EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–PR(03)59

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

ABSTRACT.

The disagreement between the weak dependence of the energy confinement time on normalised pressure, β, observed in dedicated scans and the strongly negative dependence in the confinement scaling laws used for the design of next step tokamaks and future reactors, remains an outstanding problem. As such, scans of β have been undertaken in single null, low triangularity ($\delta \approx 0.2$) ELMy-H Mode plasmas in JET with the MarkIIGB-SRP divertor. The scans varied β by a factor of 2.8 (Normalised β from 0.72-2.04) and covered a range of magnetic fields (1.5-2.3T), plasma currents (1.5-2.75MA) and safety factors (q_{95} = 2.7 and 3.3). A weak b dependence was observed both globally ($B\tau_E$ varied less than 9% across any one scan) and locally. A scan within Type I ELMy H-modes suggests that this weaker dependence is not due to ELM regimes. A statistical analysis indicates that these results are consistent with log-linear regressions performed on a wide JET database of ELMy H-modes, once correlations in the database are correctly treated.

1. INTRODUCTION

Analysing plasma energy transport in terms of dimensionless parameters [1, 2] is widely recognised as a powerful technique for comparing tokamak experiments with theory and for providing predictions for next step machines. The normalised ion Larmor radius, ρ^*, the normalised plasma pressure, β, and the normalised collision frequency, ν^*, are conventionally used to describe the three possible degrees of freedom as several classes of plasma physics models may be expressed in only one or two of these variables. Of particular relevance for this work, electrostatic transport models have no β dependence. The currently recommended ELMy H-mode energy confinement time scaling, generally referred to as IPB98(y,2), can be expressed in dimensionless form [3] as

$$B_0\tau_E \propto \rho^{*-2.70}\,\beta^{-0.90}\nu^{*-0.01}\,M^{0.96}q_{95}^{-3.0}\varepsilon^{0.73}\kappa^{2.3} \tag{1}$$

Where B_0 is the vacuum magnetic field, τ_E is the energy confinement time, M is the isotope mass, q_{95} is the safety factor of the $\psi = 0.95$ surface, ε is the inverse aspect ratio, κ is the plasma elongation, and ψ is the poloidal flux enclosed by a surface normalised to that of the last closed flux surface. The strongly negative β dependence of this scaling is a general feature of most energy confinement scalings based on multi-machine databases. However a much weaker, in many cases negligible, β dependence has been observed in dedicated experiments on both JET ($\beta^{-0.05}$) [4] and DIII-D ($\beta^{0.03}$) [5], where β was varied whilst the other parameters were held constant. The discrepancy between the JET results and a strongly negative β dependence in an earlier energy confinement scaling law, has been explained in terms of correlations in the multi-machine database, most notably between β and the aspect ratio, and differences in the energy transport dependency between the core and edge [6]. The local energy transport for these JET discharges was not studied in this work. The DIII-D experiment, however, found that the effective thermal conductivity was only weakly dependent on β ($\chi_{eff}\ \mu\ \beta^{0.11\pm 0.21}$) across the majority of the plasma. This is in contrast to an analysis of a wide JET database by Budny et al [7] which found a negative dependence ($\chi_{eff}\ \mu\ \beta^{-0.57\pm 0.05}$).

Both the JET [4] and DIII-D [5] experiments were limited to one pair of discharges, meaning that the β independence of energy confinement was only demonstrated in one region of parameter space in either machine. Further, each pair of discharges comprised one Type III and one Type I ELMy H-mode, meaning that β and ELM Type were perfectly correlated. The correlation of β with ELM Type permits two interpretations: (1) That the range of β used in the IPB98(y,2) scaling is too narrow to resolve the b dependence and gives a misleading scaling; (2) That the IPB98(y,2) b scaling is correct for Type I ELMy H-modes, but the lower confinement in Type III ELMy H-modes means that scans across ELM types do not see a b dependence. The former would result in a confinement advantage when running tokamaks at $\beta_N>1.8$, whereas the latter would not (as is currently assumed for next step predictions). The range of β covered in each pair of discharges was also limited to a factor of 1.8 for JET and 2.1 for DIII-D.

To resolve some of these issues JET has conducted three further dedicated scans of β. These are presented here along with a reanalysis of the JET ELMy H-mode database. The aim being to understand the discrepancy between dedicated β scans at JET and the wider JET database, and indicate how the discrepancy between dedicated β scans and the multi-machine database may be resolved.

