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(Doublet-III Experimental Report, 10)

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The correlations between the shape of the outermost plasma surface and the externally applied equilibrium field are derived from the magneto hydrodynamic (MHD) equilibrium analysis of dee-shaped plasmas in Doublet III. The elongation (height-to-width ratio) depends not only on the decay index value of the magnetic axis and the plasma current profile, but also on the triangularity of the plasma surface. The triangularity (triangular deformation from the ellipse) is related linearly to the hexapole field index value at the magnetic axis.

Keywords; Doublet III, D-shaped Plasma, External Equilibrium Field Elongation, Triangularity, Decay Index, Hexapole Index, Plasma Current Profile

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D型断面プラズマの形状と外部平衡磁場との相互関係
（ダブレットⅢ実験報告・10）

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（１９８１年9月３０日受理）

ダブレットⅢにおけるD型断面プラズマの電磁流体平衡解析から，プラズマ最外殻磁気面の形状と外部平衡磁場との相互関係が得られた。非円形度（縦横比）は，磁気軸でのn指数の値やプラズマ電流分布のみならず，プラズマ表面の三角形変形にも依存している。三角形度（楕円から三角形変形の度合）は，磁気軸でのh指数の値に線形な関係となっている。

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1. INTRODUCTION

A dee-shaped plasma is believed to be the most advantageous for achieving higher β values in tokamak reactors. In the INTOR design the plasma has an elongation of 1.6 and a triangularity of 0.3. A numerical calculation of the MHD equilibrium is usually carried out to deduce the plasma shape and the equilibrium field. It is unclear what kind of correlations exist between the plasma shape and the equilibrium field. It will be useful for future design work to get some simple correlations between the plasma shape and the external equilibrium field.

The experimental study of the dee-shaped plasma is carried out in Doublet III. As an analysis of these experiments, many MHD equilibria were calculated using the experimental data. Actual plasma shapes are up-down symmetric and have different triangular deformations between the upper and lower half of the plasma. However, the elongation and the triangularity of the outermost plasma flux contour are simply correlated with the parameters of the equilirium field at the magnetic axis. This report describes the relationships between the plasma shape and the external equilibrium field, which were obtained by the MHD analysis.

The elongation of the plasma shape is changed from 1.4 to 1.9 and the triangularity is scanned from 0.1 to 0.35. The density profile of the plasma current is also scanned with an internal inductance from 1.0 to 2.0.

Section 2 presents the experimental procedure of producing several kinds of dee-shaped plasmas. Definitions of the parameters of the plasma shape and the equilibrium field are described in Section 3. In Section 4, several correlations between the plasma shape and equilibrium field are presented. Section 5 discusses vertical stability and the shaping control of elongated plasmas.

2. EXPERIMENTAL PROCEDURE

Doublet III is a large tokamak with a major radius of 1.4 m and a minor radius of 0.45 m [1]. Plasma position and shape in Doublet III is controlled by 24 field shaping coils (F-coils) [2]. Each F-coil is located so close to the vacuum vessel (~ 0.1 m) that it may be considered to individually control the local flux value (ψ_i) near the plasma boundary. The L/R time of each F-coil is 0.25 -0.5 sec. The plasma shape is dependent on how the 24 F-coils and power supplies are connected. Figure 1 shows a typical connection which is used to produce elongated dee-shaped plasmas. The 17 uppermost F-coils are connected in parallel to function as a conducting shell for the passive control. The remaining 7 F-coils are left open to decrease the power supply requirement. The power supplies are indicated by square boxes in Fig. 1. A typical plasma shape is also illustrated.

Five shaping coils (1A, 1B, 2B, 6B and 7B) provide the strong pulling force from the bottom required to maintain a highly elongated plasma and two F-coils (5A and 11A) balance the pulling force from the top.

The elongation is primarily controlled by the F1A coil by regulating the ratio of ψ_{4A}/ψ_{1A} which is a ratio of the poloidal flux values measured on the surfaces of the F4A and F1A coils. Fine adjustments of the elongation are carried out by the F6B, F1B and F2B. The connection used in Fig. 1 is used to produce plasmas with elongations of 1.5 -1.8. Plasmas with small elongaions are produced by using a different connection of the field shaping coils and power supplies.

The triangularity is adjusted by modifying the connection of F-coils and power supplies and by changing the distribution of the poloidal flux values on each F-coil.

The radial position is regulated by four outside F-coils (6A, 7A, 8A and 9A). Vertical position regulation is achieved by the upper coils;10A and 12A.

The current density profile is controlled by changing the plasma current, toroidal field strength and electron density. The flat current profile is obtained under the condition of: high plasma current (I_p = 600 kA) low toroidal field (B_T = 15 kG) and low electron density (n_e = 2 x 10^{13} cm^{-3}) without sawtooth oscillations. In these discharges, the internal inductance has values of ℓ_i = 1.0 -1.3. The peaked current profile is obtained under a condition of: low plasma current ($I_p \simeq$ 400 kA), high toroidal field (B_T = 24 kG) and high electron density ($n_e \simeq$ 5 x 10^{13} cm^{-3}) with sawtooth oscillations. In these discharges, the internal inductance has values of ℓ_i = 1.8 -2.1.

