ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received – May 28, 1991)

NIFS-93 Jun. 1991

RESEARCH REPORT
NIFS Series

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NAGOYA, JAPAN

Geometric Dependence of the Scaling Law on the Energy Confinement Time in H-mode Discharges

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Abstract

The dependence of the energy confinement time τ_E in the H-mode discharges on the plasma elongation and divertor configurations is studied. Regression analysis is made on the H-mode database, while the dependence on the closed/open divertor is introduced according to the ASDEX experiments. The dependence of τ_E on the elongation factor κ was found to be positive (approximately $\kappa^{0.8}$) for the ELM free H-mode, confirming the experiments on κ-dependence in JFT-2M tokamak. The influence of the single/double null divertor configuration is also discussed.

Keywords: Energy Confinement Time, Scaling Law, H-Mode
Plasma Elongation, Single-Null and Double-Null Divertor,
Closed and Open Divertor

Recently the scaling law of the energy confinement time of H-mode has attracted much attention. The knowledge on how the energy confinement time depends on various parameters, is not only essential in understanding the physics associated with the H-mode, but also is inevitable in predicting the expected plasma parameter in the coming experiments, designed to achieve a burning plasma. Due to the large size of the planned program, the predictions must be as correct as possible, and the divergence in the expectations should be evaluated carefully.

One of the most enthusiastic efforts is those[1-3] based on the H-mode database, which was established by the groups of JET, DIII-D, ASDEX, PBX-M, PDX and JFT-2M. The dataset, containing about thousand discharges, is presently oriented towards H-mode realized by the NBI heating in the divertor configuration. Regression analyses are made to obtain the scaling law in the form of either the power law or the offset linear law. The former procedure is based upon the ansatz that the energy confinement time τ_E can be expressed in the form of the powers with respect to the plasma parameter and the injected power. The latter procedure assumes that the total stored energy W_{th} (i.e., τ_E multiplied by the heating power P) can be expressed in a form of an offset linear function of P, i.e., $W_{th}= W_0+\tau_{inc}P$. Based on the present data, both representations have similar residual statistical error, so that both can be used to predict the performance of the next step devices.

The two paper, scalings presented in Ref.[2] and Ref.[3], however, are not satisfactory with respect to the geometrical dependence, particularly that on the plasma elongation, κ (κ is the ellipticity of plasma cross section). The power law[2] concludes the negative dependence on κ, while the offset linear law[3] suggests the positive dependence. This discrepancy should be resolved, if possible, in order to improve the accuracy of the prediction. It is also noticed that, as was mentioned in Ref.[2], the distinction between the discharges in the closed divertor and those for the open divertor was not used in deriving the scalings. Experimental knowledge has shown that the elongation has favorable effect on the energy confinement time[4], and that a closed divertor provides in general better confinement time than an open one[5]. The objective of this article is to study the dependence of τ_E on the elongation, by incorporating the influence of the configuration of the divertor. Also discussed is the distinction between the single null (SN) divertor and double null (DN) divertor.

We discuss the scaling law of τ_E as a function of plasma current I_p, magnetic field B_T, plasma major radius R, average mass of plasma particle and beam particle A, total heating power P and the plasma elongation κ. The scaling study assumes that all data obey to the same law, thus allowing to evaluate the size dependence. The choice of the variable, however, contains uncertainty so as to need the examination by the experimental study. As mentioned before, the power scaling, Eq.(6) in Ref.[2] was derived by neglecting the dependence of τ_E on whether the divertor is open or closed. We here assume that a plasma with closed divertor has the same parameter dependence as a plasma with open divertor, except for a constant, i.e.,

$$\tau_E \text{ (closed divertor)} = C_{co}\, \tau_E \text{ (open divertor)}. \tag{1}$$

This assumption can be examined with respect to the dependence of I_p, B_T and P, because these parameters can be varied in ASDEX although the range of the variation (especially with respect to B_T) is limited. On the other hand, under assumption of Eq.(1), the dependence on the plasma size or elongation cannot even be checked by ASDEX alone, because only the ASDEX and PDX (the only tokamaks with κ=1) satisfy the condition of being a closed divertor in the dataset. Hence, the estimated effects of κ on the confinement time is strongly correlated with C_{co}.