Although an energy confinement scaling based on a less negative β dependence would not affect predictions for the ITER Q=10, $\beta_N=1.8$ operating point (as the bulk of the multi-machine database is collected around this value of β), it would increase the predicted performance for operation at increased β, if the stability issues of such operation could be resolved.

This paper is organised as follows: Section 2 describes the experimental set-up for the dedicated β scans, with the results discussed in section 3. A reanalysis of the JET ELMy H-mode global confinement database is presented in section 4. Finally, the results are summarised in section 5.

2. EXPERIMENTAL SET UP

Three separate scans of beta were performed at JET, operating with the MkII-SRP divertor, in single null plasmas with low triangularity ($\delta = 0.2$), moderate elongation ($\kappa = 1.7$), a minor radius of $a = 0.95$m, and a major radius of $R = 2.9$m. The relatively low triangularity was chosen to ease access to the Type III ELMy H-modes required for low β operation. The plasmas were all ELMy H-modes heated with Neutral Beam Injection (NBI) alone and fuelled by deuterium gas puffing. Discharges were tuned, by varying the NBI power and gas fuelling, until ρ^* and ν^* were matched within error bars. Two, two point scans were performed at low safety factor ($q_{95} = 2.7$). A three point scan was performed at higher safety factor ($q_{95} = 3.3$), to limit sawteeth which can trigger MHD activity known to degrade confinement.

Electron density profiles were measured with an 8 channel interferometry system [8] and a LIDAR Thomson Scattering system [9]. Electron temperature measurements are taken from the LIDAR Thomson Scattering system. Ion temperature, Z-effective and toroidal rotation profiles are measured by Charge Exchange Spectroscopy [10]. Equilibria are reconstructed using the EFIT code [11] based on data from magnetic coils [12]. NBI deposition profiles and fast particle energies and are calculated by the PENCIL [13] code.

3. EXPERIMENTAL RESULTS

The seven discharges comprising the three scans all produced steady state ELMy H-mode discharges with core sawtooth activity. Neither 3/2 Neoclassical Tearing Mode nor MARFE activity, known to reduce energy confinement, were observed in any of the discharges.

The global results for the three scans are given in Table 1. When comparing the discharges in these scans the relative errors in parameters, which are smaller than their absolute errors [14], will be used. These are estimated as 2.7% for ρ^*, 6.0% for β, 10.4% for ν^*, 8.3% for $B\tau_E$, 8.0% for $H_{IPB98(y,2)}$, and 8.2% for H_{ESGB} (see Equation 8). Although the matches to ρ^* and ν^* in scans 1 and 2 are within the measurement errors of the diagnostics, their agreement for the low β point in scan 3 is weaker. As this scan was principally conducted to study confinement variations in Type I ELMs, the low β point is less important but is included to indicate there is no evidence for a different behaviour at low β in this scan.

In all three scans the normalised energy confinement time (proportional to $B\tau_E$) changes little with β. This is in agreement with the previous scans on JET [5] and DIII-D [4]. The range of β covered by these scans is now extended to a factor of 2.8 (0.72-2.03) and the behaviour is demonstrated over a range of magnetic fields (1.5-2.3T), plasma currents (I_p=1.5-2.75MA) and safety factors (q_{95}=2.7 and 3.3). Assuming a power law dependence of normalised energy confinement ($B\tau_E$) upon β, the exponents would be 0.04±0.22 for scan1, -0.03±0.16 for scan 2, and –0.01±0.11 for scan 3. This clearly contradicts the –0.9 dependency of IPB98(y,2), as shown in Figure 1.

As in the earlier experiments, β was correlated with the ELM regime - the low β discharges being Type III and the high β ones being Type I. As illustrated in Figure 1, this is consistent with the larger JET database. To attempt to resolve the affect of the correlation between β and ELM Type, the highest two points of scan 3 were both taken in Type I ELMy H-modes. These two points are consistent with a weakly positive β dependence with exponent 0.43±0.95. This contradicts that seen in IPB98(y,2), but only by 1.4 standard deviations. Thus, while this result indicates that the energy confinement time for Type I ELMy H-modes is also weakly dependent on β, it does not exclude the strongly negative scaling of IPB98(y,2).

For scan 1, the profiles of the parameters to be matched are given in Figure 2. ρ^* and ν^* are both well matched across the plasma despite b varying from 1.06 to 1.81. Similarly, the safety factor and the ratio of ion to electron temperature also remain close. Z-effective was higher (≈25%) in the high β discharge as was the normalised toroidal rotation (20-25%).