3. DEFINITIONS OF THE PARAMETERS OF PLASMA SHAPE AND EQUILIBRIUM FIELD

Plasma shape is determined by MHD analysis using experimental magnetic data [3]. The 24 poloidal flux values measured at each F-coil are employed as the boundary condition in solving the Grad-Shafranov equation, and the plasma current profile is selected in MHD analysis to reproduce the magnetic field distribution to be the same as those obtained experimentally by the 11 partial Rogowski coils. The plasma shape derived by MHD analysis was checked experimentally by an electron density ratio of $\int n_e^V d\ell / \int n_e^U d\ell$, which are measured through a vertical (n_e^V) and horizontal path (n_e^U). Plasma shape was also confirmed by direct measurement using two TV camera systems that observe the plasma cross section tangentially. The TV pictures are taken with an H_α filter mounted in front of the TV camera so that they provide good indications of the plasma surface where the Hα light emission is intense due to the recycling hydrogen.

"Elongation (K)" and "Triangularity (δ)" represent deformations of the outermost flux contour of the plasma obtained by MHD analysis. They are defined as,

$$K = \frac{Z_{TOP} - Z_{BOT}}{R_{OUT} - R_{IN}} \tag{1}$$

$$\delta = \frac{R_{OUT} + R_{IN} - R_{TOP} - R_{BOT}}{R_{OUT} - R_{IN}} \qquad (2)$$

where the suffixes TOP, BOT, OUT, and IN mean the highest, lowest, outermost and innermost positions of the plasma surface, respectively as shown in Fig. 2.

The vertical field (B_Z) applied by F-coils is not constant inside the plasma cross section. Figure 3 shows the vertical field along the horizontal chord through the magnetic axis. The parameters of this discharge are I_p = 530 kA, B_T = 20 kG, K = 1.8 and δ = 0.3.

The vertical field (B_Z) can be decomposed into dipole (B_D), quadrupole (B_Q), and hexapole components (B_H) at the magnetic axis [4] and written along the chord through the magnetic axis,

$$B_Z(R) = B_D + B_Q \frac{R-R_o}{a_o} + B_H \frac{1}{2}\left(\frac{R-R_o}{a_o}\right)^2 + B^{err}(R) \quad , \qquad (3)$$

where R_o and a_o denote a major radius at the magnetic axis and a half width of a plasma cross section, respectively. R_o and a_o have values of 1.40 and 0.41 m in the case of Fig. 3. Each multipole field has the following values in this case: B_D = −880 Gauss, B_Q = −400 Gauss, B_H = 520 Gauss. $B^{err}(R)$ is less than 2% of B_Z. $B^{err}(R)$ is so small that the plasma shape may be considered to correlate only to the strengths of B_Q and B_H. Thus, relations between the plasma shape and equilibrium field will be discussed using the decay index $\left(n = -\frac{R}{B_z}\frac{\partial B_z}{\partial R}\right)$ and hexapole index $\left(h = \frac{R^2}{B_z}\frac{\partial^2 B_z}{\partial R^2}\right)$ at the magnetic axis.

They are written using B_Q, B_H ,

$$n = -A \frac{B_Q}{B_D} \tag{4}$$

$$h = A^2 \frac{B_H}{B_D} \tag{5}$$

where A is the aspect ratio (R_o/a_o).

The normalized internal inductance (ℓ_i) [5] represents the profile of the plasma current density. Since there is no direct measurement of the internal inductance, the value of the internal inductance derived by MHD analysis is used in this report.

4. CORRELATIONS BETWEEN PLASMA SHAPE AND EQUILIBRIUM FIELD

4.1 Relations between elongation, decay index, and triangularity

Figure 4 shows the relation between the decay index and the elongation with the triangularity as a parameter. The circles and triangles show the results of MHD calculation. There is a one-to-one relationship between the elongation and the decay index when the triangularity is fixed. A plasma with a small triangular deformation needs a large absolute value of the decay index in order to sustain the same elongation.

Figures 5 and 6 illustrate the influences of triangularity on elongation more clearly. Figure 5 shows the relation between the decay index and triangularity with the elongation as a parameter. By keeping the elongation constant, the absolute value of the decay index decreases ~ 0.4 as the triangularity increases from 0.1 to 0.3. Solid curves are parabolic fittings by $n = n_o + 5\delta^2$. Figure 6 shows the relation between elongation and triangularity when the decay index is kept constant. The circles and triangles show MHD calculations with a decay index of $n = -1.2 \sim -1.3$ and $n = -1.4 \sim -1.5$, respectively; the dotted lines are parabolic fittings by $K = K_o + 4\delta^2$. By keeping the decay index constant ($n \simeq -1.4 \sim -1.5$), the increment of the triangularity from $\delta = 0.15$ to $\delta = 0.3$ results in the increment of the elongation from $K = 1.5$ to $K = 1.8$.