ASDEX team has investigated the effect of the divertor configuration on the energy confinement time. It has been reported that with the same conditioning on the wall, the energy confinement time is 1.57(1±0.09) times better than L-mode scaling in the open divertor (DIV-II with large conductance), while 2.25(1±0.18) times better in the closed divertor (DIV-I). The uncertainties (0.09 or 0.18) are to be interpreted as one standard deviation. Based on this observations we employ the parameter

$$C_{co} = 1.43. \tag{2}$$

The regression study is done basically for the subset of the H-mode database which is called the "standard dataset". The selection criteria of this subset are described in section 2 in Ref.[2]. In addition to the selection criteria leading to the standard dataset, three other constraints have been imposed to derive Eq.(6) in Ref.[2]:

1. The ELM free data in the standard subset without PDX data.
2. The B_T dependence is forced to be $B_T^{0.15}$.
3. The A dependence is forced to be $A^{0.5}$.

We will keep the last two constraints in the present paper to prove our main point, even a B_T dependence that is, at present, contradicted the unconstraint fits (approximately $B_T^{0.5}$ for the ELM-free and $B_T^{0.65}$ for the ELMy data, see, Ref. [6]). It is not necessary to derive a negative κ-dependence without sacrificing part of the data (with low-κ, and a relatively low H-mode multiplication factor). The diamagnetic energy confinement time τ_{dia} is used for JET and ASDEX, and the MHD energy confinement time τ_{MHD} is used for DIII-D, PBX-M, PDX and JFT-2M. These criteria limit the number of observations subject to the regression study to JET[244], DIII-D[34], ASDEX[16], PBX-M[155], JFT-2M[218]. The regression study for these data with the transformation on the ASDEX data by factor of $1/C_{co}$ shows the fitting

$$\tau_E = 0.056\, C_{div}\, I_P^{0.97}\, B_T^{0.15}\, R^{1.57}\, P^{-0.52}\, A^{0.5}\, \kappa^{0.72} \tag{3}$$

where

$$C_{div} = \begin{Bmatrix} 1 \text{ (open divertor)} \\ C_{co} \text{ (closed divertor)} \end{Bmatrix} \tag{4}$$

Figure 1 shows the comparison of the experimental data with the scaling law. The estimated standard deviations of the coefficient are 0.014 for I_P, 0.048 for R, 0.012 for P, 0.060 for κ and about 5%(=0.003) for the constant. Needless to say, these errors indicate the uncertainty in the coefficients, only under the assumptions that the form of the scaling and the chosen set of variables are correct. It does not reflect the uncertainty in C_{div} and in the exponent of A and B_T. The root mean square error (RMSE) for Eq.(3) is reduced to 12.3% compared with that for Eq.(6) in Ref.[2]. This scaling law, Eq.(3), has a positive exponent on κ. The qualitative deviation on κ-dependence of the power low in Ref.[2] from the offset linear form is resolved.

The PDX configuration in the database is considered as a closed divertor, but the confinement time of PDX data shows a hidden parameter dependence on the ratio of divertor D_α intensity to that in the midplane $D_\alpha(div)/D_\alpha(mp)$[2,7]. When the conductance of the baffle plate is large, $D_\alpha(div)/D_\alpha(mp)$ is small and the enhancement of τ_E is small. Then we assume that the PDX data with the value of $D_\alpha(div)/D_\alpha(mp)$ less than 5 are the data of open divertor configuration. This assumption gives the possibility to extract κ dependence in wider range at open divertor configuration. The regression study with open divertor data [JET, DIII-D, PBX-M, PDX with the additional criterion (21 observations) and JFT-2M] shows the fitting

$$\tau_E = 0.052\, I_P^{0.96}\, B_T^{0.15}\, R^{1.58}\, P^{-0.52}\, A^{0.5}\, \kappa^{0.84}. \tag{5}$$

The regression study for the open divertor data with the transformation on the ASDEX data by factor of $1/C_{co}$ shows the fitting

$$\tau_E = C_{div}\, \tau_E^I\, \kappa^{0.81} \tag{6-1}$$

Where

$$\tau_E^I = 0.052\, I_P^{0.96}\, B_T^{0.15}\, R^{1.59}\, P^{-0.52}\, A^{0.5}\, . \tag{6-2}$$

The estimated standard deviations of the coefficient in Eqs.(5) and (6) are 0.013 and 0.013 for I_p, 0.048 and 0.047 for R, 0.013 and 0.012 for P, 0.057 and 0.045 for κ, and about 4.0%(=0.0021) and about 3.8%(=0.0020) for the constant, respectively. These fittings have also a positive exponent on κ and shows the reduction of uncertainty on κ.

