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OPTICAL VISUALIZATION OF ELECTRIC AND MAGNETIC FIELD PERTURBATIONS IN TOKAMAK DISCHARGES BY HYDROGEN PELLET INJECTION

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ABSTRACT: Two-dimensional intensity distribution mappings of photographs of pellet ablation cloud trajectories in the TFR and TS tokamaks reveal irregular shapes of the luminous striations. The observed features are not well understood, but can be described and interpreted as the first direct visual observation of pre-existing electric and/or magnetic field perturbations in the hot core of tokamak plasmas. It is suggested to use pellet injection as a diagnostic tool for the study of plasma structures and transport phenomena.

INTRODUCTION

When hydrogen (deuterium) pellets are injected into ohmically heated tokamak plasmas, their ablation undergoes strong fluctuations in space and time. Time-integrated photographs of the ablation clouds show a series of radially displaced luminous striations extending on the average along the local magnetic field lines. The emission is essentially due to Balmer line radiation from neutral H (D) atoms and minor contributions originating from free-free and free-bound radiation involving only the hydrogen (deuterium) ion.

With neon doped pellets one obtains longer striations, since the neon ions with their longer ionization times diffuse over longer distances and also contribute to the radiation.

Pellet emission photographs taken on the Fontenay-aux-Roses tokamak (TFR) from 1984 to 1986 showed cases where one or more striations exhibited radial and / or poloidal excursions along the toroidal direction. Recent pictures of ablation clouds of D_2 pellets injected into TORE SUPRA (TS) also exhibit these features.

In the following, the observations are described and possible effects which may cause these anomalies are discussed. The conclusion is that the observations are very probably a direct visual manifestation of electric and/or magnetic field perturbations.

EXPERIMENTAL TECHNIQUE

Figure 1 gives a schematic sketch of the observation conditions.

On TFR, the pellets were injected in radial direction into the plasma with an angle of *8 deg* relative to the horizontal plane. The ablation clouds were photographed from below the injection plane with a mean angle of $\gamma \cong -48$ *deg* relative to the horizontal plane.The injection velocities were of the order of $V_p \approx 600$ *m/s*, the pellets contained on the average $N_a = 8 \cdot 10^{18}$ atoms. The pictures were taken on 'Polaroid' films. The pictures were digitized using an automatic scanning digital micro-densitometer. The numeric data files were used for the exploitations. For further details of this technique see the refs.[1-2]).

On TS, the pellets are injected radially in the horizontal plane. ($V_p = 600$ *m/s*, $N_a \approx 4 \cdot 10^{20}$ atoms). The ablation clouds are currently photographed from above the injection plane using a CCD camera. For the measurements described here, the angle of observation relative to the injection plane is $\gamma \cong 102$ deg.

For calibration purposes, a 'reference screen' with reference lines in both toroidal and radial direction was introduced into the toroidal chambers of TFR and TS and photographed at the same angle as the ablation clouds. For both the TFR and TS ablation clouds and 'reference screens', the light intensity of the photographs has been scanned in radial direction (r) at different toroidal positions (Z) leading to a two-dimensional intensity mapping in the (r,Z)-plane. No smoothing procedures were applied.

EXPERIMENTAL RESULTS

The luminous striations on well-exposed photographs of ablation clouds represent in general 'cigar-like' straight lines. When an ablation cloud is viewed with an oblique angle γ relative to the injection plane, the striations appear at radius r with an angle $\alpha'(r)$ relative to the toroidal magnetic field direction. Reversal of the field direction reverses the angle $\alpha'(r)$ irrespective of the chemical composition of the pellet [1]. By measuring $\alpha'(r)$ at different radii it is possible in most cases to obtain the true magnetic field angle $\alpha(r)$ and, thus the radial profile of the safety factor $q(r)$ [1-4], in good agreement with $q(r)$ obtained by other methods. A detailed description of this technique is given in Ref.[2].

From time to time one observes irregularly striated ablation clouds or cloud regions in which the striations are not so well defined. Figure 2a shows a photograph taken on TFR. In particular, two striations are visible which cross each other with an angle of approximately *15 deg*. This optical 'X-point' is situated in the region of the $q = 1$ surface. On the right of this crossing the striations are not well defined. Figure 2b is a photograph taken on TS, on which two 'anomalous features' can clearly be distinguished: in the lower half appears a 'bifurcation' of striations; andthe luminous striations which extend from the 'bifurcation point' to the upper part of the photograph are slightly curved and seem to form an 'island-like shape'. Left to this feature a second bifurcation of striations seems to occur. Owing to the more diffuse character of the striations in this region, this bifurcation is not so clearly distinguible as the first one. It also seems, that an 'optical X-point' also occurs on this photograph. One further sees a broad curved zone of lower intensity which traverses the whole picture.The toroidal deflection of this zone is in the direction of the electron current (opposite to the direction of the plasma current Ip). and follows the pellet orbit.

With a high degree of probability it can be excluded that these anomalous features are caused by pellet fragments entering into very different regions of the plasma column. Photographic pictures of ablation clouds of fragmented pellets look very different. It is also unlikely that over-exposure or re- absorption of light causes the visual aspect of deformed striations in the cases which are described in the present paper. It rather seems that the 'anomalous features' described here have another origin.

The following figures summarize the results of the two-dimensional intensity scanning of several ablation clouds with deformed luminous striations. The dots (squares, triangles) represent the intensity maxima as a function of the two-dimensional scanning.

Figure 3 shows an intensity mapping with 4 striations from TFR for a deuterium pellet doped with 1% neon injected during the current plateau. Injection is from right to left, x and y are the original photometer scanning co-ordinates approximately parallel to the radial and toroidal direction respectively. The radial width of the individual striations is approximately *3 mm*.

The striation on the right side is relatively straight and its inclination relative to the toroidal direction leads to $q(r) \cong 2.3$. The next striation to the left clearly shows radial deviations from a straight line which are outside the experimental uncertainties, but the 'overall direction' still shows an inclination relative to the toroidal direction associated with a resonant surface near $q = 2$. The intensity maxima of the two striated features on the left side show radial excursions which resemble magnetic islands as they are known from projections of magnetic surfaces on the (r,Θ)-plane. Within the experimental errors, they are situated close to $q = 2$.

The toroidal length of the two 'island-like shapes' deduced from the photographs and taking into account the diagnostic geometry, is approximately *6 cm* with a radial extension of approximately *0.7* cm.

Multipellet injection is currently being carried out on TS. Figures 4 and 5 show intensity mappings of striations of the first and fourth pellet of a series of five pellets injected into a TS discharge. (There are more striations, but only the most interesting have been plotted here). Injection is from left to right.

In these and the following figures, x and *YPix* represent the original intensity scanning axes. *YPix* points in the toroidal direction Z, with the origin of Z set to an arbitrary position. The lines positioned at $Z = 0.05, 0.10, \ldots m$ represent exact radial chords in the injection plane. x is parallel to the radial direction r. Two toroidal reference lines situated at the major radii $R = 2.754$ and $2.654\ m$ have been inserted. They have been taken from the photograph of the 'reference screen'. Since the abscissa is slightly non linear in terms of r (or R) due to the oblique observation angle γ, the abscissa has not been drawn as a function of r (or R).

In Fig.4, three striations are shown which exhibit radial excursions changing along the toroidal direction. The two striations to the right side again show together an 'island-like' feature whereas the left striation folows roughly the excursions of the middle one. The radial excursions have an extension of approximately *1 cm*. The toroidal length of the 'island-like shape' is approximately *20 cm*.