Since the absolute value of the decay index required to maintain a given elongation is reduced by the triangular deformation, a dee-shaped plasma is considered to be positionally more stable than an elliptical plasma.
Figure 7 depicts the measured growth rates of vertical instability without an active feedback control of the vertical position. A plasma with a small triangularity (δ = 0.16 -0.2) becomes vertically unstable at an elongation of K ≈ 1.6. However, a plasma with a large triangularity (δ = 0.25 -0.30) shows the same instability at the relatively high elongation of K ≈ 1.75.
This dependence of the vertical instability on the triangularity is correlated mainly to the relationship of the decay index and the triangularity. As shown in Fig. 4, a decay index of -1.45 is required to maintain an elongtion of 1.6 for plasmas with δ = 0.16 - 0.20. However, the same decay index can maintain an elongation of 1.75 for plasmas with δ = 0.25 -0.30. Positional instability depends only on the value of the decay index [6]. Triangular deformation of a plasma cross section is a great advantage in stably maintaining a highly elongated plasma against positional instability.

4.2 Relations between elongation, decay index, and internal inductance

The elongation of the plasma shape also depends on the profile of the plasma current density. Figure 8 shows the relation between the decay index and the internal inductance when the elongation and triangularity are kept constant. As the plasma current profile peaks, a larger absolute value of the decay index is required to maintain a given shape. When the current profile peaks further, the required decay index is reduced. The absolute value of the decay index is decreased by ~ 0.1 when the internal inductance changes from 1.5 to 1.0 or 2.0. Since the required dipole field strength (B_D) increases linearly to the plasma current profile (ℓ_i) to sustain a constant plasma position, the required quadrupole field strength (B_Q) first increases at a greater rate, and later at a lesser rate than the linear rate against ℓ_i. The solid curve shows the analytical calculation [7] for an elliptic plasma (δ = 0) with K = 1.55. This calculation shows the same tendency as the results of MHD analysis; the discrepancies of the absolute value are due to effects of the triangular deformation. Figure 9 shows a relation between the decay index and the elongation with the plasma current profile as a parameter. The absolute value of the decay index is decreased by ~ 0.1 in all elongations by the flat or very peaked current profile. This dependence, however, is smaller than the dependence on the triangular deformation of the plasma shape.

4.3 Relation between triangularity and hexapole index

Figure 10 shows the relation between the triangularity of the plasma shapes and the applied hexapole index (Eq. (5)). The closed points show the results of MHD analysis and a dotted line is a linear fit by $h = -3.7 - 8.6\delta$. This data includes a wide range of elongations from 1.5 to 1.8. It is shown that the hexapole index is linearly related to the triangular deformation. The triangularity shows little dependence on other parameters in this data. The scatters of MHD calculations are caused by the higher order deformation (for example, up-down asymmetry, minor change in a small part of the plasma surface, etc.).

5. SUMMARY

Although actual cross sections of dee-shaped plasmas in Doublet III are up-down asymmetric and are deformed from a simple expression of elliptical and triangular deformation, the plasma shapes are simply correlated with the equilibrium field. Using the parameters of the outermost plasma shape and the parameters of the equilibrium field at the magnetic axis, which are obtained from MHD equilibrium analysis, the following correlations are obtained for various kinds of dee-shaped plasmas with elongations of $K \simeq 1.4 - 1.9$, triangularities of $\delta = 0.1 - 0.35$, and internal inductances of $\ell_i = 1.0 - 2.1$,

1) The elongation of the plasma shape depends not only on the decay index and the profile of the plasma current density but also on the hexapole index (triangularity).

2) The triangular deformation of the cross section tends to reduce the absolute value of the decay index required to produce a given elongation. This is preferable for vertical stability of an elongated plasma.

3) A plasma with a medium internal inductance ($\ell_i \approx 1.5$) requires a relatively larger absolute value of the decay index than values with either a smaller or larger internal inductance ($\ell_i \approx 1.0$ or 2.0) in order to sustain a given elongation and triangularity.

4) The triangularity has a linear relation to the hexapole index and shows little dependence on the other parameters for the range of elongations from 1.5 to 1.8.

Acknowledgement

The authors would like to express their sincere gratitude to Dr. T. Ohkawa and the staff of the General Atomic Company for their great hospitality. This experiment was carried out with the fine support of the diagnostics group under Dr. R. Fisher and the machine operations group under Dr. R. Callis. The authors would like to thank Drs. M. Yoshikawa and S. Mori and the staff at the Japan Atomic Energy Research Institute for their continuing encouragement throughout this work.

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Figures

Fig. 1 A control schematic of dee-shaped plasmas. Voltage gains are indicated on the power supplies and differential emplifiers. Feedback signals are shown as inputs for differential emplifiers. the uppermost 17 field-shaping coils are connected parallel to each other and connected to an ohmic heating power supply. Thick lines show the electric power flow with arrows indicating directions. D, V, and R denote thyrister power supplies and T and V are chopper power supplies.

Fig. 2 Definition of coordinates in a plasma shape.

Fig. 3 Experimentally applied vertical field (B_Z) and a dipole (B_Z), quadrupole $B_Q \frac{R-R_o}{a_o}$, and hexapole $\frac{B_H}{2}\left(\frac{R-R_o}{a_o}\right)^2$ components on a horizontal chord through the magnetic axis. B_{err} is less than 2% of B_Z. The magnitudes of these components are : B_D = -880 Gauss, B_Q = -400 Gauss, B_H = 520 Gauss.

Fig. 4 The relation between the decay index and the elongation with the triangularity as the parameter. The decay index value is defined at the magnetic axis; the elongation is the weight-toi-width ratio of the outermost plasma surface.