One can compare the divergence of the original data to the predicted scaling law. Figure 2 illustrates the comparison between the experimental data and scaling law, focusing at the dependence on κ. Figure 2(a) examines the new scaling law, indicating $\tau_E(\exp)/\tau_E^I$ as a function of κ. Figure 2(b) tests old scaling law of Eq.(6) in Ref.[2], showing $\tau_E(\exp)/\tau_E^{norm}$ as a function of κ (where the old scaling law expressed as $\tau_E=\tau_E^{norm}\ \kappa^{-0.19}$). It is clearly shown that the deviation of the data from the fitting formula can be reduced by introducing the dependence of τ_E on the closed divertor.

The positive dependence of τ_E on κ is compared to the study in JFT-2M experiment. The JFT-2M group has reported the κ-dependence in the limiter H-mode experiment, then the direct comparison needs further careful study. Even though the comparison remains to be a preliminary nature, the κ dependence of $\kappa^{0.6\sim1.0}$ on τ_E from Fig.5 in Ref.[4] shows the agreement to Eq.(3), (5) or (6) within the experimental error. This finding also the ansatz that τ_E(limiter) is given by τ_E multiplied by a coefficient C_{LD}.

We finally note the influence of the number of the null points on τ_E. Since the SN configuration has the different conductance of neutral particles from the DN configuration, the difference in the averaged enhancement factor would be possible for these two configurations[8]. Figure 3 demonstrate the histogram of enhancement factor of ASDEX and JET. This comparison shows τ_E is better for DN than SN by factor of 1.08 for ASDEX data. On the contrary, JET data shows τ_E is better for SN than DN by a factor of 1.1. These difference are within the one standard deviation of the dataset. Although this difference may not be insignificant from the rigorous statistical basis, but must be taken into account in applying the scaling law for the projection of the next step devices.

In summary, we have studied the dependence of the energy confinement time on the plasma elongation and the divertor configuration. By discriminating the open divertor configuration from the closed one, we obtained the scaling law of τ_E which contains the positive dependence of κ, as

$$\tau_E = 0.053\, C_{div}\, I_P^{0.96}\, B_T^{0.15}\, R^{1.59}\, P^{-0.52}\, A^{0.5}\, \kappa^{0.81}.$$

By the modification of the scaling law, we can resolve the discrepancies between the k-dependence in the scaling law and that was found in experiment. This result is compared successfully to the experimental study on κ effect. Also discussed is the effect of the single null divertor and double null divertor. These results will reduce the uncertainties in the prediction of future devices.

It is also noted that the new scaling law predicts a little bit lower value for the future large device with an open divertor configuration. If one neglects the distinction with respect to the open and closed divertor, one has the expectation of τ_E=5.4sec from Eq.(6) in Ref.[2] for the ITER grade parameters; I_P=22MA, B_T=4.85T, P=160MW, A=2.5, R=6m, a=2.15m and κ=2.2. On the contrary, the new scaling law gives τ_E=4.8sec for the same parameters. This reduction in the expected value of τ_E is explained that the target plasma will not be benefited by the improvements due to the closed divertor configurations, which was beneficial for ASDEX plasmas (τ_E=6.9sec for the ITER parameters with a closed divertor configuration). Further study to improve the quality of the data is still necessary in order to establish the dependable scaling law for the H-mode plasmas.

We acknowledge to the H-mode database activity, particularly to the experimental group which contributed their data to the database, for allowing the access to and the analysis on the data. Thanks are due to the discussions during the H-mode database workshop in JET 1990. Three of the authors (KI, SII and OK) acknowledge to JFT-2M group for the hospitality during their stay at JAERI. Part of the work was supported by the collaboration program between JAERI and universities on fusion and the Grant-in Aid for Scientific Research of MoE Japan.