As the ion and electron channels are strongly coupled, plasma transport is best studied in terms of the effective thermal conductivity, χ_{eff}, where

$$\chi_{eff} = \frac{n_e\chi_e + n_i\chi_i}{n_e + n_i} \qquad (2)$$

Figure 3, shows the effective thermal conductivity normalised to B_T. The core, which is affected by sawteeth behaviour, and the edge, dominated by ELM behaviour, are not studied here. Very little variation in the effective thermal conductivity (-10 to 20%) between the two discharges is observed across the whole profile. A similar trend is seen in scan 2. Thus the two scans are consistent with no b scaling to the accuracy of the global and profile measurements. As β was increased in a given scan, the edge pedestal β rose along with the β of the core, despite the transition to a different ELM Type and a fall in ELM frequency (from 14Hz to 210Hz for scan 1, for example). Hence, it would appear that, for the range of β covered, the ELMs do not limit the edge pedestal.

4. ANALYSIS OF JET ELMY H-MODE DATABASE

The β dependency observed in the experiments described in section 3 is now compared with that observed in a wider JET database of ELMy H-modes covering the period 1994-2001 [15]. To avoid isotope effects, the data set will be restricted to deuterium plasmas. As configuration, minor radius and major radius do not vary significantly across the database, the regression will be with respect to the four variables (I_p,P_{loss},$\overline{n}_e$,B_0), where $P_{loss} = P_{IN} - \dot{W}_{th}$ is the loss power across the separatrix, $\overline{n}_e$ is the line averaged electron density, P_{IN} is the sum of the ohmic and auxiliary power coupled to the plasma, and W_{th} is plasma thermal energy. A log-linear regression gives a fit for the energy confinement time of

$$\tau_E \propto I_p^{0.96\pm0.04} P_{loss}^{-0.57\pm0.02} \overline{n}_e^{0.29\pm0.04} B_0^{-0.01\pm0.04} \tag{3}$$

with an RMSE of 13.5%. This can be expressed in dimensionless form as

$$B_0\tau_E \propto \rho *^{-2.2} \beta^{-0.5} \nu *^{-0.1} q_{95}^{-2.2} \tag{4}$$

Although this has a weaker negative β dependence than the IPB98(y,2) scaling, it is still greater than that observed in section 3. However, the correlation matrix for this regression (Table 2) indicates that strong correlations exist within the JET ELMy H-mode database. The tendency to perform experiments at q_{95} values close to 3, results in a strong correlation between current and field, but has little affect the scaling in the other three normalised parameters. However, the strong correlations in some of the other variables, most notably density and power, does.

A principal components analysis provides an indication of how these correlations can allow the β dependence to change, whilst being compensated by a correlated variable. Table 3 shows the principal components for the log-linear regression of Equations 3 and 4. The two weakest components (P_3 and P_4) describe only 7% of the variation in the data and can be taken to represent combinations of parameters which are closely correlated. P_4 describes the principal correlation, largely that of I_p to B_o, and P_3 the second largest, representing a correlation involving β. When transformed to normalised parameters, P_3 can be described by

$$F = \rho *^{-1.7}\, \beta \nu *^{-0.2}\, q_{95}^{-0.5} \tag{5}$$

which, when raised to a power and multiplied by equation (4), can replace the β dependence with altered powers of the other variables, particularly ρ*. As the distribution of the data in the database with respect to β is not uniform, with the bulk of the data being in the range $0.9<\beta_N<2.0$, the β dependence is particularly susceptible to this form of variation.

One method for overcoming the poor conditioning of the JET database with respect to β is to add extra weight to the discharges at the extremes of β variation. To this end, the database was split into three regions (Table 4) and normalised weighting factors were applied to each region to give it equal weight in a log-linear regression. Using these weights the resulting fit becomes

$$\tau_E \propto I_p^{0.96\pm0.05} P_{loss}^{-0.59\pm0.02} \bar{n}_e^{0.40\pm0.04} B_0^{-0.02\pm0.04} \tag{6}$$

which can be expressed in dimensionless form as

$$B_0 \tau_E \propto \rho *^{-2.7}\, \beta^{-0.2} \nu *^{-0.1}\, q_{95}^{-2.2} \tag{7}$$

This fit has a RMSE of 13.6%. Whilst still retaining some negative β dependence, the weighting method has resulted in a scaling which is more consistent with the results of section 3.

