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GLOBAL ENERGY CONFINEMENT SCALING
FOR NEUTRAL-BEAM-HEATED TOKAMAKS

By

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ABSTRACT

A total of 677 representative discharges from seven neutral-beam-heated tokamaks has been used to study the parametric scaling of global energy confinement time. Contributions to this data base were from ASDEX, DITE, D-III, ISX-B, PDX, PLT, and TFR, and were taken from results of gettered, L-mode type discharges. Assuming a power law dependence of τ_E on discharge parameters κ , I_p , B_T , $\bar{n}_e$, P_{tot} , a , and R/a , standard multiple linear regression techniques were used in two steps to determine the scaling. The results indicate that the discharges used in the study are well described by the scaling $\tau_E \propto \kappa^{0.28} B_T^{-0.09} I_p^{1.24} \bar{n}_e^{-0.26} P_{tot}^{-0.58} a^{1.16} (R/a)^{1.65}$.

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MASTER

The design and planning for large auxiliary heated devices such as INTOR and TFCX has led to the need to parametrize the dependence of global energy confinement time in neutral-beam-heated tokamaks presently or recently operating on discharge parameters such as I_p , B_t , $\bar{n}_e$, P_{tot} , κ (plasma elongation) and, in particular, plasma size. Similar types of scalings in ohmic devices have evolved over the years to the point where they successfully and reliably describe both the low and high density regimes of ohmic operation.¹⁻⁴ In fact, preliminary results from TFTR ohmic operations indicate the consistency of the calculated τ_E 's with neo-Alcator scaling, implying a successful extrapolation of this scaling from "small" ohmic tokamaks to a large one.

Scaling studies for neutral-beam-heated tokamaks have generally been performed using individual data sets from each experiment, with few attempts to study the collective results. One such attempt was made by Goldston,⁴ who determined a global average dependence of τ_E on I_p , P_{tot} , and κ from PDX, D-III, ASDEX, and ISX-B results, and derived the dependence of τ_E on plasma size, resulting in the scaling

$$\tau_E \propto I_p \kappa^{1/2} P_{tot}^{-1/2} a^{-0.37} R^{1.75} \quad (1)$$

for L-mode deuterium-target plasmas. The size scaling in Eq. (1) is approximately size^{2.4} ($\sim L^{2.4}$, where L is some plasma dimension since for fixed $\bar{n}_e$, B_t , etc., I_p scales with size), and is slightly weaker than that described in ohmic scalings ($\sim L^3$). Goldston cautioned of the large uncertainties in the a and R regression coefficients owing to the similar aspect ratios of the

machines involved. It was also noted that, at constant power, H-mode plasmas could be described by a similar scaling but with approximately twice the numerical coefficient.

A different approach to the formulation of neutral beam injection (NBI) energy confinement scaling is taken in the work to be presented here. Rather than derive a global scaling based on reported individual machine scaling results, actual representative discharges from seven NBI tokamaks were collected, and an NBI tokamak database was built. Data were taken from gettered, L-mode experiments on ASDEX,⁶ ISX-B,^{7,8} DITE,^{9,10} D-III (GA Team),^{11,12} PDX,^{13,14} TFR,¹⁵ and PLT^{16,17} over a wide range of operating parameters. Only discharges with $P_{inj} > 2 P_{OH}$ were included in the data set. A list of the number of representative discharges and the parameter limits for data from each machine are given in Table 1. In the Table 1 P_{tot} is the sum of the ohmic and absorbed neutral beam power, except for the PLT(S) discharges described below. While the PDX discharges had D^0 injection into H^+ plasmas, all the others had H^0 injection into D^+ plasmas, except for PLT, which had a mixture of $D^0 \rightarrow H^+$ and $H^0 \rightarrow D^+$ discharges.