Fig. 5 The relation between the decay index and the triangularity with the elongation as the parameter.

Fig. 6 The relation between the elongation and the triangularity with the decay index as the parameter.

Fig. 7 The growth rates in the vertical instability. The triangular deformation decreases both the decay index requirement and vertical instability. This data is measured at B_T = 15.24 kG, I_p = 400 - 650 kA, $\overline{n}_e$ = (3-5) x 10^{13} cm^{-3}.

Fig. 8 The relation between the decay index and the plasma current profile. The solid curve shows the theoretical prediction for an elliptic plasma with K = 1.55 (Ref. (7)).

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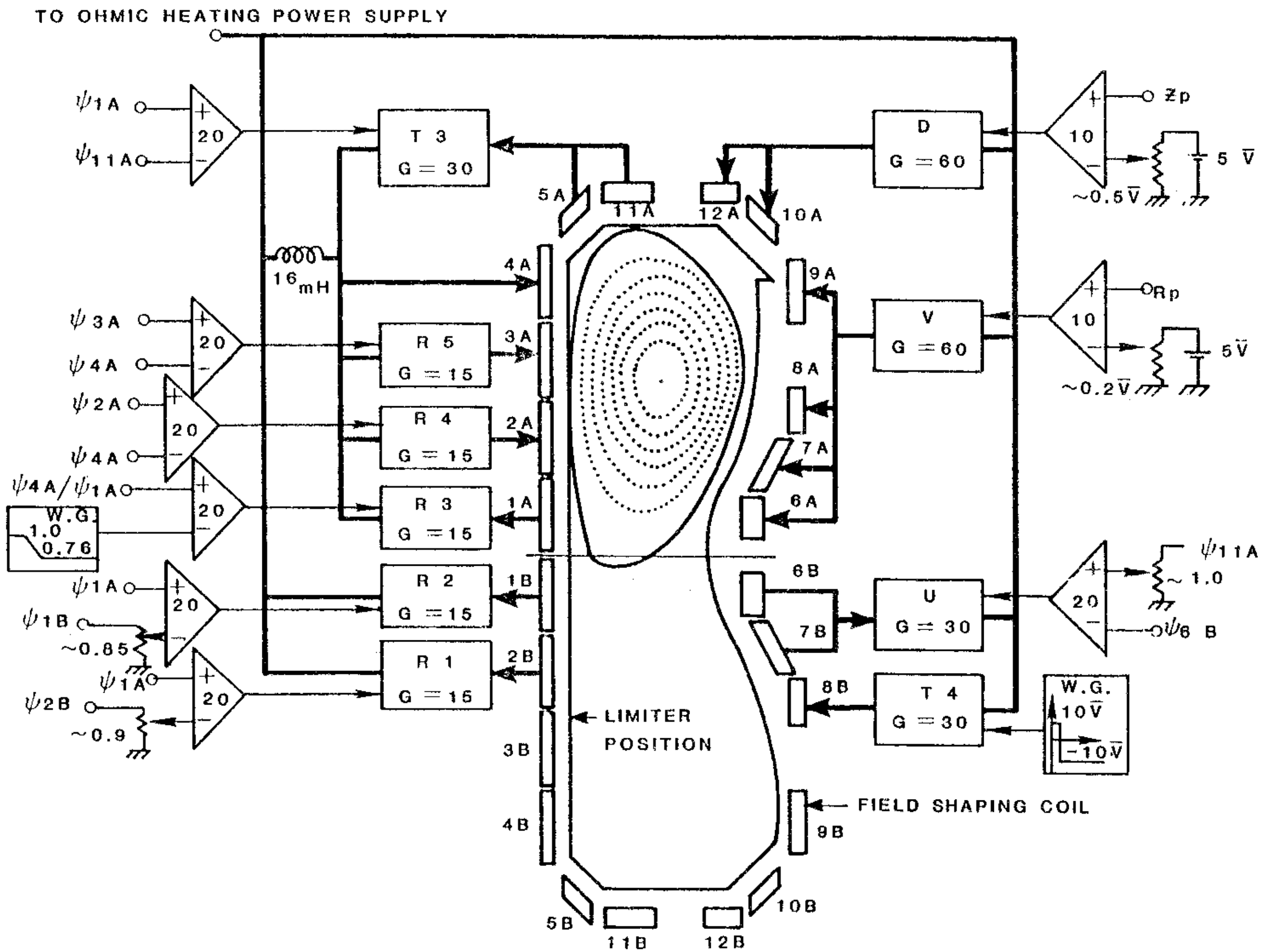

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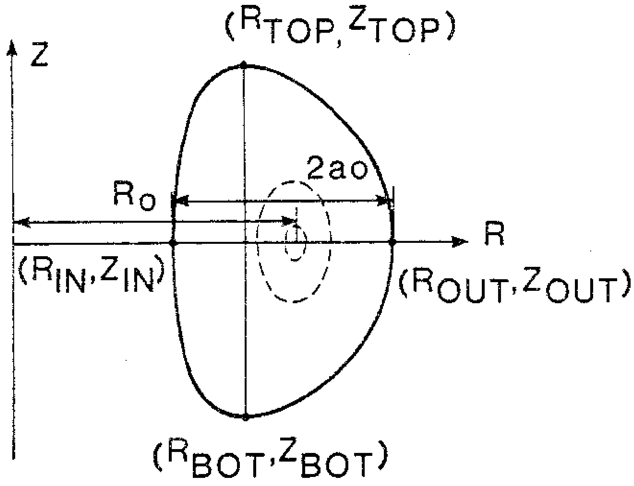