Finally, if both the electrostatic (β^0) and Gyro-Bohm ($\rho*^{-3}$) constraints are imposed upon the data [16], the resulting scaling is

$$B_0 \tau_E \propto \rho_i^{-3} \beta^0 \nu_{ei}^{-0.11} \tag{8}$$

with an RMSE of 14.20%. For comparison, the IPB98(y,2) scaling with the same database has a RMSE of 13.91%. This scaling is consistent with the β dependency of all three scans of section 3 (Figure 4) and is also consistent with that seen in the wider JET database.

SUMMARY

As in previous experiments performed at DIII-D [5] and JET [4], it has been shown that the β scaling of the energy confinement time in dedicated scans at JET is weaker than in the IPB98(y,2) scaling. This behaviour was reproduced in three β scans at differing magnetic fields (1.5-2.3 T), currents (I_p=1.5-2.75MA) and safety factors (q_{95}=2.7 and 3.3), indicating that this is a generic feature of JET plasmas. The range of β covered has also been extended to a factor of 2.8 (β_N=0.72-2.04). A scan including two Type I ELMy H-modes indicates that the behaviour is independent of ELM regime, although an error analysis has demonstrated that a strongly negative β dependence of energy confinement time for Type I ELMs alone is still consistent with the data. Further experimental data would be required to resolve this issue. An analysis of the effective thermal conductivity profiles indicates that this behaviour is consistent across the entire plasma outside of the sawtooth region and within the pedestal. All three scans are consistent with the β independent energy confinement time seen in electrostatic transport models.

The disagreement between these results and the strongly negative β dependence of the energy confinement time calculated by a log-linear regression to a wider JET database, is explained in terms of correlations between parameters in the database which permit a range of scalings within the error bars of the regression, as demonstrated by a principal components analysis. A weighting method has been shown to improve the consistency between the dedicated scans and the data in a large (335 discharges) JET ELMy H-mode JET database. An electrostatic Gyro-Bohm model has also been shown to give a reasonable fit to the entire JET ELMy H-mode database.

ACKNOWLEDGEMENTS

This work has been conducted under the European Fusion Development Agreement and is partly funded by EURATOM and the United Kingdom Engineering and Physical Sciences Research Council.

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Scan	**Pulse number**	**Time (s)**	**ρ^* (10^{-3})**	**ν^***	**β_N**	**$B\tau_E$ (Ts)**	**$H_{98(y,2)}$**	**H_{ESGB}**
1	58400	14.9	4.53	0.102	1.81	0.91	1.05	0.91
	58402	26.6	4.48	0.115	1.06	0.89	0.93	0.96
2	58394	24.4	5.19	0.118	2.04	0.81	1.15	1.02
	58401	22.2	5.14	0.093	0.96	0.83	0.98	1.08
3	60593	7.7	5.42	0.142	2.03	0.52	1.08	0.92
	60859	7.6	5.20	0.149	1.55	0.47	0.97	0.88
	60598	23.4	4.71	0.160	0.72	0.51	0.83	0.95

Table 1: Data for the three β scans performed at JET. Parameters are averaged over time windows of at least two energy confinement times.

	In(I_p)	**In(P_{loss})**	**In($\bar{n}_e$)**	**In(B_0)**
In(I_p)	1.00	0.38	0.55	0.82
In(P_{loss})	0.38	1.00	0.75	0.46
In($\bar{n}_e$)	0.55	0.75	1.00	0.50
In(B_0)	0.82	0.46	0.50	1.00

Table 2: The correlation matrix for a log-linear regression of energy confinement time to 4 variables over a database of 335 ELMy H-modes on JET 1994-2001.

	P_1	**P_2**	**P_3**	**P_4**
Proportion	0.61	0.32	0.05	0.02
In(I_p)	0.38	0.58	0.06	-0.72
In(P_{loss})	0.72	-0.56	-0.39	-0.11
In($\bar{n}_e$)	0.44	-0.09	0.86	0.23
In(B_0)	0.38	0.59	-0.31	0.64

Table 3: The principal components of the correlation matrix of Table 2.

Range of β	$\beta_N<0.9$	$0.9<\beta_N<2.0$	$2.0<\beta_N$
Weighting factor	1.68	0.42	6.7

Table 4: The weighting factors used in the fit of Equation 6.