The global energy confinement times were determined from magnetics for all except the TFR and PLT discharges, so that β for the former sets of discharges contained both beam and thermal plasma pressure contributions. When calculated global confinement times were not included in the data sets, τ_E was determined from the measured β assuming discharge equilibrium. The TFR confinement times were derived from thermal pressure only and input power computed taking into account charge exchange and orbit loss of beam ions. Two sets of PLT discharges were included in the data base. The PLT(T)¹⁷ confinement times were derived in much the same way as the TFR points. The PLT(S)¹⁶ confinement times were derived also from thermal pressures, but in a

much simpler fashion: $Z_{\text{eff}} = 1$ and $T_i(r)/T_i(0) = T_e(r)/T_e(0)$ were assumed, with $T_e(r)$ measured by Thomson scattering and $T_i(0)$ by passive charge exchange. In addition, the injected power was not corrected for shine-through, charge exchange, or bad orbit loss in this latter set of PLT points.

Finally, because of the uncertainties associated with the beam slowing down to plasma mixture, any dependence of τ_E on plasma isotope was ignored in this exercise. It should be noted, however, that ASDEX $H^0 \rightarrow H^+$ and $H^0 \rightarrow D^+$ L-mode experiments indicate an $A_p^{1/2}$ dependence of the energy confinement time.⁶

To offset any artificial weighting in the scaling due to the disparate number of discharges for each machine, the scaling were performed in two steps. In step one, the data from each machine was constrained to some small range in a and R for that machine. In this way, subsequent parametric scalings for the size-constrained data from each machine were derived independent of any a or R variation. The scaling was performed in the simplest fashion, by assuming a power law dependence of energy confinement on the various discharge parameters, assumed to be uncorrelated, and by using the standard IMSL multiple linear regression package, RLMUL. This first step resulted in a set of five scalings, one for each machine, (ISX-B, DITE, D-III, PDX, and ASDEX) of τ_E on κ , I_p , B_T , $\bar{n}_e$, and P_{tot} . (TFR and PLT data were not used in step 1 or step 2 because of the difference in the way τ_e was computed.) Weighted averages of the resulting regression coefficients and variances were then calculated according to the formula

$$\langle \alpha \rangle = \frac{\sum \alpha_i / \sigma_i^2}{\sum 1 / \sigma_i^2} \quad (2)$$

all machines

and

$$\frac{1}{\sigma^2} = \frac{1}{\sigma_i^2} \quad (3)$$

all machines

to obtain the most probable global regression coefficient for each independent variable and its variance.¹⁸ Here, the α_i represents the regression coefficients for some arbitrary independent variable, and the σ_i^2 represents the variances of the coefficients, reflecting the size of the confidence limits.

The final result of step 1 was, therefore, an average "global" scaling of τ_E on all the discharge parameters except for plasma size. In step 2, the dependence of τ_E on plasma size was determined by first forcing each individual machine's size-constrained data to the scaling produced by step 1. The numerical coefficient for each machine which best fit the data was then determined, and the variation in this numerical coefficient among the machines was taken to reflect the variation of energy confinement on plasma size. A multiple linear regression on the numerical coefficient was then performed using the plasma dimensions as independent variables. This last step is similar to the a and R scaling step performed by Goldston.⁴ However, since the aspect ratio among the machines is similar, i.e., R/a varied only from 3.3 to 4.7, uncertainties in the a and R regression coefficients would be large, as found by Goldston.⁴ In an effort to minimize uncertainties in at least one of the size variables, the regression on plasma size in this exercise was done using a and R/a as the independent variables. This technique resulted in less of an uncertainty in the regression coefficient of

a, but more in that of R/a than would have resulted in a or R had the regression been performed on these two as the independent variables.

Once the parametric size scaling was determined, all the data, including the TFR and PLT data, and data not limited by the previous size constraints, were fit to the resultant global parametric scaling to determine the best fit numerical coefficient.