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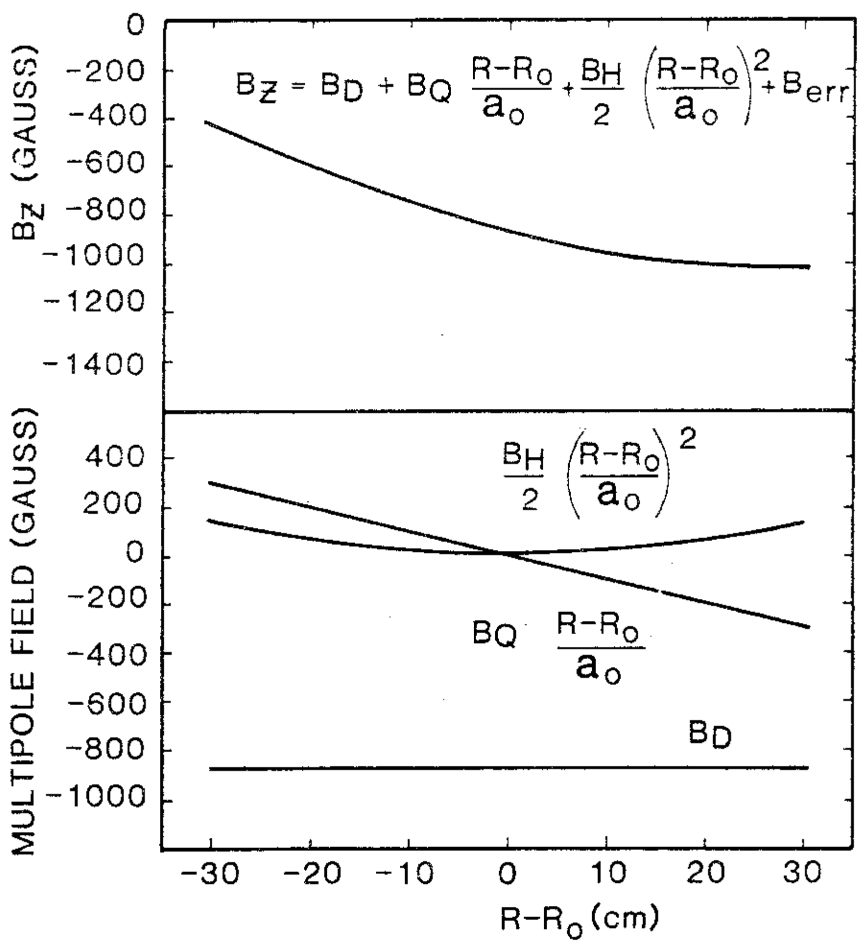

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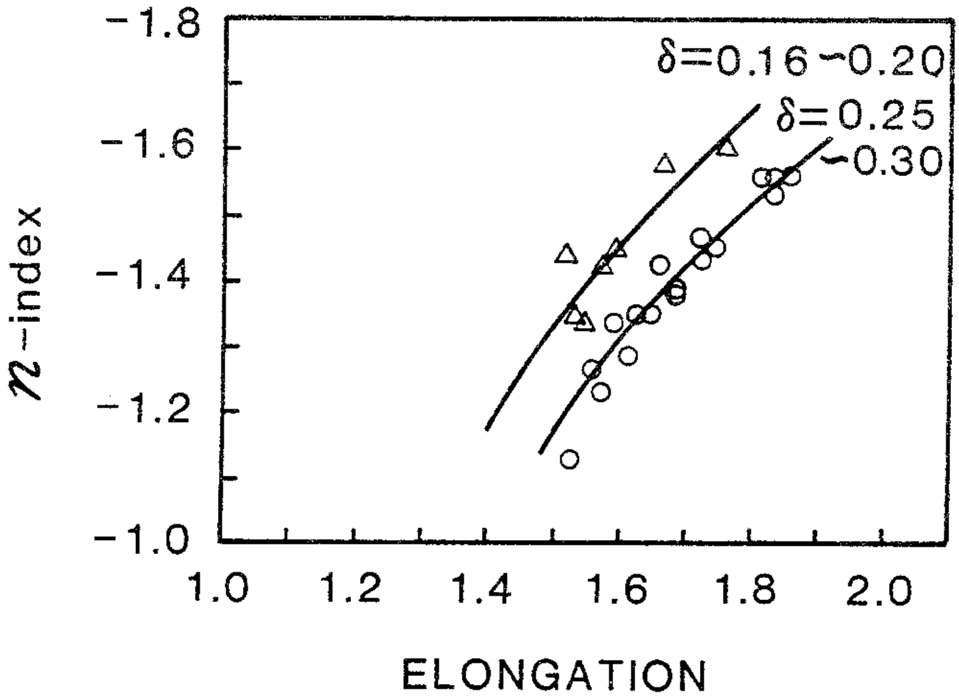