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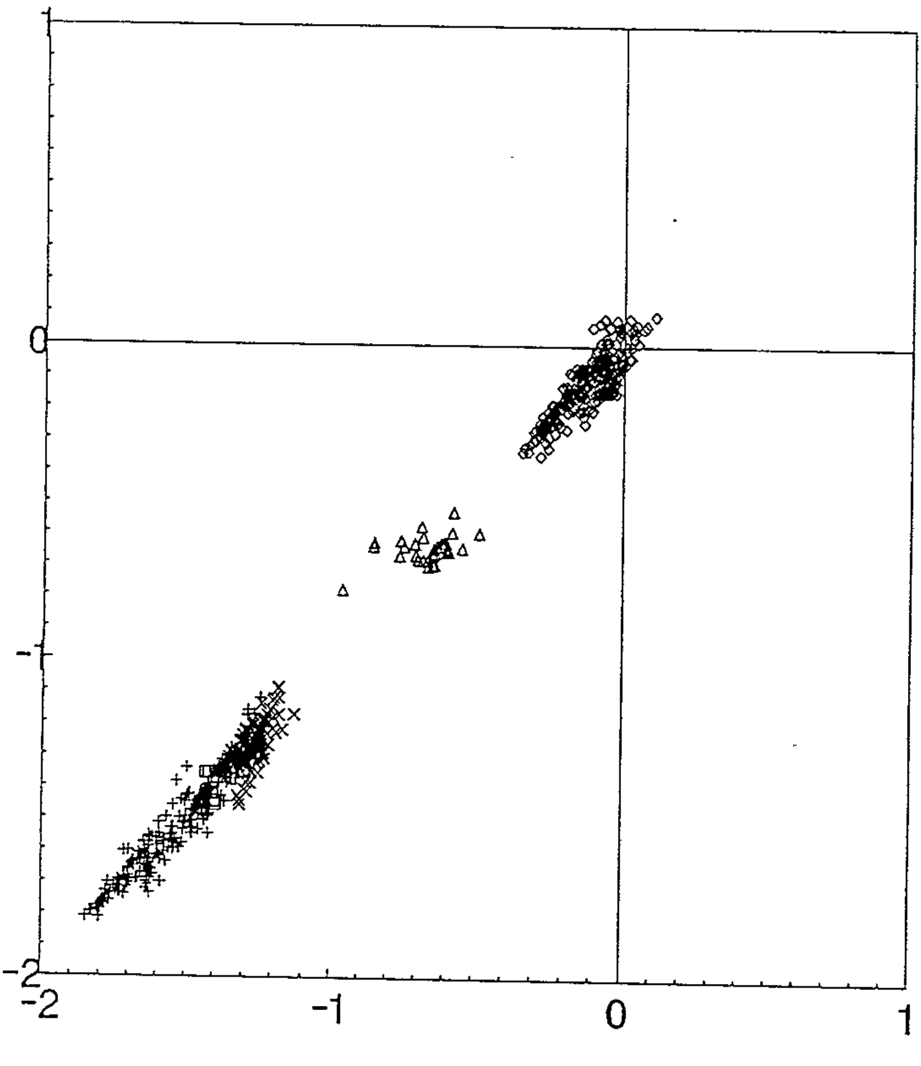
Figure Captions

Fig.1 The comparison of the experimental data with the scaling law for the ELM free H-mode in the standard data set without PDX data. The regression study is made for these data with the transformation on the ASDEX data by factor of $1/C_{co}$ (=1/1.43). Symbols of square, triangle, diamond, plus, x and star show tokmaks of ASDEX, DIII-D, JET, JFT-2M, PBX-M and PDX, respectively.

Fig.2 The comparison between the experimental data and scaling law, focusing at the dependence on κ. (a) shows $\tau_E(\exp)/\tau_E^{I}$ as a function of κ. (b) shows $\tau_E(\exp)/\tau_E^{norm}$ as a function of κ (where the scaling law of Eq.(6) in Ref.[2] is expressed as $\tau_E=\tau_E^{norm}\kappa^{-0.19}$).

Fig.3 The histogram of enhancement factor ($\tau_E/\tau_{ITERT89P}$) in DN and SN of (a)ASDEX and (b)JET. The average of the enhancement factors at DN/SN are 2.32/2.15 and 2.06/2.22 for ASDEX and JET, respectively. And one standard deviation at DN/SN are 0.24/0.13 and 0.16/0.27 for ASDEX and JET, respectively.