The result of the fitting exercise indicates that the data are well described by the fit

$$\tau_E(\text{msec}) = 2.77 \times 10^{-5} \kappa^{0.28} B_T^{-0.09} I_p^{1.24} P_{\text{tot}}^{-0.58} \bar{n}_e^{0.26} a^{1.16} (R/a)^{1.65}$$

(4)

where B_T is in Tesla, I_p in kA, P_{tot} in MW, $\bar{n}_e$ in 10^{13} cm^{-3} , and a and R in cm. The correlation coefficient¹⁸ for this fit is $R^2=0.94$. Table 2 contains the individual fits for each machine (size constrained where necessary), and the regression coefficients and their uncertainties for each independent parameter. The row labeled "global fit" is the result of the two-step fitting process leading to Eq. (4). The uncertainties in a and R in this row are the estimated standard deviations of the regression coefficients.¹⁹

The scaling clearly shows that the strongest dependence, neglecting the size scaling, is on plasma current. Density and plasma elongation dependencies are slight, but part of the advantage elongation holds is the ability to operate higher currents, holding all other parameters fixed. This is seen most clearly by comparing the ISX-B and D-III scalings. While the κ dependence is greater for D-III than for ISX-B, the D-III current dependence

is weaker. Thus, the current and elongation dependencies are, to some extent, interdependent.

The power dependence indicates a continual deterioration of confinement with increasing input power, holding all the other parameters fixed. In addition, the parametric scaling in Eq. (4) is not inconsistent with those developed by Perkins²⁰ and Connor, Taylor, and Turner,²¹ and satisfies the Connor-Taylor constraints for both finite- β , collisional, and resistive MHD plasma models.²²

Figure 1 shows the experimental τ_E plotted against the τ_E determined from Eq. (4). Included in this figure is all the available data in the data base. The data are well ordered by the fit given in Eq. (4), except for some points from the PLT(S) data set. The scatter from this data set is due to several sources. Points for which $\tau_E^{\text{EXP}} > \tau_E^{\text{FIT}}$ typically have lower currents (< 400 kA), while those that have $\tau_E^{\text{EXP}} < \tau_E^{\text{FIT}}$ typically have lower density ($\leq 2.0 \times 10^{13} \text{ cm}^{-3}$). This is consistent with the reported results of this data,¹⁶ which suggest little I_p scaling and a stronger density scaling ($\sim \bar{n}_e^{1/2}$) than is seen in Eq. (4). Shine through losses, if accounted for in this lower density data, would increase the experimental τ_E 's by approximately 10%.

At this point it is worth cautioning against viewing the size scaling as definitive in light of the uncertainties of the regression coefficients. Expressing the size scaling differently, it is seen that $\tau_E \propto a^{-0.49} R^{1.65}$. A more appropriate way to view the size scaling would be to consider it as a length to some power: these results suggest that, if viewed this way, $\tau_E \propto L^{2.4}$ taking, as before, $I_p \propto L$, in contrast to the ohmic neo-Alcator scaling which has $\tau_E \propto L^3$.

Recently, much attention has focused on extrapolating scaling laws such as those given in Eqs. (1) and (4) to reactor size machines such as TFTR, INTOR, and TFCX. For these extrapolations, a more convenient way to express the τ_E scaling is in terms of plasma parameters exclusively. Letting

$$P_{TOT} = U / \tau_E \quad (5a)$$

and

$$U = \frac{3}{2} < \beta_T > \frac{B^2}{2\mu_0} 2\pi^2 k a^2 R \quad (5b)$$

where U is the plasma stored energy and $<\beta_T>$ is the volume-averaged toroidal β -value, Eq. (4) can be rewritten as

$$\tau_E (\text{sec}) = 1.46 \times 10^{-23} B_T^{-2.98} I_p^{2.95} a^{-3.93} R^{2.55} <\beta_T>^{-1.38} \bar{n}_e^{-0.62} \kappa^{-0.71} \quad (6)$$

with I_p in Amperes, a and R in meters, and $\bar{n}_e$ in 10^{19} m^{-3} . Unfortunately, Eq. (6) leads to rather pessimistic predictions of τ_E for TFTR, INTOR, and TFCX, given the respective design parameters. This is due partially to the continuous degradation of τ_E on total heating power, and also to the weaker dependence on plasma size than expected from neo-Alcator scaling [seen more clearly in Eq. (4)]. Several points should be made. First, the scaling was