Figure 5 represents the intensity mapping of five striations of the ablation cloud of the fourth pellet. The alignements of the points of the two striations on the right side define the direction of well-behaved straight lines following the magnetic field line. The 3rd striation shows radial excursions and a splitting ('bifurcation') of its lower half. The two striations on the left yield a picture of an apparent optical 'island-like' shape. The maximum separation of the two striations is *1.2 cm*, the length of this 'island' is approximately *10 cm*.

The inclination of the striations relative to the toroidal direction is weak, since the observation angle γ is small. Under these conditions it is not possible to determine $q(r)$ from the angle of inclination $\alpha'(r)$.

However, from the plasma parameters measured immediately before injection one can calculate $q(r,t)$. The result is shown in Fig.6 for the two pellets (p1,p4). For this experiment the magnetic axis lies at major radius $Ro \simeq 2.396$ m whereas the two 'island-like' features appear at the same major radius of $R \approx 2.704\ m$ corresponding to a plasma radius of $r \approx 0.328\ m$ relative to the magnetic axis. It follows from Fig.6 that this is the region of $q \approx 1.5$ within the experimental errors.

We show in Fig.7 the intensity mappings of the three striations which form on the photograph of Fig. 2b the clearly distinguible 'island-like shape' and the bifurcation in the lower half of the figure. The toroidal extension of the 'island-like shape' is of the order of *0.20 m*. The excursion in radial direction of the *bifurcted* striation reaches *0.013 m*. The whole 'anomalous behaviour' of the striations seen on the photograph extends over a radial region of at least *4* to *6 cm*.

Fig.8 shows the relevant plasma parameters and the calculated radial $q(r)$ - profile immediately before injection. $Ne(r)$ and $Te(r)$ have been used to calculate from the neutral shielding model [5] the atom deposition per unit length, dNa/dr. It follows from this figure that the 'anomalous behaviour' of the striations occurs in a broad region around $q \approx 1.5$.

We give for comparison in Fig.9 intensity mappings of striations which appear on the photograph as visible well-separated straight lines, with the exception of a perturbation in the region from $R \approx 2.706$ to 2.672 m where a striation exhibits a large radial excursion (triangles) which become diffuse in the upper half. The circles aligne well along lignes whose inclination changes when one proceeds from left to right. For this experiment the magnetic axis lies at $Ro = 2.305\ m$. The perturbed striation thus lies relative to the magnetic axis at radius $r \cong 2.706\ m - Ro = 0.40\ m$. It follows from Fig.10 that this is again the region about $q \approx 1.5$. It should be mentioned that the ablation in the region of the $q = 2$ surface situated at $R \approx 2.848\ m$ (corresponding to $r \approx 0.54\ m$) is too weak to permit conclusions about anomalous striations in this region.

It is an interesting fact that these apparently irregular structures occur more often at low than at high electron density of the basis plasma. This is particularly visible in multi-pellet injection experiments. The features seem to be erratic.

Most recently a 2-stage high-speed single-pellet injector has been installed on TS. On some photographs we see the same features as described in this paper.

Before leaving the description of the experimental results, we would like to point out a feature always visible in the "straight" lines of intensity maxima. It is quite conspicious on figures 3 and 9 and also present but less clearly on figures 4, 5 and 7. There seems to be a small amplitude short wavelength wiggle of all these points around the averaged straight line. We do not want to insist on this feature, which may be below the resolution of our measurements, but only to point out the fact that it seems to be always present, whereas the large amplitude wanderings and bifurcations appear only on a minority of lines and in an apparently erratic way.

POSSIBLE EXPLANATIONS

The question is: what causes the radiating channels to deviate sometimes significantly from a straight line ? In the first place, it is important to understand that these features are 2-D projections of radiating flux tubes. Therefore, the observed crossings are not real magnetic X-points but projection effects as shown in Fig.11. In the following we consider effects which could be made responsable for the observed features.

The fact that *well-behaved* striations show up an angle $\alpha'(r)$ relative to the toroidal direction, and that $\alpha'(r)$ reverses when the toroidal field induction is reversed, has led to the conclusion that the striated cloud plasma must be confined in magnetic flux tubes [1-4]. This is the reason, why striated pellet ablation clouds can be used to determine $q(r)$ from the inclination angle $\alpha'(r)$. Using the same argument one could think that *deviations from a straight line* are direct visual manifestations of magnetic field perturbations.

However, the angles which are measured lead to magnetic field perturbation amplitudes much larger than the poloidal magnetic field. An alternative possibility is that to the motion of the luminous matter along the flux tube another velocity component is added, for instance due to local electric field perturbations.

These magnetic and/or electric field perturbations can be of two origins:
- either they correspond to pre-existing perturbations in the basis plasma, related to electrostatic or magnetic turbulence,
- or they are caused by the pellet itself.

We will discuss the possible mechanisms for these two cases. These considerations will lead to the conclusion that the observed features are likely due to pre-existing plasma properties made visible by the luminous striations.

1. Perturbations caused by the Pellet

a.) Deformation of flux tubes by mechanical forces; Alfvén waves

The ablated matter of mass $m_{p,s}$ in a confined luminous striation s carries along it the kinetic energy $m_{p,s} V_p^2 / 2$ (of the order of $10^{-4} - 10^{-5} J$). As soon as the matter is sufficiently ionized, an average force of order $F_{p,s} = m_{p,s} V_p / \Delta t_s$ is exerted on the flux tube s, where Δt_s is an interaction time of the order of the times for ablation and ionization. The force $F_{p,s}$ deflects the flux tube in the direction of the pellet velocity. An estimate of the order of magnitude for the deflection d of a flux tube at $B = 4$ Tesla yields $d \approx 10^{-5}$ m for TFR and TS. This value is by far too weak to be observable. Even if this effect would be important, every striation should show the same deformation. This is not observed.

The formation and propagation of Alfvén waves can be excluded because of the high mass density of a striation and its low electrical conductivity.

b) Current Density and Electric Potential Perturbations caused by the Pellet

The sudden obstruction of field lines by a non conducting body (the deuterium ice) surrounded by a highly resistive shell (the neutral gas cloud) interrupts the current locally, and is at the origin of a large potential perturbation because the electrons remain in thermodynamic equilibrium in the very dense region surrounding the pellet. The affected region is moving with the pellet in radial direction, and with the dense weakly ionized cold matter in the toroidal direction. A complete description of the different magneto-hydrodynamic, electrostatic and kinematic effects of this disturbance is very difficult to achieve.

Qualitatively we can predict that a negative perturbation of the currrent density ($\delta J = -\bar{J}$) will be created on the field lines intersected by the pellet, surrounded by a sheath with a positive current density perturbation such that inside a flux tube with a diameter approximately equal to the neutral and weakly ionized cloud, the integral of the perturbation is zero. The consequence would be that even on irrational surfaces, an O-point island-like magnetic structure will appear locally, although it may not be coherent all around the torus. The consequent azimuthal magnetic field perturbation ($B \leq 0.1$ T) is in any case too small to justify the pitch of the deviated striations whereas approximately $2T$ would be needed to explain the observations.

More important, a space charge modification is induced by the obstruction, leading to localized electric potential perturbations at most equal to a few times kT_e, with a radial extension δr in between the pellet and the neutral gas cloud radius. A helical motion of the ionized matter around the obstructed field lines would then be induced, with an azimuthal velocity of order $V_a \simeq \dfrac{kT_e}{B\,\delta r} \leq 10^5$ m/s which can be compared to the velocity of the ablated matter <u>along</u> the field lines which is of the order of 10^4 m/s. This effect is compatible with the short wavelength wiggles briefly mentioned at the end of the experimental section, but cannot explain the large structures and bifurcations which appear erratically, as it should occur around every flux tube.