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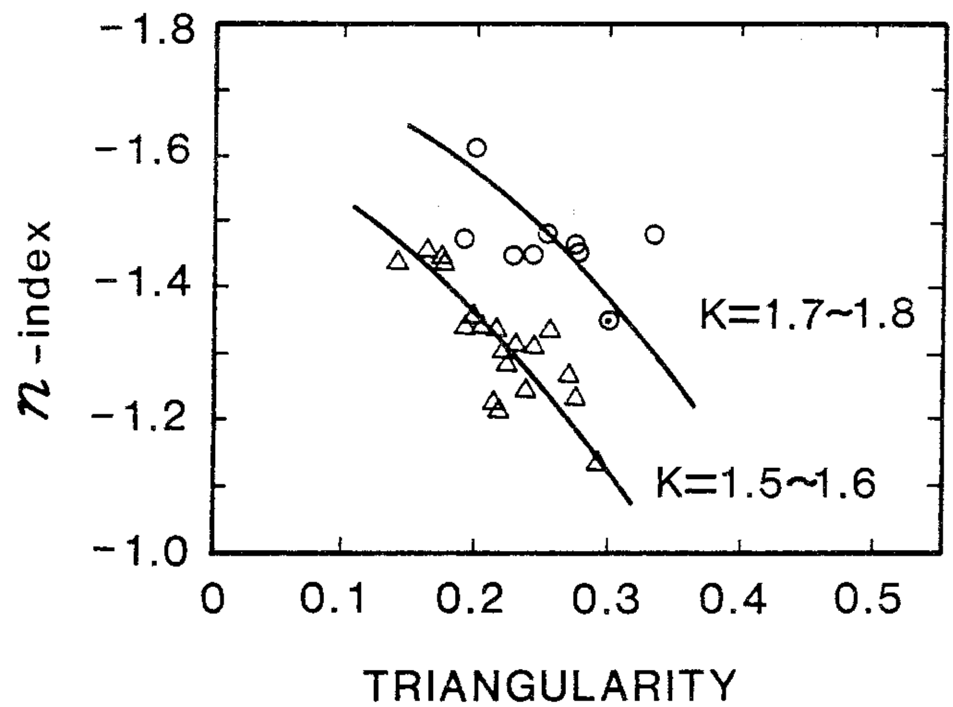


Fig. 5 The relation between the decay index and the triangularity with the elongation as the parameter.

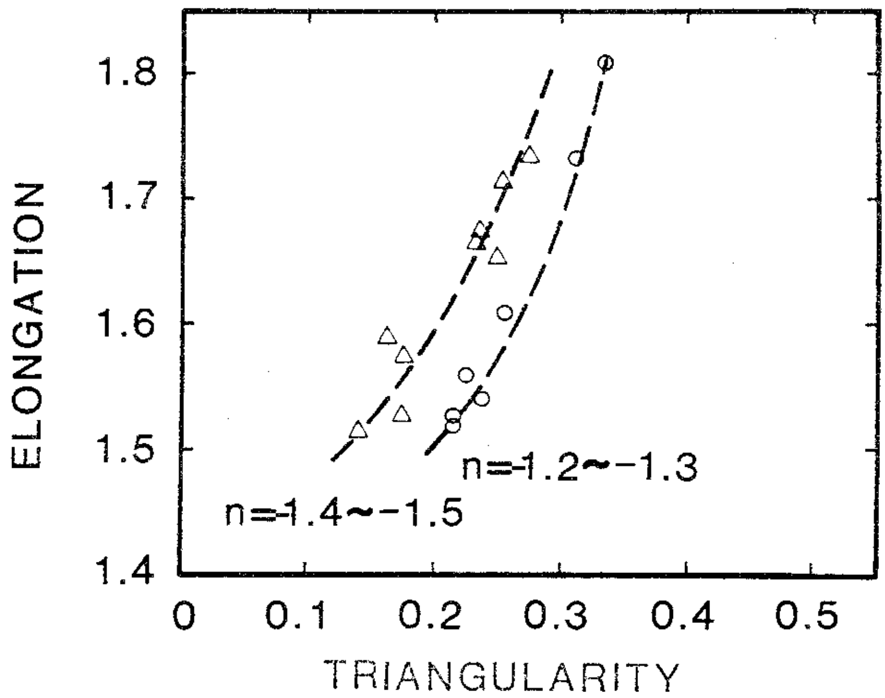
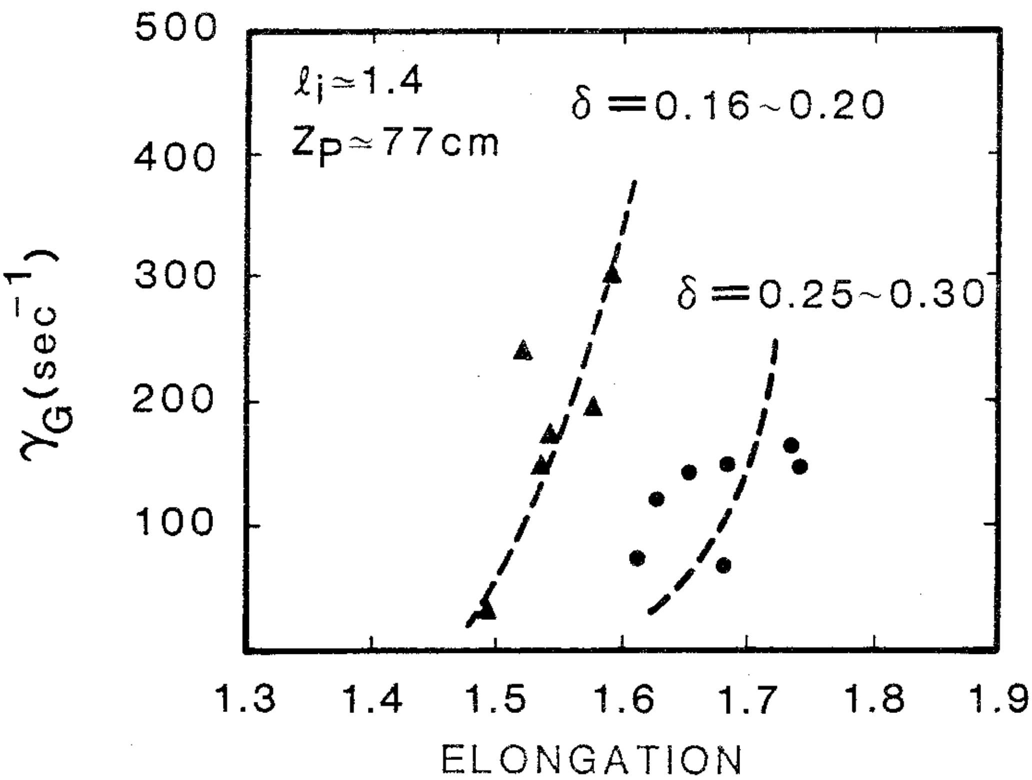