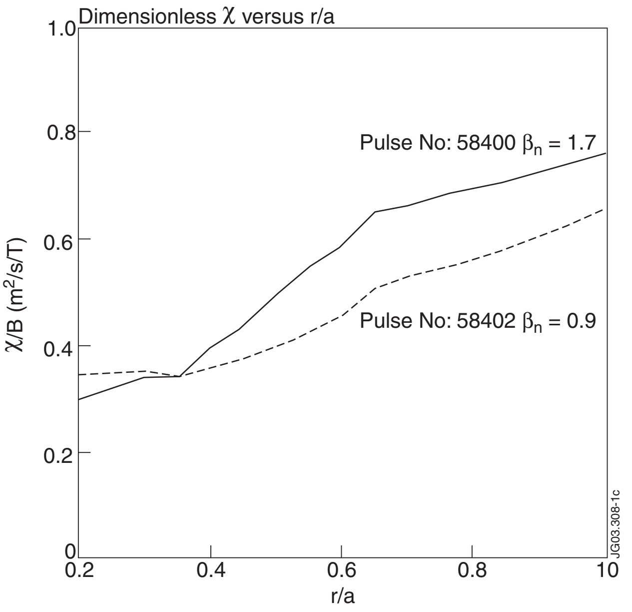

Figure 1: Data from gas fuelled, NBI and ICRH heated, JET steady state, ELMy H-modes 1994-2001 (red crosses for Type I ELMy H-modes, blue circles for Type III ELMy H-modes) with the three β scans (see Table 1) overlaid. Scan 1 is represented by purple diamonds, scan 2 by black squares and scan 3 by orange circles. The energy confinement time is normalised to the IPB98(y,2) scaling of Equation 1.

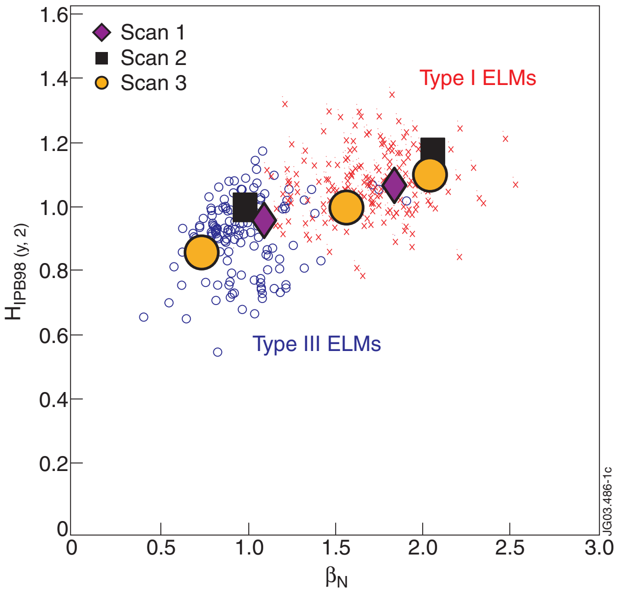

Figure 2: Plasma profiles for q_{95}=2.7, d≈0.2, ELMy H-mode JET Pulse No's: 58402 and 58400 (scan 1 in Table 1). Pulse No: 58402 (dotted line) is a 2.35MA/1.9T, Type III ELMy H-mode and Pulse No: 8400 (solid line) is a 2.75MA/2.3T, Type I ELMy H-mode.

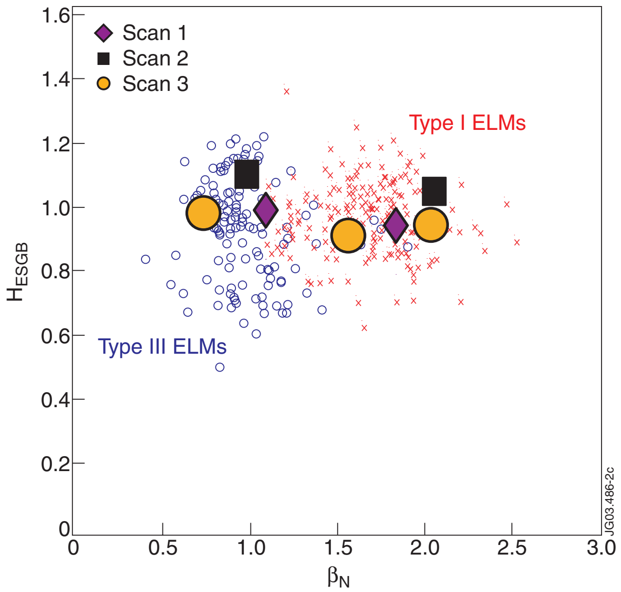

Figure 3: Radial profiles of effective thermal conductivity normalised to toroidal magnetic field for the discharges of Figure 2. Despite a 105% increase in β the change in normalised thermal conductivity remains small (<20% everywhere).

