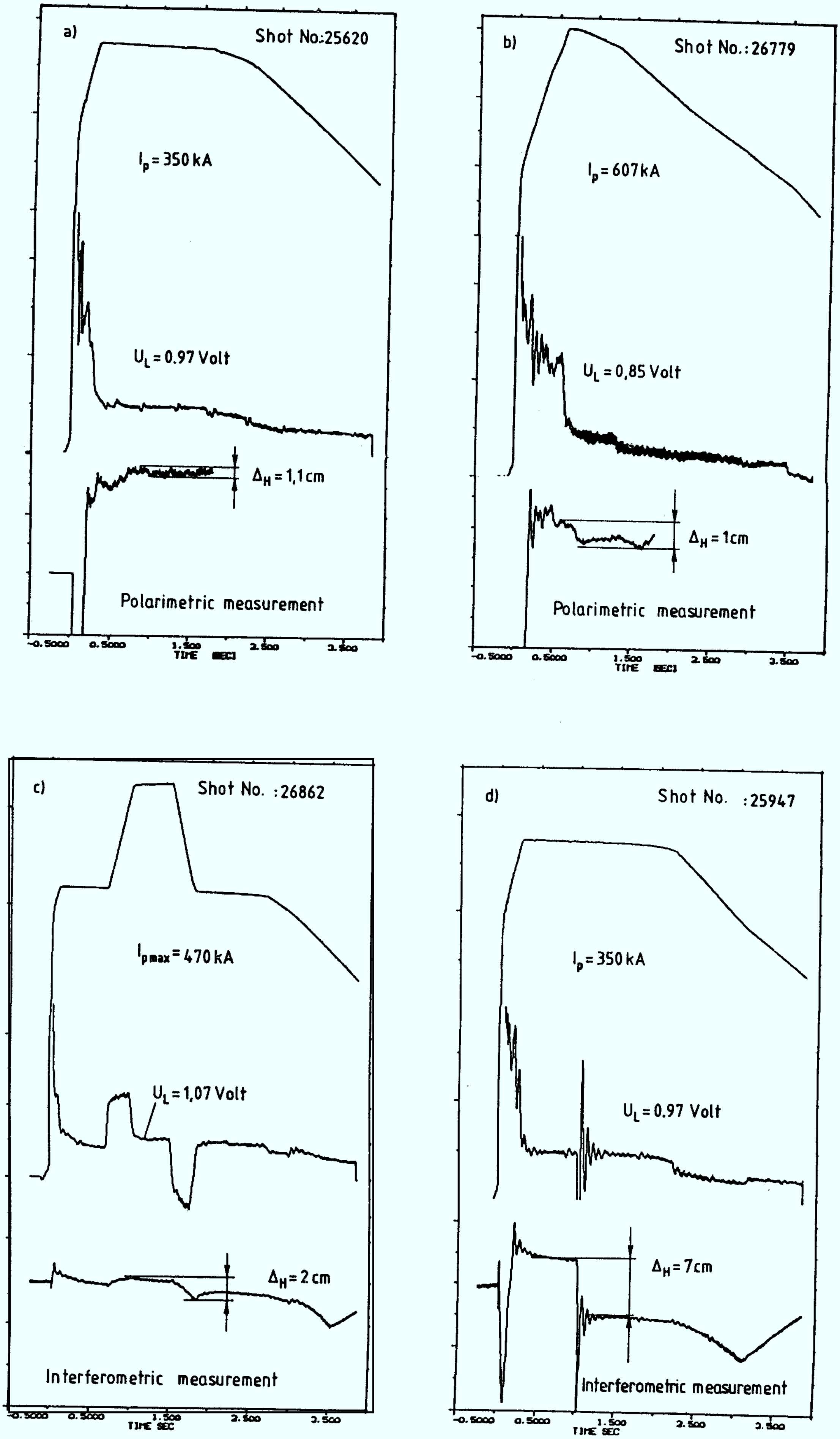

a)
Shot No:25620
$I_p = 350$ kA
$U_L = 0.97$ Volt
$\Delta_H = 1{,}1$ cm
Polarimetric measurement
-0.5000
0.5000
1.500
TIME (SEC)
2.500
3.500
b)
Shot No.: 26779
$I_p = 607$ kA
$U_L = 0{,}85$ Volt
$\Delta_H = 1$ cm
Polarimetric measurement
-0.5000
0.5000
1.500
TIME (SEC)
2.500
3.500
c)
Shot No. : 26862
$I_{pmax} = 470$ kA
$U_L = 1{,}07$ Volt
$\Delta_H = 2$ cm
Interferometric measurement
-0.5000
0.5000
1.500
TIME SEC
2.500
3.500
d)
Shot No. : 25947
$I_p = 350$ kA
$U_L = 0.97$ Volt
$\Delta_H = 7$ cm
Interferometric measurement
-0.5000
0.5000
1.500
TIME SEC
2.500
3.500