derived from L-mode experiments; however, operating regimes exist, such as divertor H-mode, in which energy confinement times during NBI can be a factor of two (or more) greater than those in the L-mode. These operating scenarios clearly should be considered for future design. Second, and more important, is that the scalings derived from a particular set of data are descriptions of that data set, and since they are governed in part by assumptions of the scaling, they may not be relevant for larger devices. For instance, one assumption that was made in the scaling was that $\tau_E \propto P^\alpha$. It has been shown by the GA D-III group that their results may be fit equally well by either a P^α or a $(a+b/P)$ dependence.¹⁸ The latter power dependence obviously has less severe impact on energy confinement at high beam powers than the former. In order to perform a size-scaling study of the type shown here, based on $\tau_E \propto (a + b/P)$, an extrapolation to $P_{tot} \rightarrow \infty$ for each of the machines would be required. This extrapolation process would entail unacceptable uncertainties in many cases.

In conclusion, a two-step multiple linear regression approach has been used to fit data collected from seven neutral-beam-heated tokamaks. The energy confinement is found to scale as $L^{2.4}$, with practically no dependence on toroidal field and a slight dependence on density and plasma elongation. The scaling serves as a description of the data set used in its determination. Modifications to the scaling may become necessary with results of NBI on larger devices such as TFTR and JET.

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Table 1

Parameter Ranges for the NBI Tokamak Database

Machine	#Points	a(cm)	R(cm)	κ	$B_T(T)$	I_P (kA)	$\bar{n}_e (10^{13} \text{ cm}^{-3})$	P_{tot} (MW)
ISX-B	108	25-27	92-95	1.05-1.54	0.74-1.51	62-214	1.5-13.20	0.73-2.36
DITE	205	15-27	109-129	1.0	0.90-2.70	67-258	0.98-9.91	0.33-2.02
TFR	4	17-19	96-98	1.0	3.7-4.1	232-300	8.7-12.9	0.58-1.12
O-III	212	34-44	142-143	0.95-1.79	0.62-2.42	225-810	2.00-9.90	0.81-4.93
PDX	46	42-44	143	1.0	0.70-2.2	230-480	2.1-7.0	1.01-5.47
PLT(T)	16	40	134	1.0	2.52-3.26	384-538	1.72-6.30	1.47-3.38
PLT(S)	54	40	134	1.0	2.03-3.25	260-580	1.20-5.90	1.00-2.92
ASDEX	32	40	165	1.0	2.2	195-380	2.7-5.85	0.67-2.30

Table 2

Individual and Global Energy Confinement Time Scalings

Machine	Constraint	R/a	10	κ	B_T	I_p	$\bar{n}_e$	P_{tot}	a	R/a
ISX-B	a=26-27 cm R=93-95 cm	3.55	-2.38 ± 0.13	0.00 ± 0.07	-0.11 ± 0.07	1.51 ± 0.06	0.09 ± 0.03	-0.67 ± 0.03	-	-
DITE	a=23-27 cm R=117 cm	4.68	-1.92 ± 0.10	-	-0.21 ± 0.05	1.23 ± 0.005	0.46 ± 0.03	-0.76 ± 0.04	-	-
D-III	a=37-40 R=144-147 cm	3.78	-0.67 ± 0.23	0.46 ± 0.10	0.32 ± 0.09	0.86 ± 0.10	0.08 ± 0.04	-0.66 ± 0.03	-	-
PDX	a=42-44 cm R=143 cm	3.33	-1.61 ± 0.17	-	-0.08 ± 0.14	1.13 ± 0.15	0.32 ± 0.14	-0.37 ± 0.06	-	-
ASDEX	a=40 cm R=165 cm	4.13	-1.13 ± 0.23	-	-	1.11 ± 0.08	-0.27 ± 0.15	-0.27 ± 0.07	-	-
Global fit			-4.56 ± 0.10	0.28 ± 0.16	-0.09 ± 0.07	1.24 ± 0.06	0.26 ± 0.03	-0.58 ± 0.03	1.16 ± 0.27	1.65 ± 0.42

FIGURE CAPTIONS

FIG. 1. Experimentally energy confinement times, τ_E^{EXP} determined plotted versus the value derived from the scaling given in Eq. (4), τ_E^{FIT} , for all 677 discharges.

Fig. 1

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