Fig.1



0**-1.26 Ip**0.974 Bt**0.15 P**-.516 A**0.5 R**1.565 k**0.723)

Fig.2 (a)

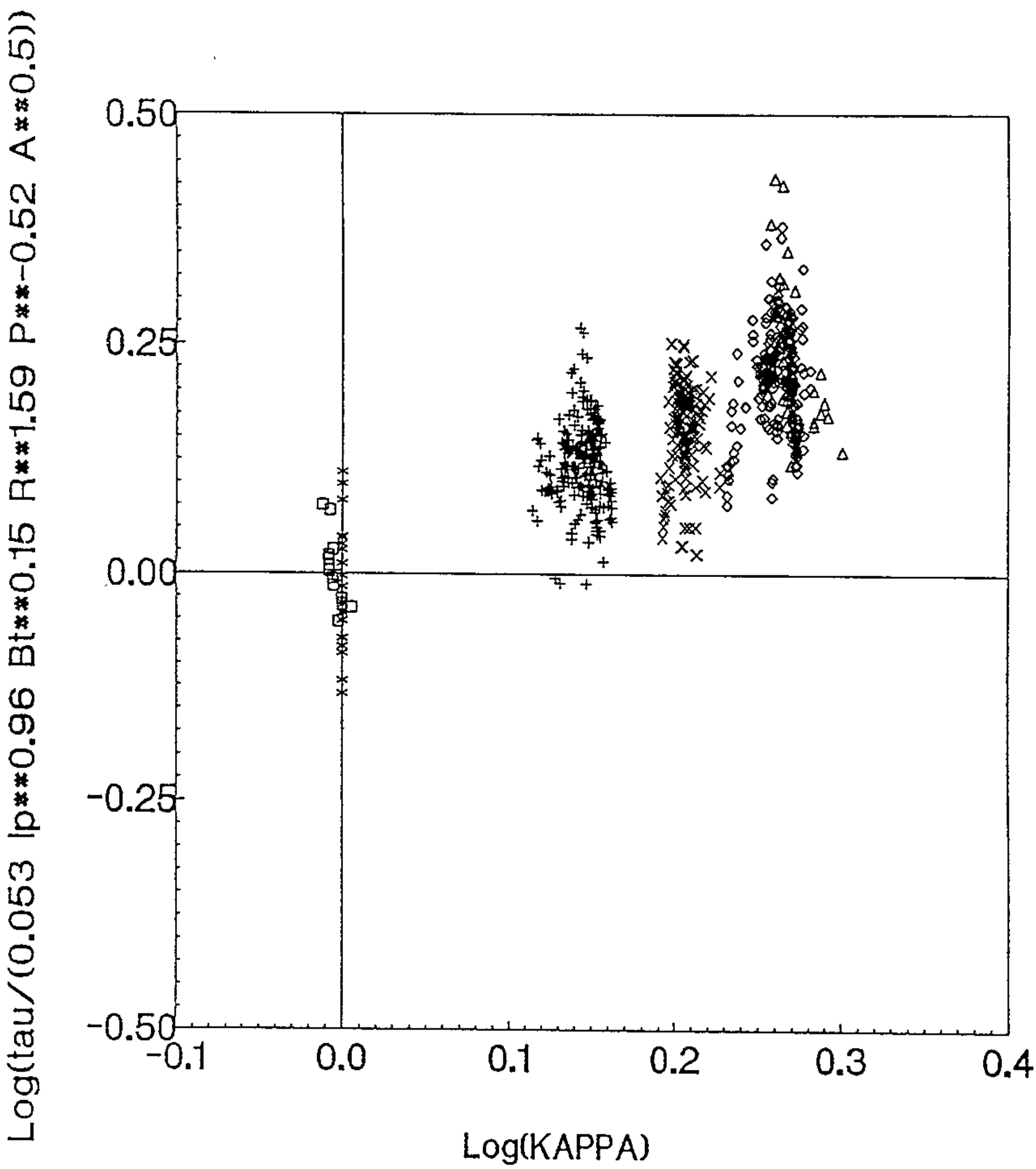

0.50
0.25
0.00
-0.25
-0.50
-0.1
0.0
0.1
0.2
0.3
0.4
Log(KAPPA)
Log(tau/(0.053 Ip**0.96 Bt**0.15 R**1.59 P**-0.52 A**0.5))