This erratic character of the large deviations of the striations from the local toroidal direction is the strongest argument in favour of a mechanism based on a pre-existing plasma structure.

2. Pre-existing Plasma Structures

As dense pellet matter expands along magnetic field lines with a velocity of about 10^4 m/s, high frequency electrostatic turbulence is not a very plausible mechanism which could cause the deflections of the striations. On the other hand, we have seen before that magnetic field deviations compatible with the observations need magnetic field perturbations of irrealistic amplitudes ($\sim 2\ T$) to explain directly these structures.

The most likely explanation, in our present state of understanding, is that medium m-number magnetic islands ($m \sim 2\text{-}15$) are present in the plasma. As we remarked in [6-7], such islands,which may be thought of as well ordered island-like toroidal structures imbedded in a semi-stochastic sea, would exhibit electric potential perturbations, because of viscosity: the ion fluid must be static with respect to the magnetic structure, hence the pressure gradient has to be compensated by an electric potential U [6] giving a field strength typically of the order of $10^2 eV/10^{-2} m$. This will lead to a tranverse motion whose velocity is of the order of $V \sim \frac{1n\ \delta T}{B\ \delta r} \sim$ 10^4 m/s (where $\delta T/\delta r$ is the temperature gradient across the island), compatible with the observed deviations. We do not claim to be able to invoke a specific mechanism for these instabilities; they can be tearing, non linear micro-tearing, thermal filamentation or bootstrap destabilized, and we have no indication in favour of any specific destabilizing mechanism. But the fact that a different experimental analysis shows the existence of a staircase-like q- profile with shear plateaus indicating the likely presence of magnetic islands [8], with a statistic of occurence in rough agreement with our data, suggests this as a very plausible candidate. Further observations are needed to give a definite answer.

CONCLUSION

Photographs of ablation clouds injected into tokamak plasmas yield luminous striations which erratically show marked deviations from straight lines. Estimates of different effects depending on both pellet ablation and heating processes and on inherent plasma properties lead to the conclusion that it is unlikely that the observed features are caused by the pellets.

Although the mechanisms responsable for the radial and/or poloidal excursions are not well understood, the structures on the photographs can be interpreted qualitatively as direct visual manifestations either of pre-existing electric fields or of irregularities of the magnetic structure.The observations described could eventually be used as a new experimental method to measure electric and magnetic field perturbations and to verify assumptions made in models for anomalous transport in tokamak plasmas. If our preliminary conclusions (namely that large erratic deviations of the luminous striations from straight lines reflect the electric potential across pre-existing magnetic islands as those measured by the method described in [8]) are verified, a fairly complete description of the detailed plasma structure can be obtained by conbining these two methods.

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FIGURE CAPTIONS

Figure 1: Schematic representation of pellet injection experiments and conditions of observation on TFR and TS.

Figure 2: a. Photograph of an ablation cloud taken on the TFR tokamak showing an 'optical X-point'; discharge Nr 88031.
b. Photograph of an ablation cloud taken on the TS tokamak with 'bifurcated' and curved striations ; discharge Nr 4150, first pellet.

Figure 3: Intensity mapping in the (r,Z)-plane of striations of a neon doped pellet injected into the TFR discharge Nr.94351 with $B_t = 4.5\ T$, $I_p = 183\ kA$, $R_0 = 0.98\ m$. y points nearly in radial direction r, x in the toridal direction Z. $\Delta x = 5\ mm$ correspond to $\Delta Z \approx 5.6\ cm$ in the TFR chamber.

Figure 4: Mapping of intensity maxima of three striations of the first pellet injected into TS discharge Nr 2687. ($B_t = 3.8\ T$, $I_p = 0.944\ MA$, $R_0 = 2.396\ m$). Z is in toroidal direction with the origin set to an arbitrary position.

Figure 5 Mapping of intensity maxima of five striations of the fourth pellet injected into TS discharge Nr 2687. Same conditions as in Fig.4.

Figure 6: Plasma parameters for TS discharge Nr.2687 immediately before injection of pellet 1 (-p1) and pellet 4 (-p4). The plasma center $r = 0$ corresponds to a major radius of $R_0 = 2.396\ m$. The penetration depths of the two pellets are indicated by the arrows labeled *r1* ,*r4*.

Figure 7: Intensity mapping of striations of the first pellet injected into TS discharge Nr.4150.($B_t = 3.92$ T, $I_p = 1.408\ MA$, $R_0 = 2.306\ m$).

Figure 8: Plasma parameters for TS discharge Nr. 4150. *dNa/dr* is the atom deposition profile.

Figure 9: Mapping of the intensity maxima of the striations for the sixth pellet injected into TS discharge Nr.41530 ($B_t = 3.92\ T$, $I_p = 1.41\ MA$, $R_0 = 2.305\ m$).

Figure 10: Plasma parameters for TS discharge Nr.4153 immediately before injection of pellet 6. *dNa/dr* is the atom deposition profile.

Figure 11: Schematic representation of radiating fluid channels twisting around the magnetic axis Γ an island. The projection onto the focal plane yields an 'island-like' shape.