Fig. 3

Fig.4

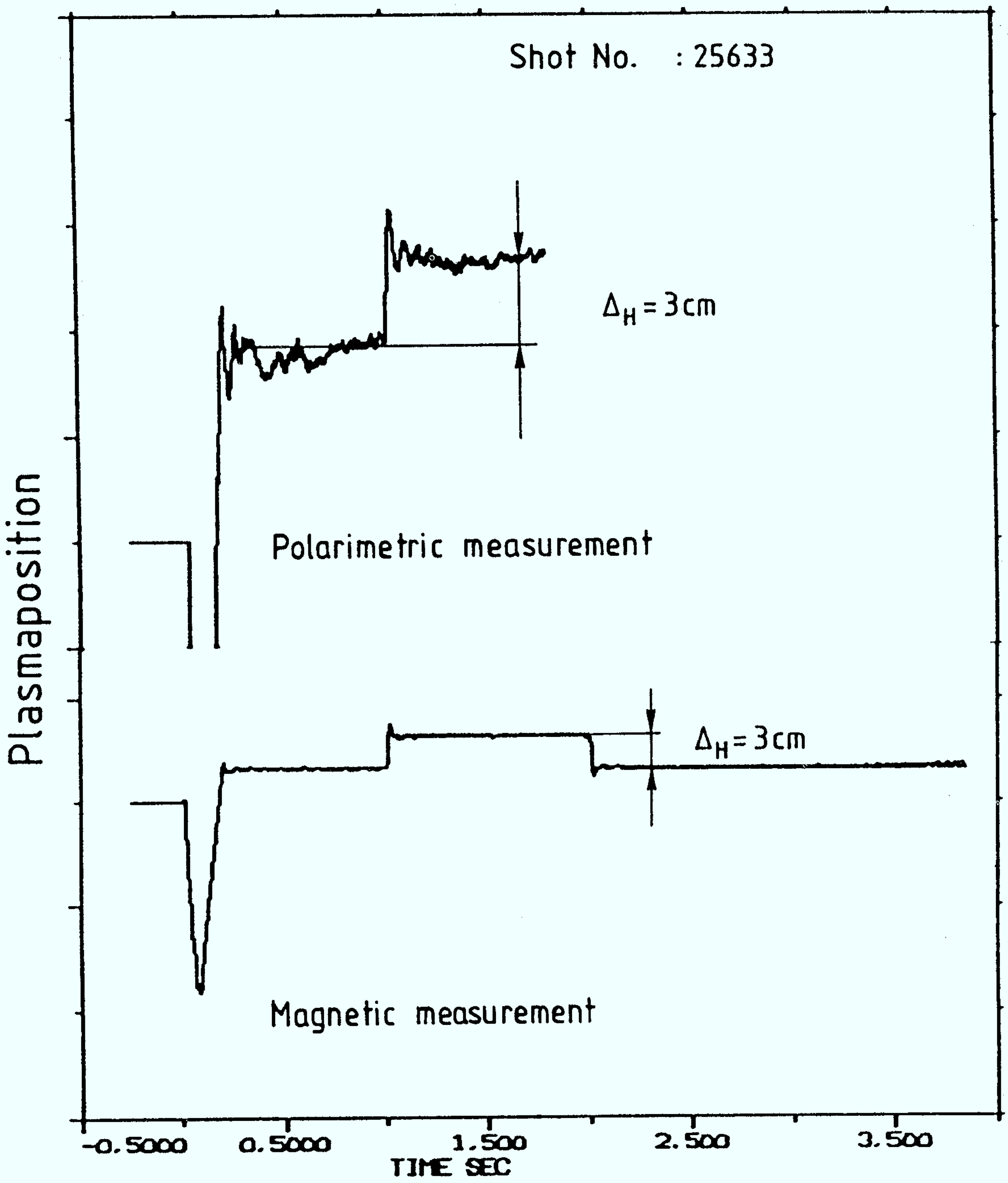

Shot No. : 25633
$\Delta_H = 3cm$
Polarimetric measurement
$\Delta_H = 3cm$
Magnetic measurement
Plasmaposition
-0.5000
0.5000
1.500
2.500
3.500
TIME SEC