Fig.2 (b)

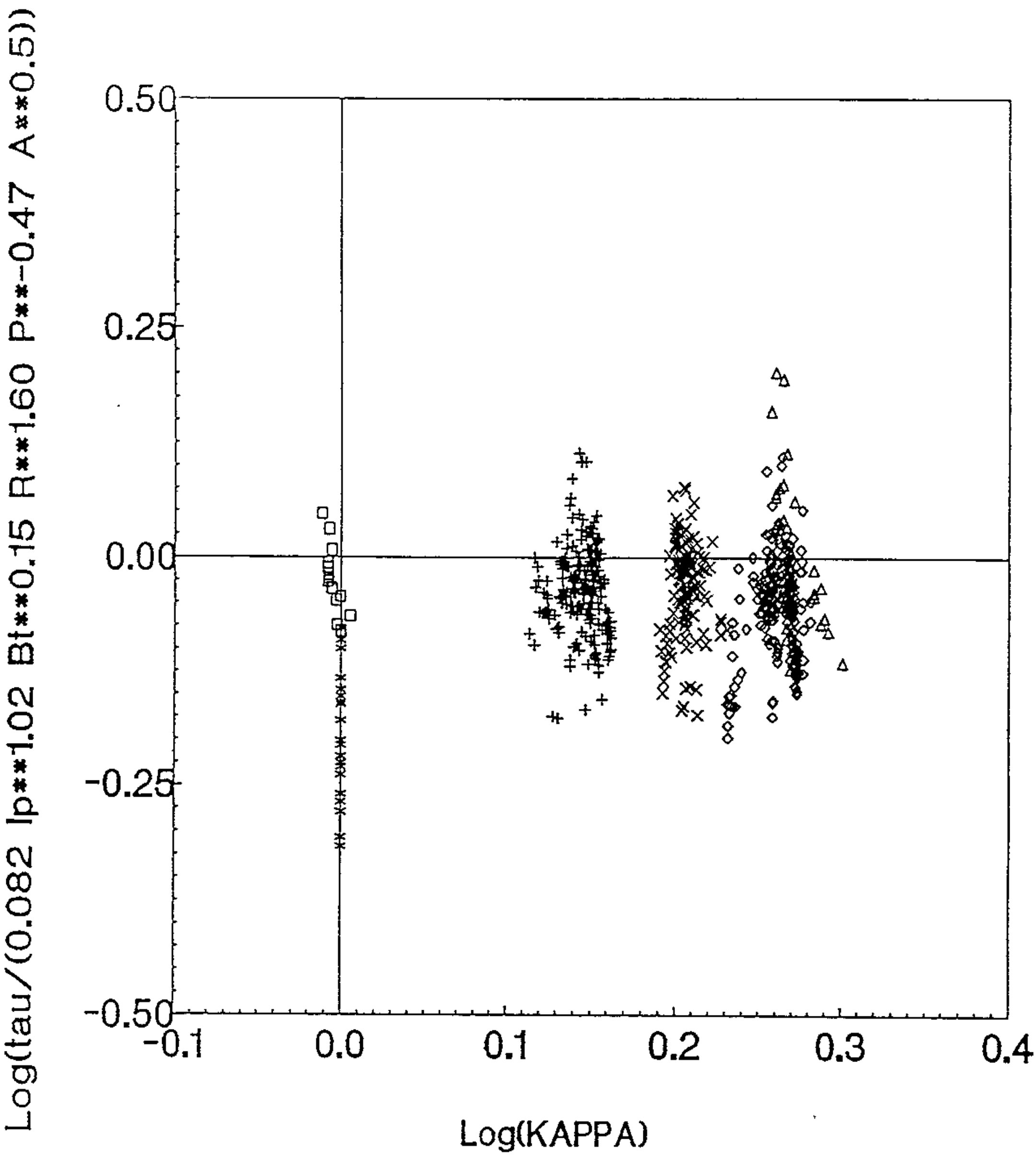

Log(tau/(0.082 Ip**1.02 Bt**0.15 R**1.60 P**-0.47 A**0.5))
0.50
0.25
0.00
-0.25
-0.50
-0.1
0.0
0.1
0.2
0.3
0.4
Log(KAPPA)

Fig.3(a)