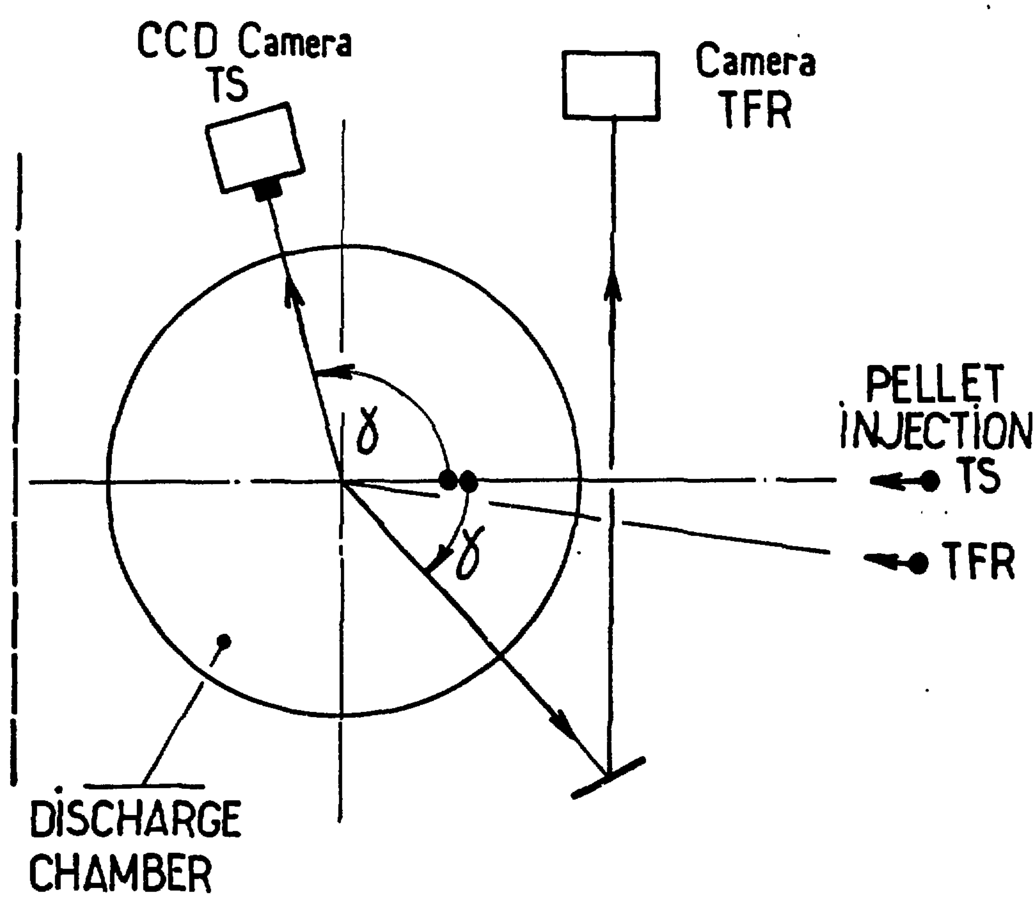
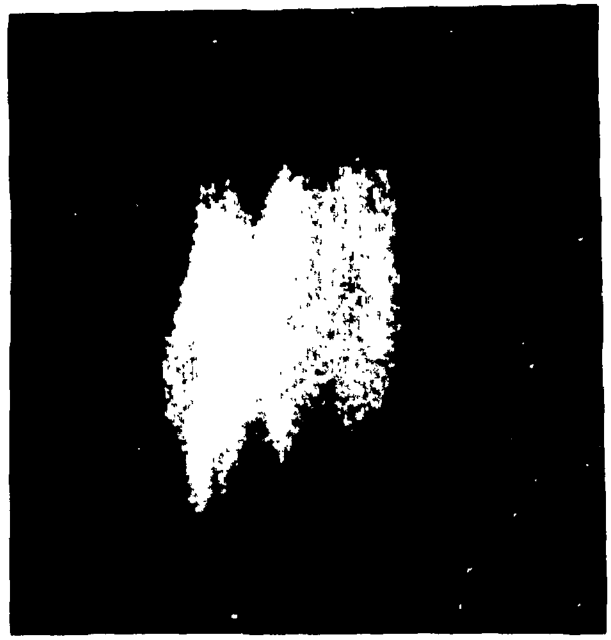
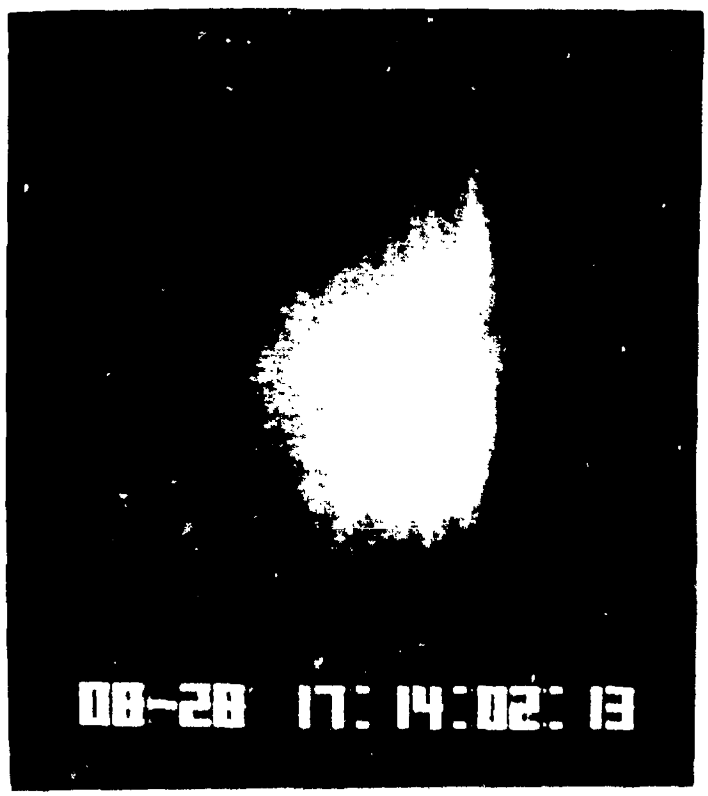

CCD Camera
TS
Camera
TFR
PELLET
INJECTION
TS
TFR
γ
γ
DISCHARGE
CHAMBER

Figure 1



a.



b.