Fig. 6 The relation between the elongation and the triangularity with the decay index as the parameter.



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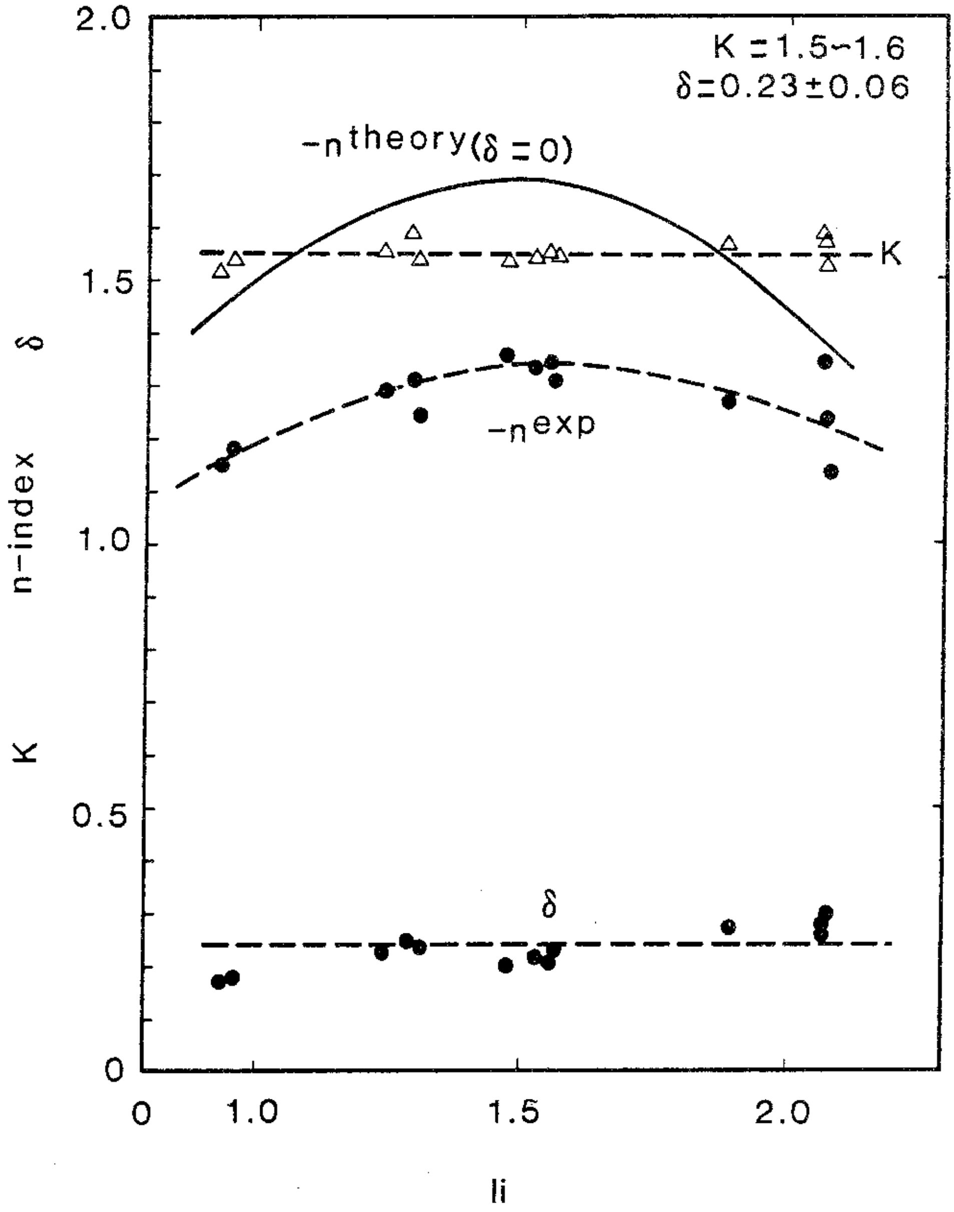