Fig. 5

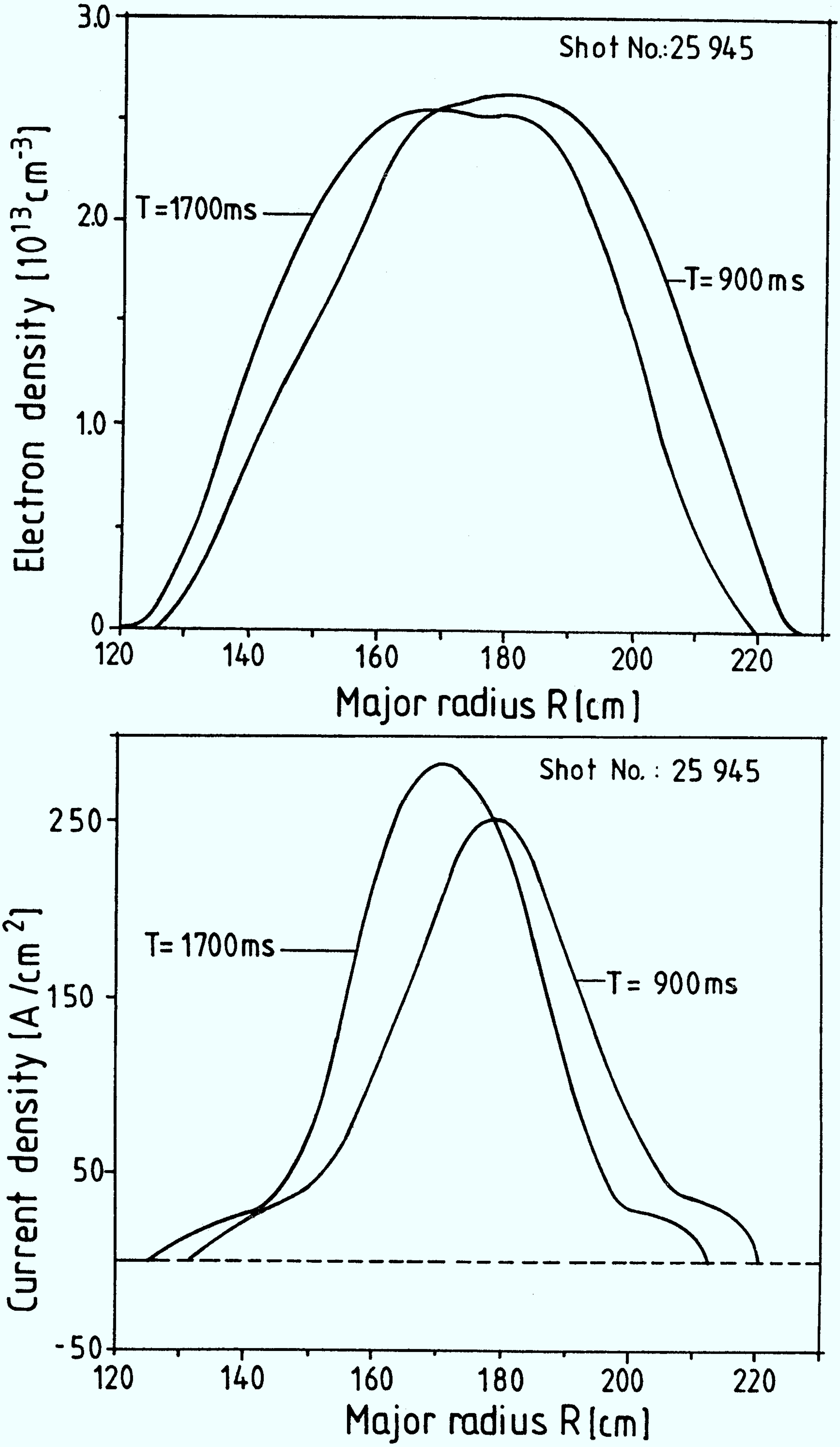

Shot No.:25 945
T=1700ms
T=900ms
Electron density [10^{13}cm^{-3}]
3.0
2.0
1.0
0
120
140
160
180
200
220
Major radius R [cm]
Shot No. : 25 945
T= 1700ms
T= 900ms
Current density [A /cm^2]
250
150
50
-50
120
140
160
180
200
220
Major radius R [cm]