Figures 2a, b

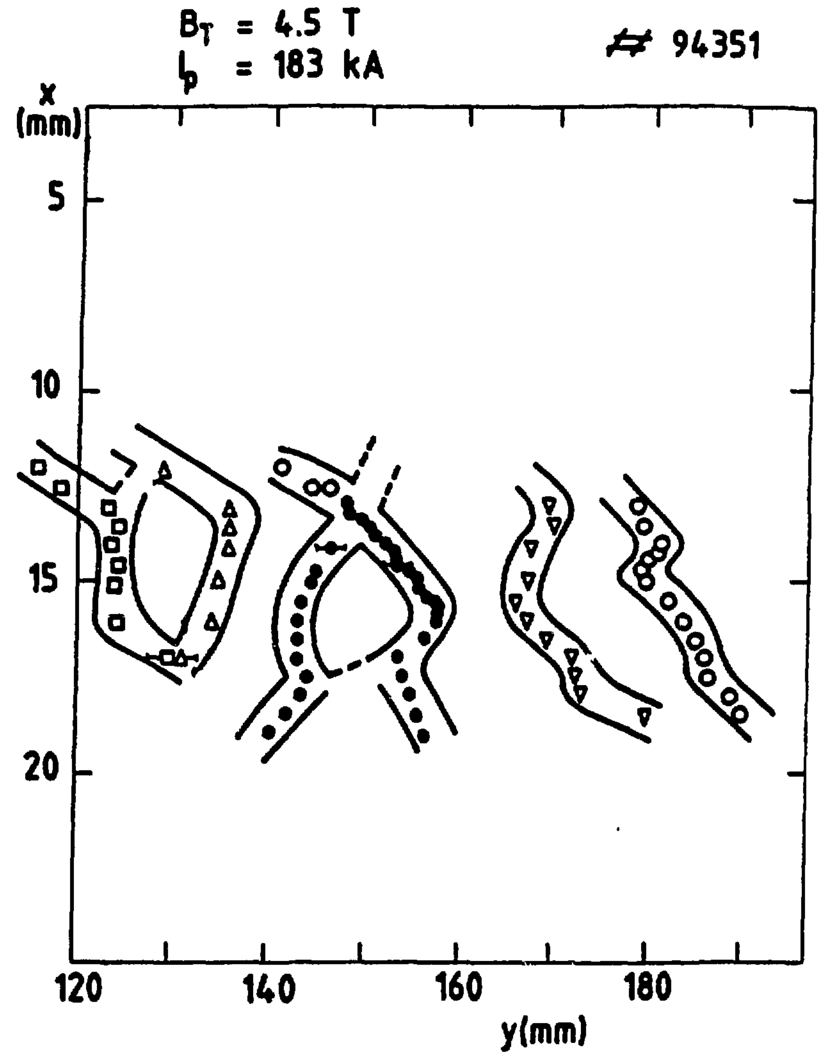


Figure 3

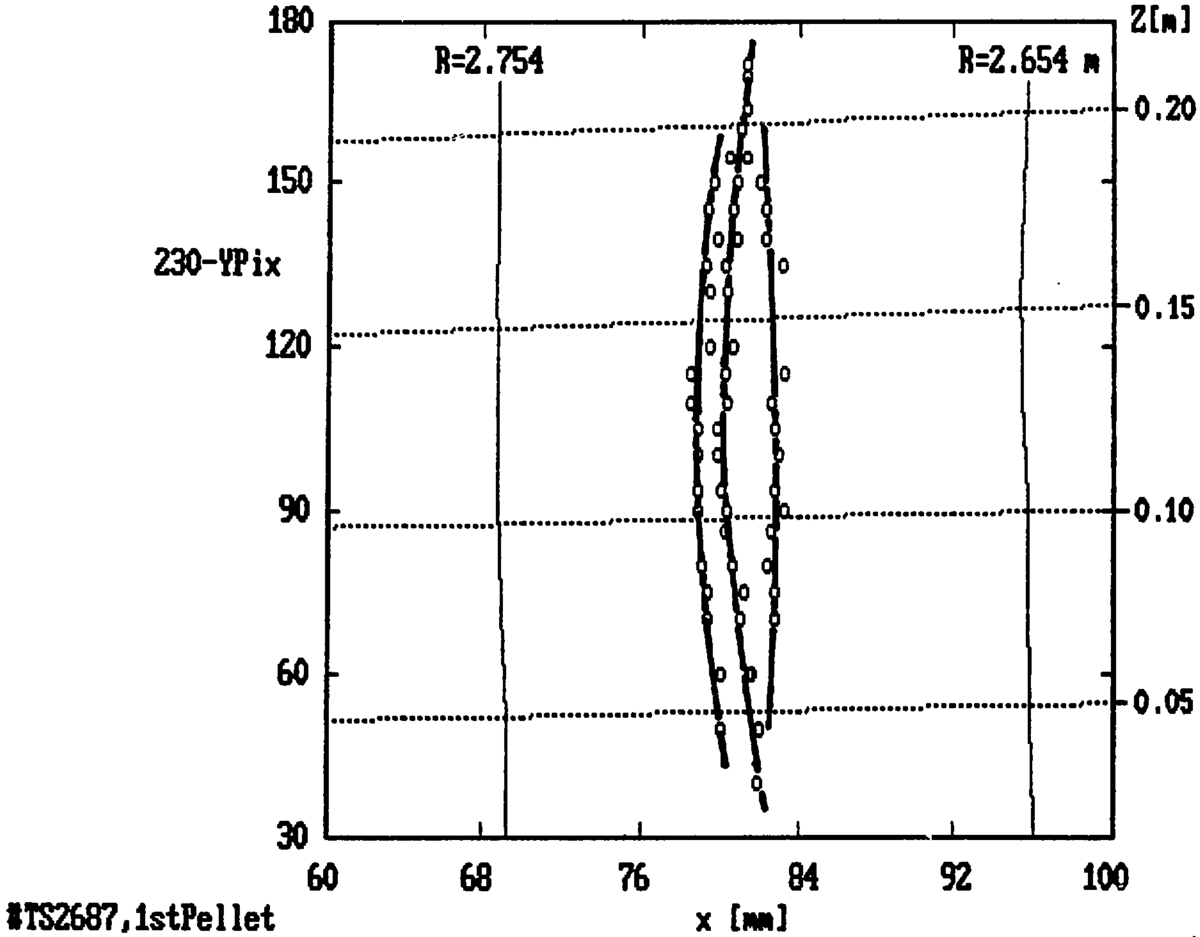

180
150
120
90
60
30
230-YPix
R=2.754
R=2.654 m
Z[m]
0.20
0.15
0.10
0.05
60
68
76
84
92
100
x [mm]
#TS2687,1stPellet

Figure 4

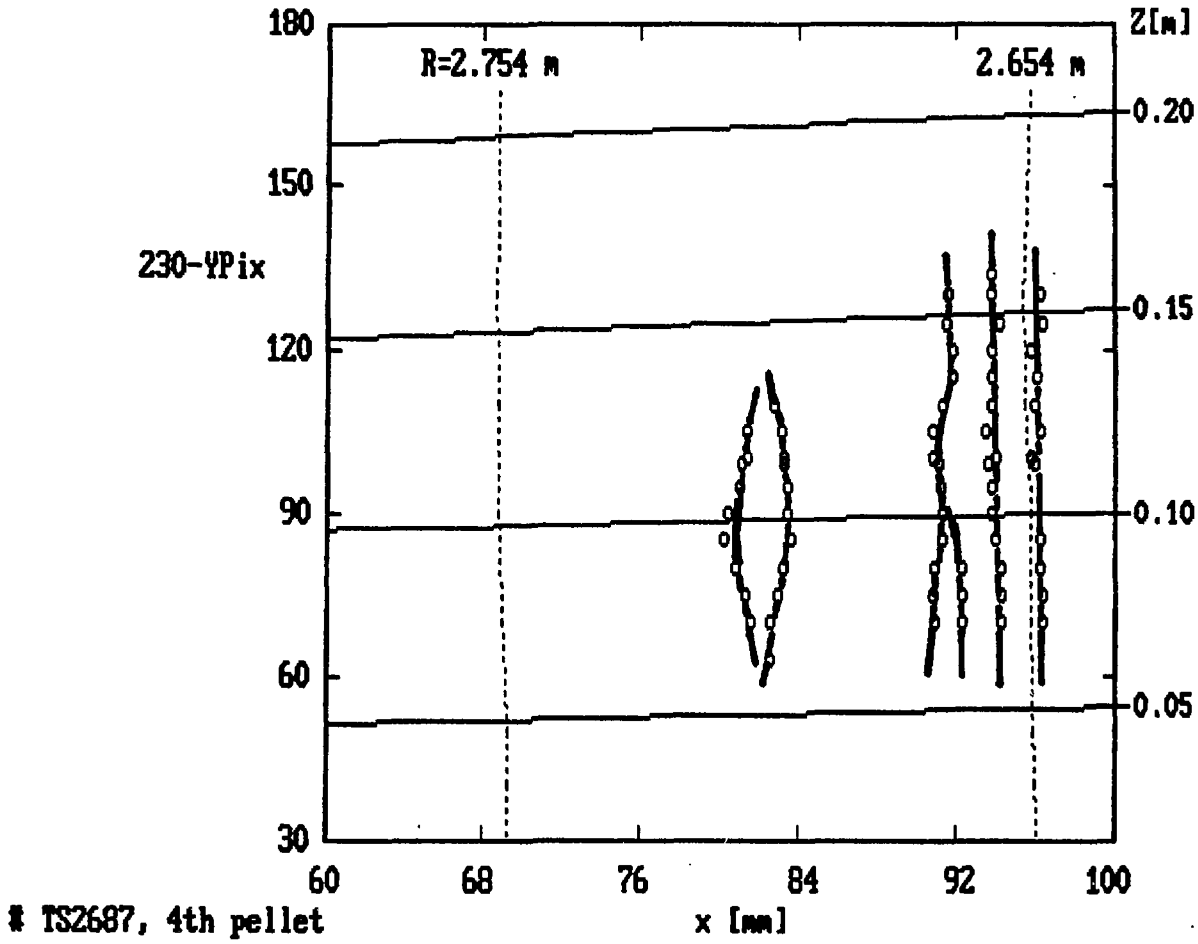

180
150
120
90
60
30
230-YPix
R=2.754 m
2.654 m
Z[m]
0.20
0.15
0.10
0.05
60
68
76
84
92
100
x [mm]
TS2687, 4th pellet