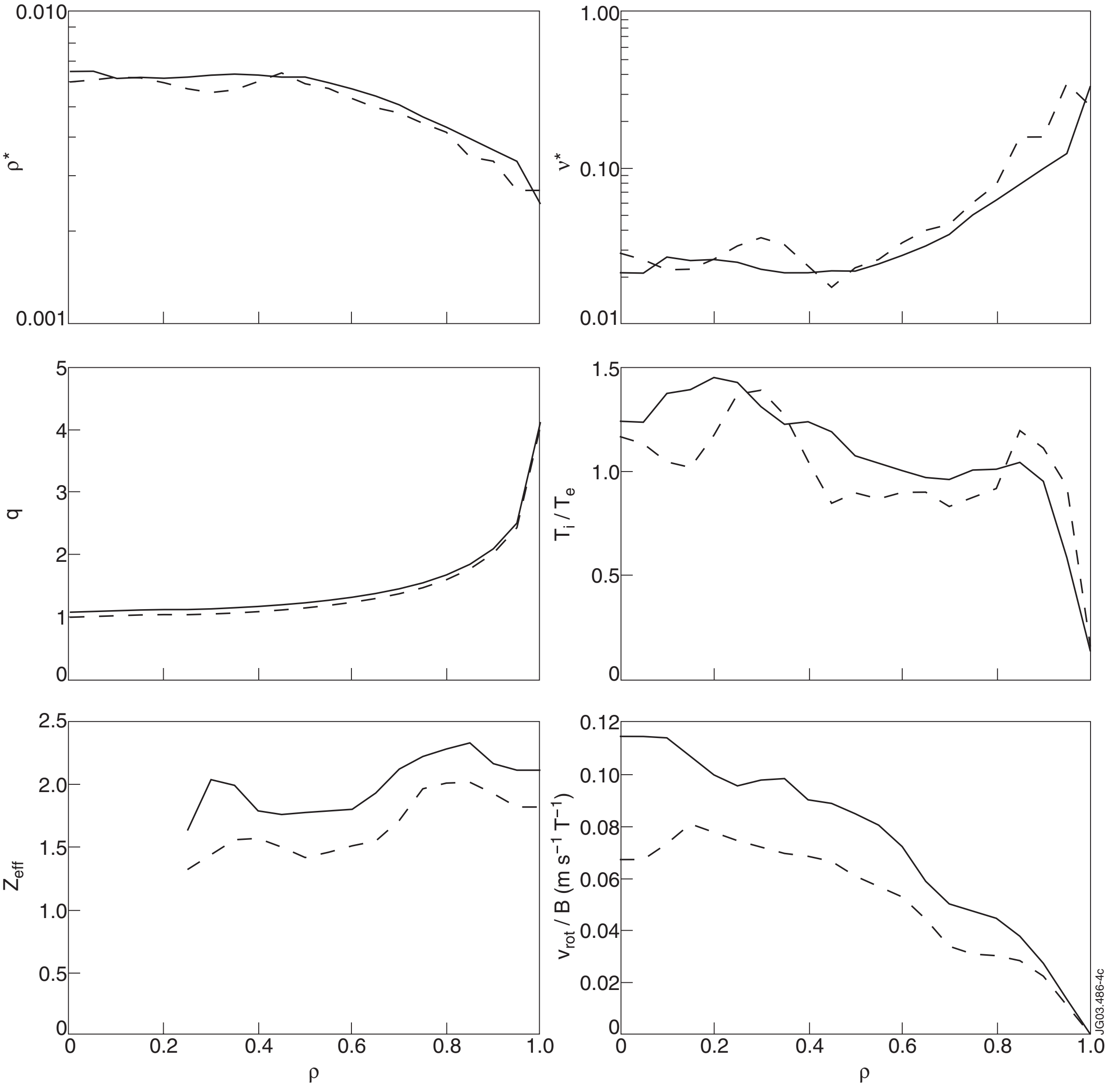

Figure 4: Data of Figure 1, showing the fit of the plasma energy confinement time to a log-linear Electrostatic Gyro-Bohm regression with weightings dependent on the values of β *(Table 4).*