Fig. 6

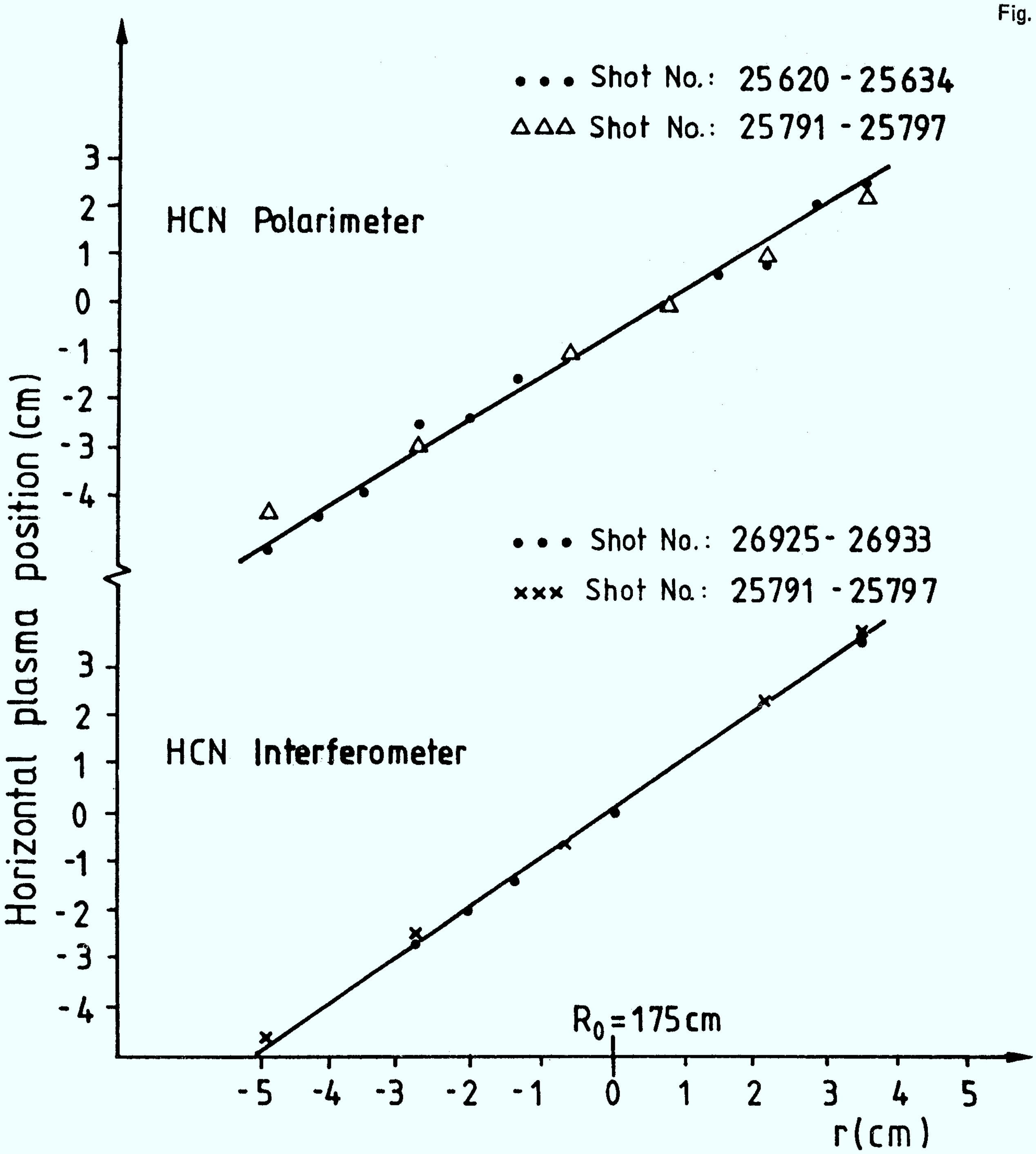
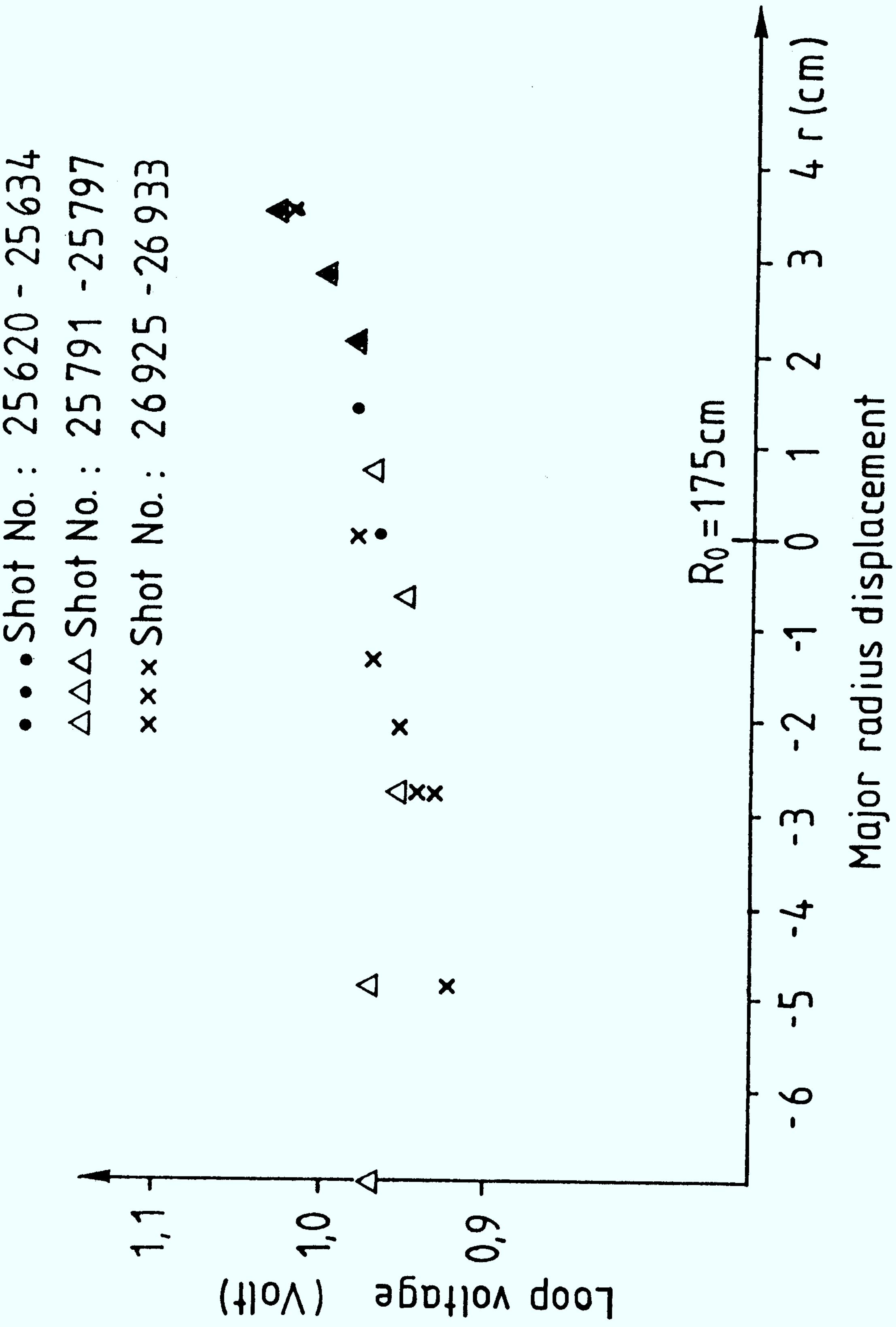

• • • Shot No.: 25620 - 25634
△△△ Shot No.: 25791 - 25797
HCN Polarimeter
• • • Shot No.: 26925 - 26933
××× Shot No.: 25791 - 25797
HCN Interferometer
Horizontal plasma position (cm)
3
2
1
0
-1
-2
-3
-4
$R_0 = 175$ cm
-5
-4
-3
-2
-1
0
1
2
3
4
5
r(cm)

Fig. 7


• • • Shot No. : 25620 - 25634
△△△ Shot No. : 25791 - 25797
× × × Shot No. : 26925 - 26933
Loop voltage (Volt)
1,1
1,0
0,9
R₀=175cm
-6
-5
-4
-3
-2
-1
0
1
2
3
4
r (cm)
Major radius displacement