Figure 5

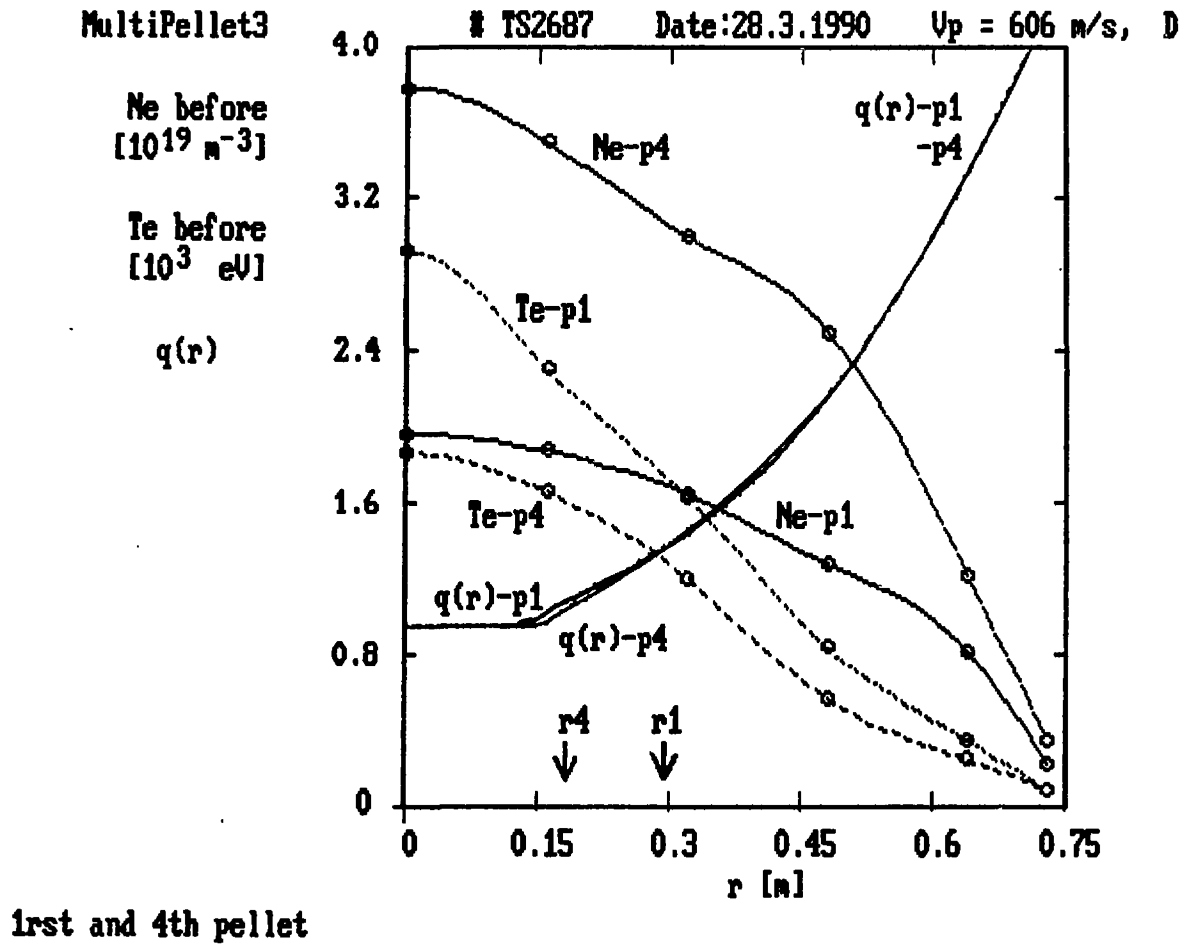
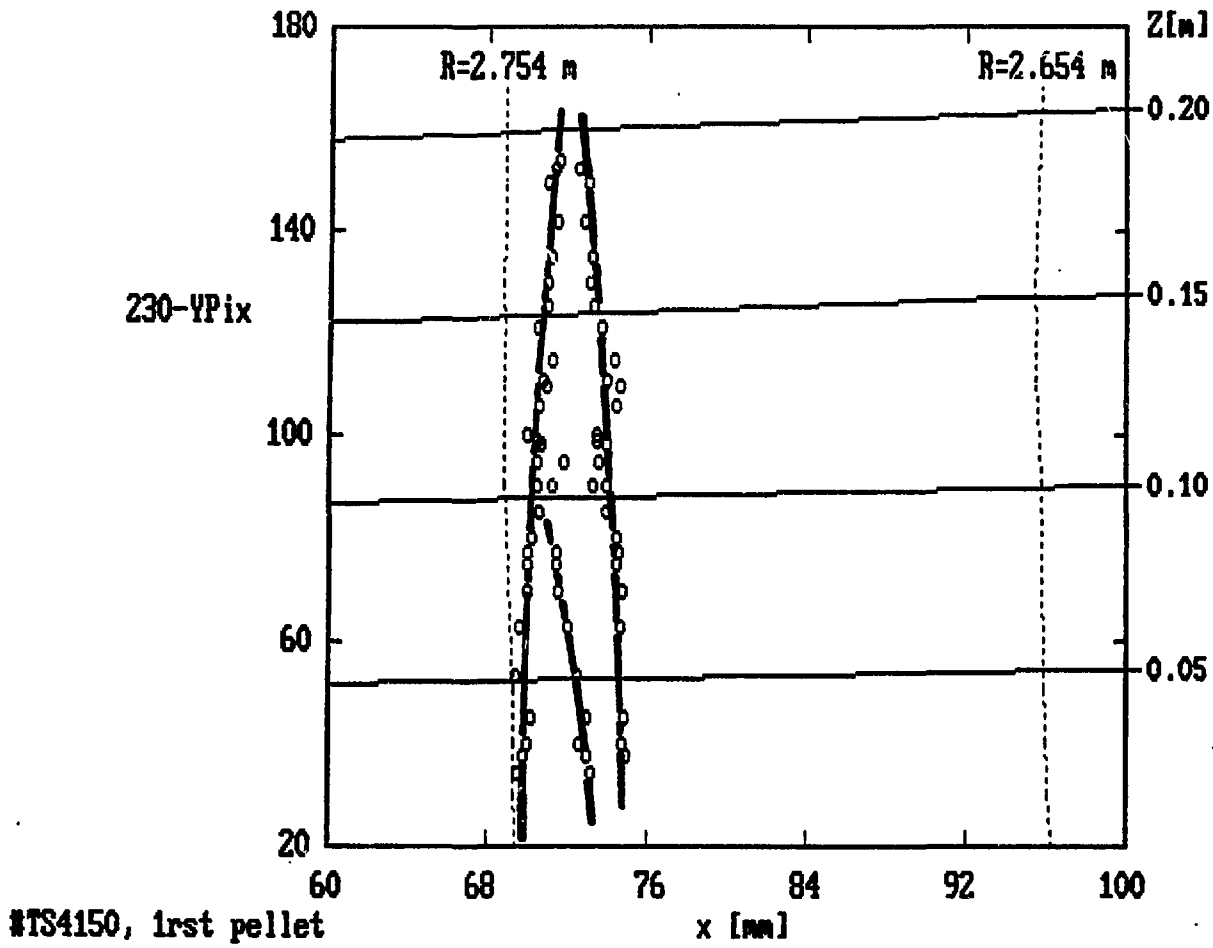
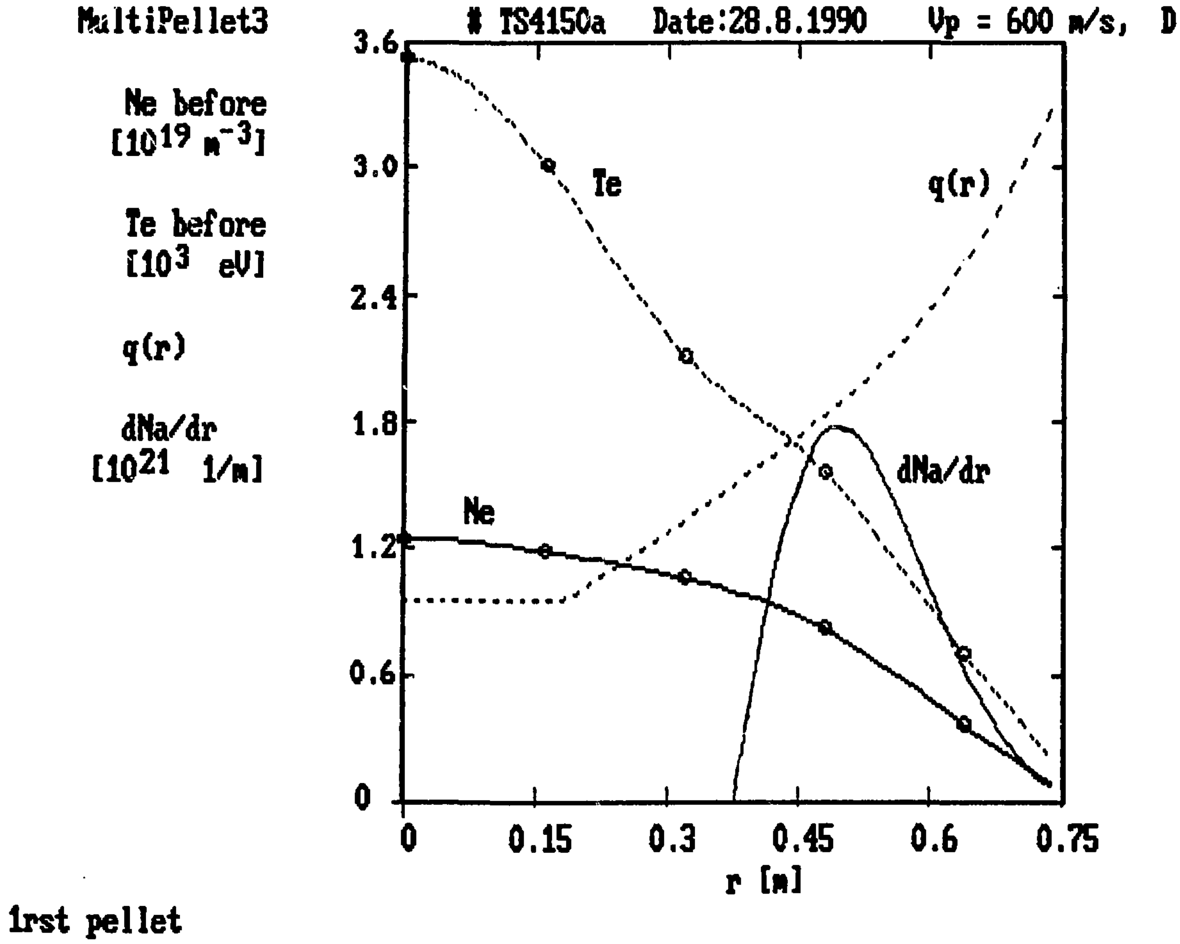