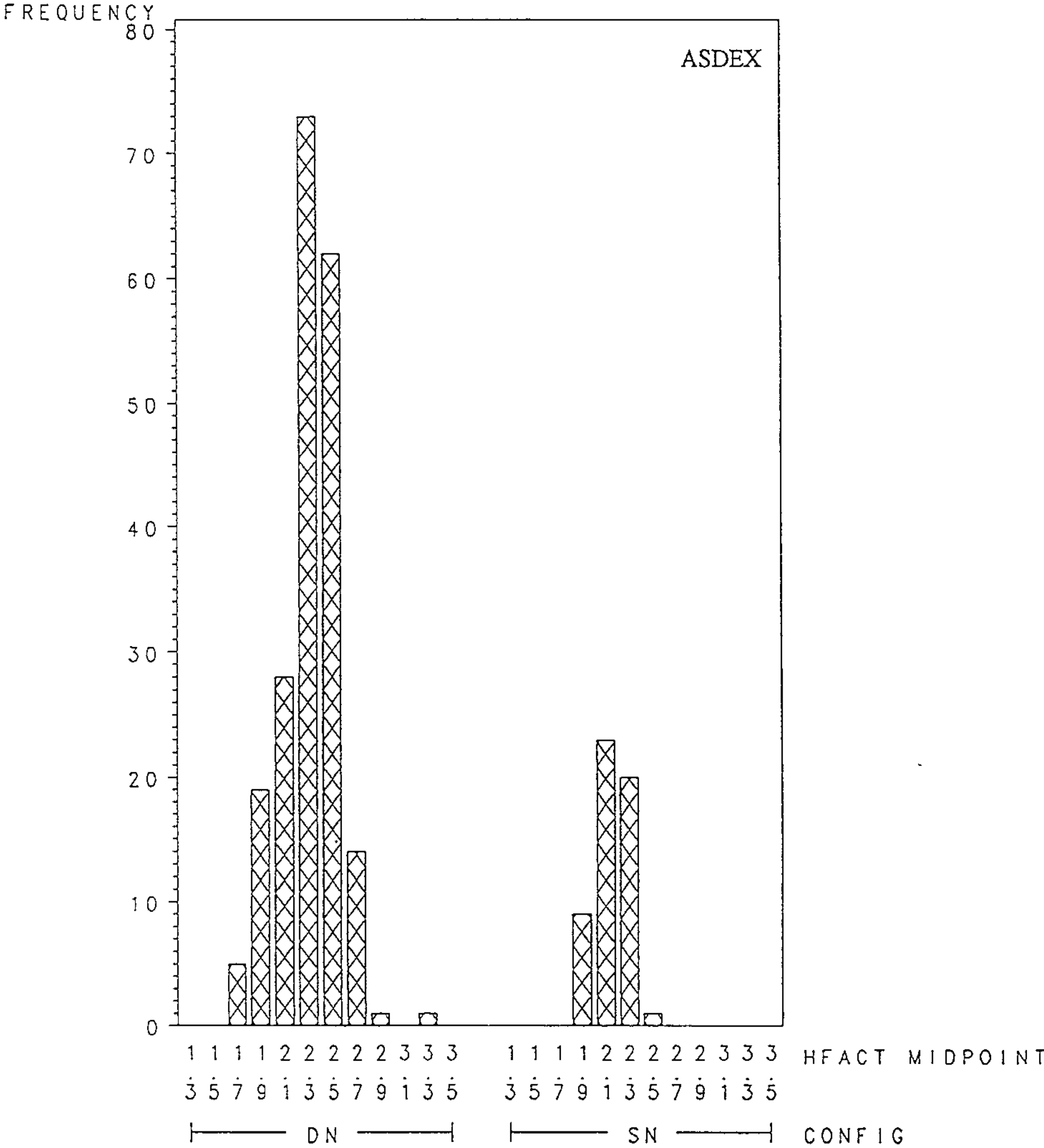
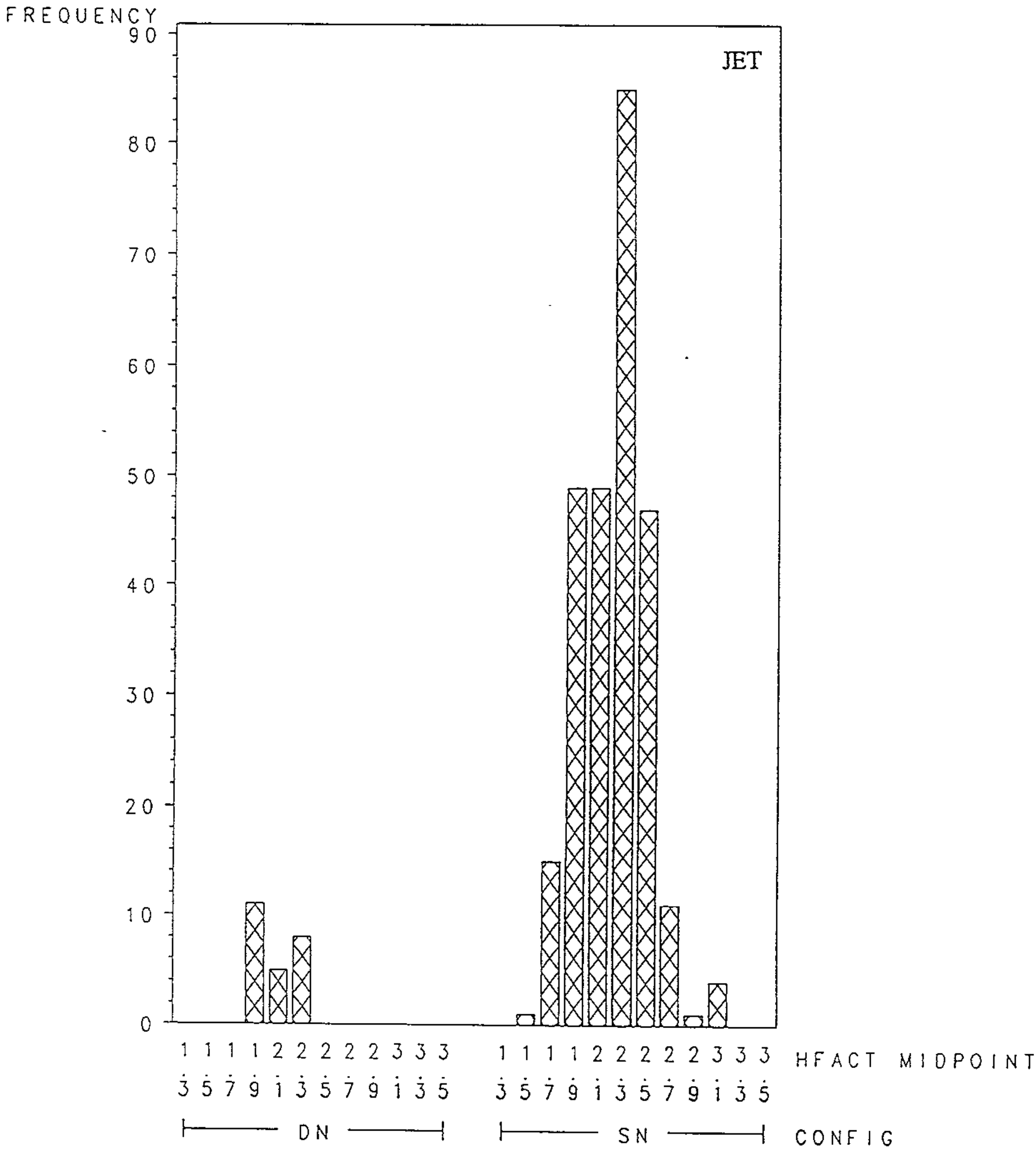

FREQUENCY
80
70
60
50
40
30
20
10
0
ASDEX
1.3 1.5 1.7 1.9 2.1 2.3 2.5 2.7 2.9 3.1 3.3 3.5
1.3 1.5 1.7 1.9 2.1 2.3 2.5 2.7 2.9 3.1 3.3 3.5
HFACT MIDPOINT
DN
SN
CONFIG

Fig.3 (b)



FREQUENCY
90
80
70
60
50
40
30
20
10
0
JET
1.3 1.5 1.7 1.9 2.1 2.3 2.5 2.7 2.9 3.1 3.3 3.5
1.3 1.5 1.7 1.9 2.1 2.3 2.5 2.7 2.9 3.1 3.3 3.5
HFACT MIDPOINT
DN
SN
CONFIG

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