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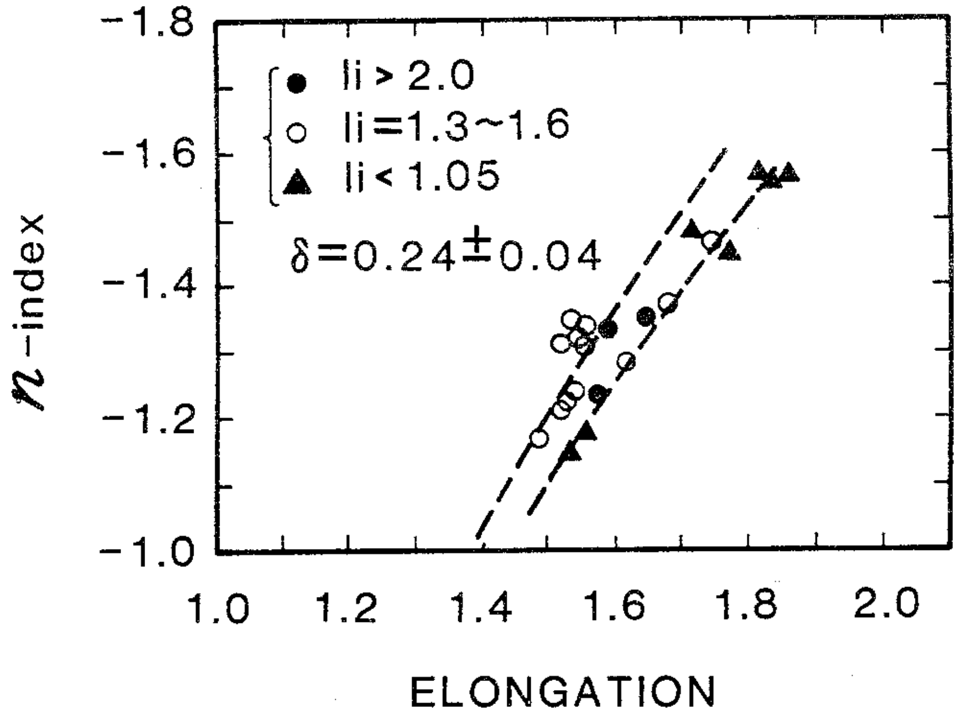

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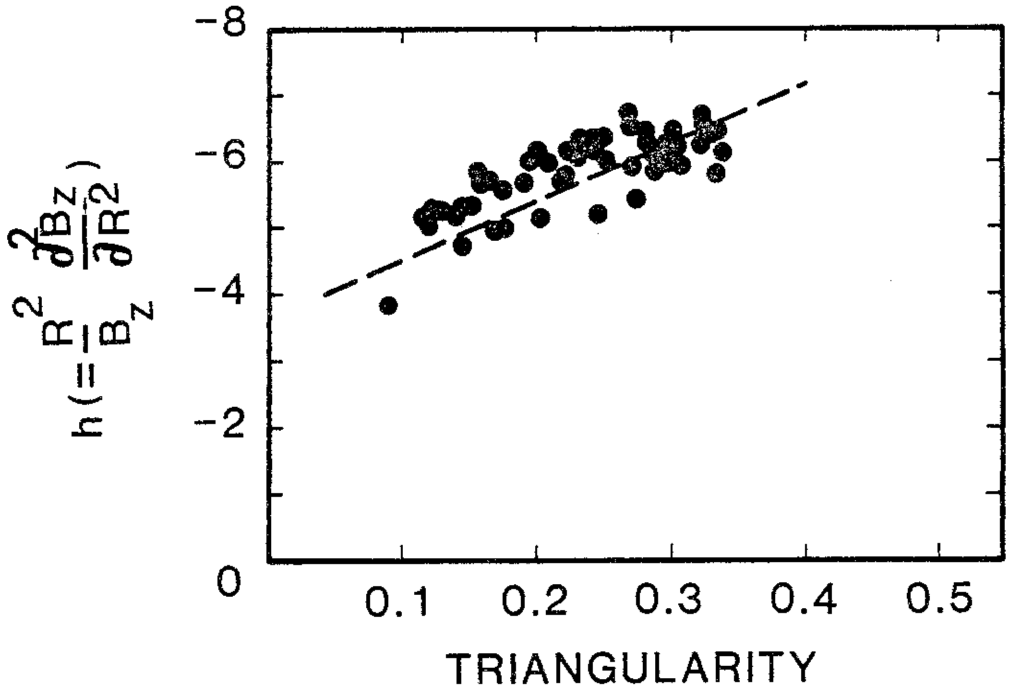

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