MultiPellet3
TS2687 Date:28.3.1990 Vp = 606 m/s, D
Ne before
[10^19 m^-3]
Te before
[10^3 eV]
q(r)
4.0
3.2
2.4
1.6
0.8
0
Ne-p4
Te-p1
Te-p4
Ne-p1
q(r)-p1
-p4
q(r)-p1
q(r)-p4
r4
r1
0
0.15
0.3
0.45
0.6
0.75
r [m]
1rst and 4th pellet

Figure 6



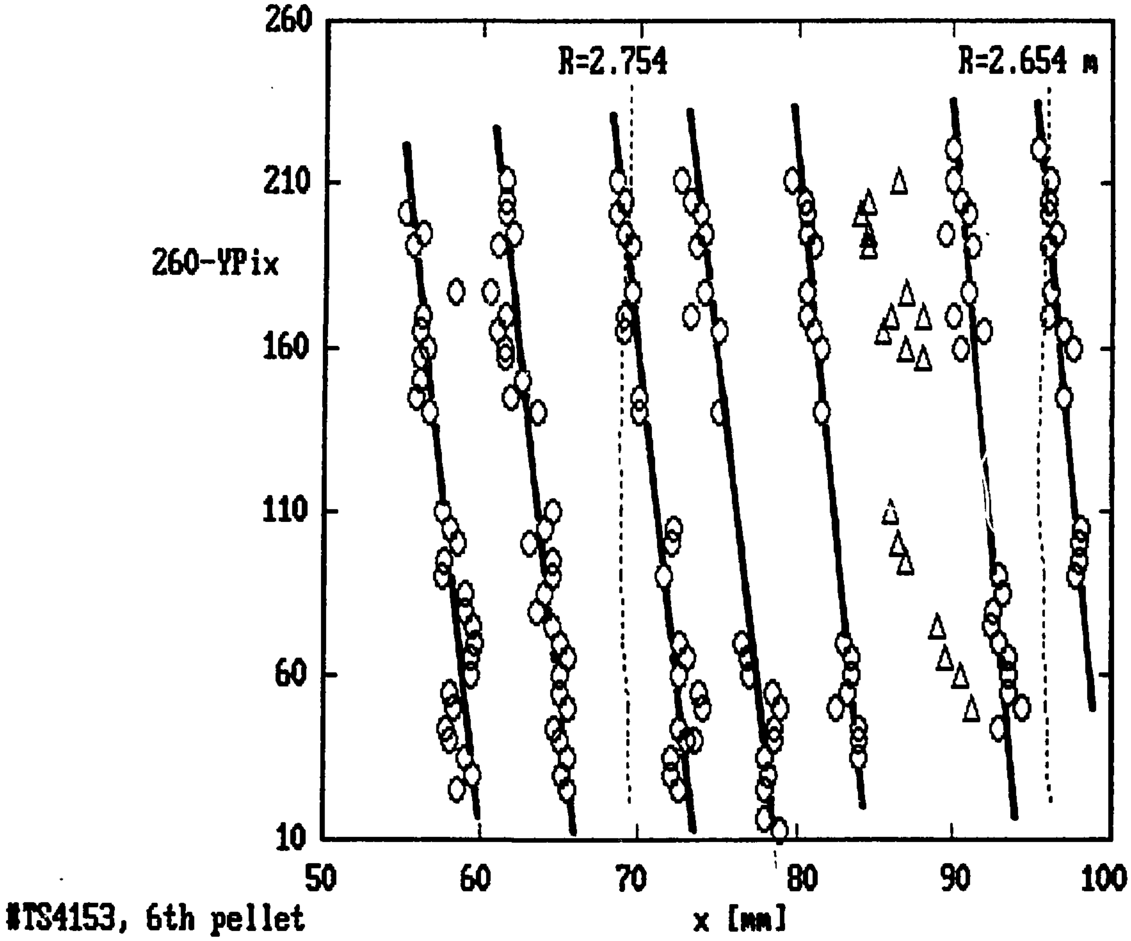
180
140
100
60
20
230-YPix
Z[m]
R=2.754 m
R=2.654 m
0.20
0.15
0.10
0.05
60
68
76
84
92
100
x [mm]
#TS4150, 1rst pellet

Figure 7



MultiPellet3
TS4150a Date:28.8.1990 Vp = 600 m/s, D
Ne before
[10^19 m^-3]
Te before
[10^3 eV]
q(r)
dNa/dr
[10^21 1/m]
3.6
3.0
2.4
1.8
1.2
0.6
0
Te
q(r)
dNa/dr
Ne
0
0.15
0.3
0.45
0.6
0.75
r [m]
1rst pellet

Figure 8



R=2.754
R=2.654 m
260-YPix
260
210
160
110
60
10
50
60
70
80
90
100
x [mm]
#TS4153, 6th pellet

Figure 9

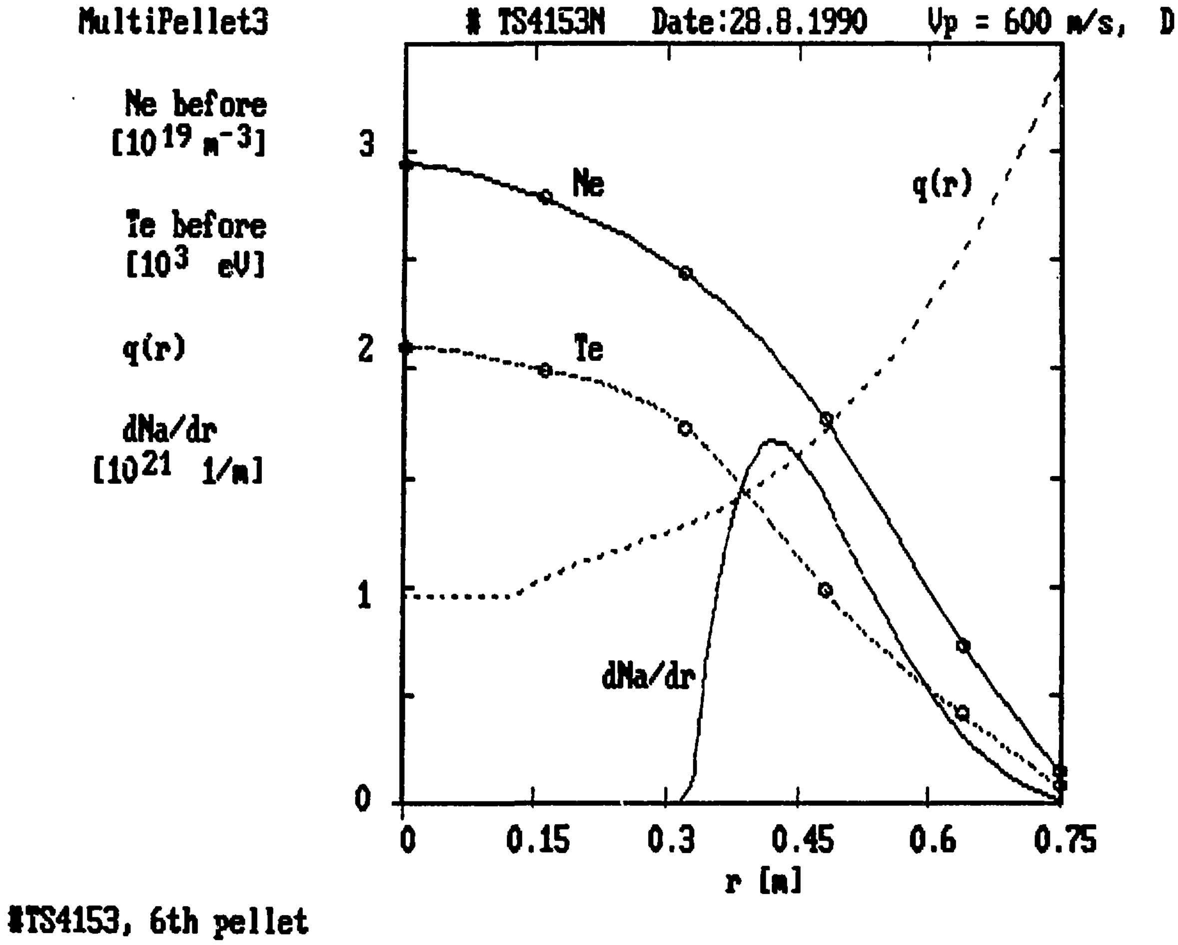

MultiPellet3
TS4153N Date:28.8.1990 Vp = 600 m/s, D
Ne before
[10^19 m^-3]
Te before
[10^3 eV]
q(r)
dNa/dr
[10^21 1/m]
Ne
Te
q(r)
dNa/dr
0
1
2
3
0
0.15
0.3
0.45
0.6
0.75
r [m]
#TS4153, 6th pellet

Figure 10

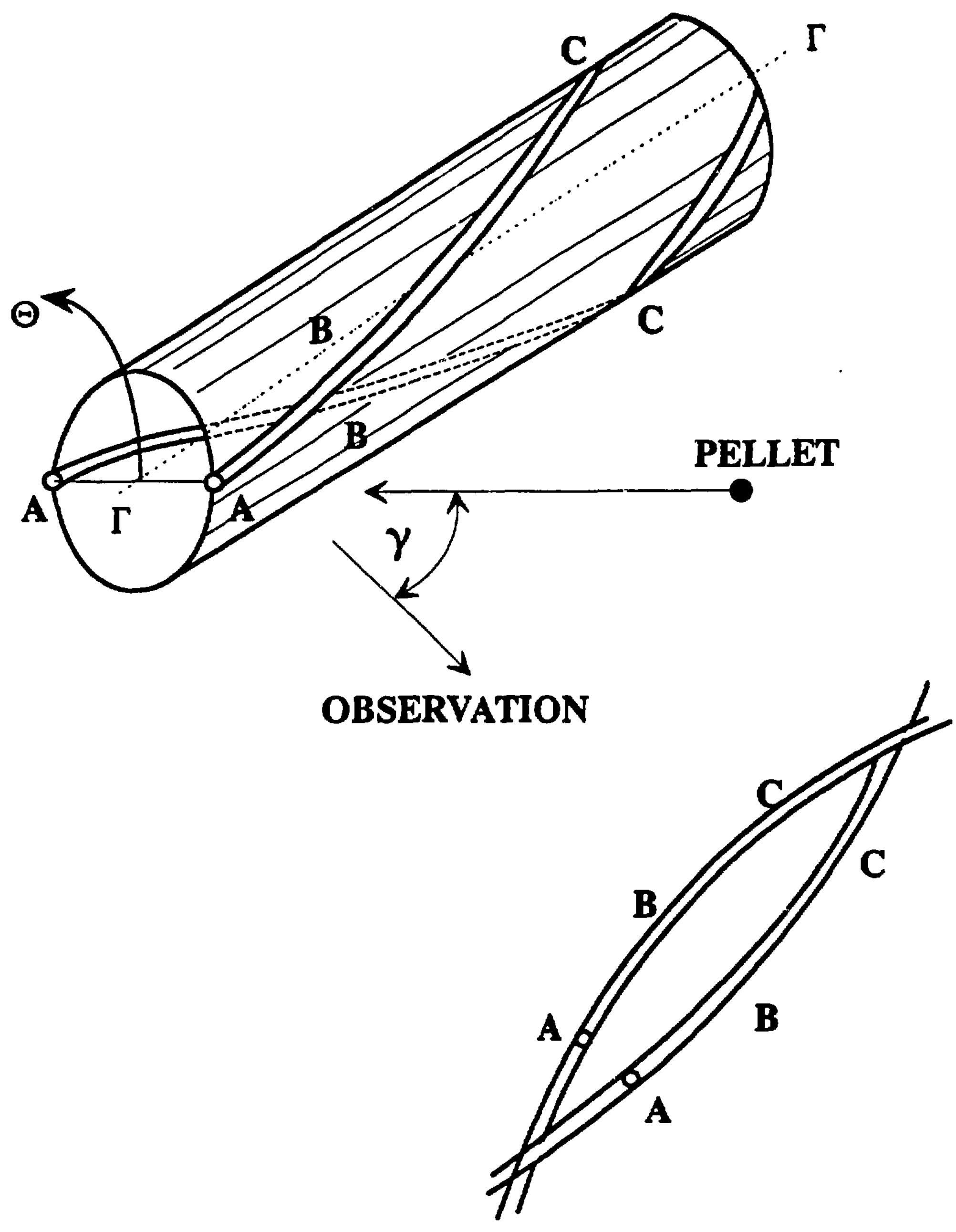


Figure 11