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A REVIEW OF ENERGY CONFINEMENT
AND LOCAL TRANSPORT SCALING RESULTS
IN NEUTRAL-BEAM-HEATED TOKAMAKS

By

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**A REVIEW OF ENERGY CONFINEMENT
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ABSTRACT

Over the past several years, tokamak neutral beam injection experiments have evolved from the brute force study of the effects of global discharge characteristics (I_p , $\bar{n}_e$, P_{heat} , etc.) on energy confinement to the appreciation that there are effects more subtle, yet controllable, that may influence confinement dramatically. While this evolution from first to second generation experiments is derived from an empirical understanding of "low" and "high" energy confinement modes and how to achieve them operationally, the underlying physics is still unknown. Several theories with different physical bases appear to describe the global scaling of the low confinement mode discharges quite well. On the other hand, little agreement has been found between theoretical and experimentally deduced values of local transport coefficients. While it is known operationally how to achieve any one of several types of high confinement mode discharges, here too, the underlying physics of the transport associated with these modes is poorly understood.

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1. INTRODUCTION

Energy confinement results from tokamak neutral beam injection (NBI) experiments over the past several years have led to a natural division of the experiments into first and second generations. The first generation experiments, initially testing the efficacy of neutral beam injection, later focused on how the plasma energy confinement time was influenced by variations in global discharge parameters such as plasma current, toroidal magnetic field, plasma density, heating power, and plasma elongation. These experiments were carried out in tokamaks of varying sizes, with the plasmas limited by poloidal or toroidal mechanical limiters or through use of magnetic divertors. On a global scale the plasmas were found to behave similarly from machine to machine; for instance, energy confinement times typically decreased by a factor of two to four from the ohmic value with onset of neutral beam heating, and the equilibrium values of τ_E (total energy confinement time) during NBI were found to vary most strongly with plasma current. Parametric scalings deduced from these first generation experiments, however, led to discouraging estimates of τ_E for reactor-sized machines. In addition, little agreement was found between theoretically predicted and experimentally deduced local transport coefficients. On the other hand, recent global scalings of τ_E , derived from MHD and drift wave theory, do yield good agreement with experimental results.

The second generation of NBI experiments, which is still in progress, is marked by an evolving appreciation and empirical understanding of the way that more subtle effects influence energy confinement and transport. Operating modes comprising the second generation experiments are operations with ungettered discharges and trace impurity injection into poloidal limiter discharges, operation with a limiter designed for trapping particles (scoop limiter), injection of pellets to aid plasma fueling, operations in a magnetic divertor configuration in which the divertor chamber and main chamber are connected via a narrow channel, and operations in a divertorlike "expanded boundary configuration." The confinement results in these operating modes are more varied, but are also generally more encouraging than those in the first generation experiments. Scaling laws for these second generation experiments are difficult to develop because of the aforementioned variability and because of the less quantifiable nature of the key parameters. While empirical

knowledge of these operating modes is maturing, the underlying physics here is also not understood.

In this article, the major results of the first and second generation NBI experiments will be reviewed. Because of the broad scope of these experiments, it would be impractical to attempt to discuss all aspects of these tokamak experiments; consequently the review will focus on experimental and theoretical scalings of global energy confinement time and local transport coefficients. This article will discuss what scalings exist, and how well they describe existing data. Previously published review articles cover other aspects of ohmic and NBI results.^{1,2} This review, also, will limit itself primarily to the results of neutral beam heating experiments and, in Sec. II, will touch upon some of the recent results of RF auxiliary heating experiments.

II. FIRST GENERATION RESULTS (L-MODE)

It was recognized early that ohmic heating alone would be insufficient to heat plasmas to thermonuclear temperatures. To increase temperatures up to the required values, neutral injection was developed as an auxiliary heating technique. The earliest neutral injection results came from small tokamaks such as CLEO,^{3,4} ATC,⁵⁻⁷ ORMAK,⁸⁻¹⁰ and TFR.¹¹⁻¹³ In the early experiments of these machines, neutral beam injection (NBI) was found to be effective in heating ions to temperatures well above those in purely ohmic discharges, even with modest values of injected power. Impressive central ion temperatures of ~ 1.8 keV were obtained in ORMAK,⁹ for instance, with injection powers of 360 kW and line-averaged densities of $\sim 2.8 \times 10^{13} \text{ cm}^{-3}$. The ion heating was found to take place with either the tangential injectors of ATC, ORMAK, and CLEO, or the near-perpendicular injection in TFR.

These early results indicated only limited heating of the electrons with NBI. A peculiarity of these experiments was that the total neutral injection power was merely comparable or even less than the ohmic heating power of the electrons. Consequently, the neutral beams typically accounted for only $\sim 20\%$ of the total electron heating power. With $P_{\text{inj},e}/P_{\text{oh}} \sim 2$, an increase in $T_e(0)$ from an ohmic value of ~ 0.3 keV to 0.7 keV during NBI was observed on ORMAK.¹⁰ Also recognized in these experiments was the role of operation at low Z_{eff} to minimize the deleterious effect of impurity radiation on electron temperature.

These early experiments pointed to the efficacy of NBI as a source of substantial plasma heating. With this base set of results, larger machines with higher neutral beam injection power were constructed in order to study the physics of NBI further, and this time in collisionality regimes closer to those of reactors. The remainder of this review will focus on these later experiments, with particular emphasis on the scaling of energy confinement time with discharge parameters.

The first widely accepted global scaling of energy confinement time actually emerged from ohmic results from a number of experiments.¹⁴ This scaling, in which $\tau_E \propto \bar{n}_e a^{2q/2}$ where $\bar{n}_e$ is line-averaged plasma density, a is the plasma minor radius, and q is the inverse cylindrical rotational transform, was adopted as a benchmark to compare to NBI results, and to assess the requirements and feasibility of attaining scientific breakeven in such devices as TFTR, and producing positive net power in a demonstration tokamak test reactor. The ohmic energy confinement scaling was called INTOR or Alcator scaling. A modification to this ohmic scaling was made by Pfeiffer and Waltz;¹⁵ in this scaling $\tau_E \propto \bar{n}_e a R^2$, and was subsequently called "neo-Alcator" scaling.

Results of NBI experiments from a number of tokamaks led to energy confinement results that were quite different from those expected from INTOR scaling. For discharges with densities ≥ 2.5 to $3.0 \times 10^{13} \text{ cm}^{-3}$ and injected powers greater than approximately twice the ohmic power, the energy confinement time decreased at the onset of NBI by a factor of 1.5 to 4 from that observed during the ohmic phase.^{13,16-30} (A list of NBI experiments with the respective machine parameters is given in Table I.) An example of the evolution of a typical NBI discharge from PDX is shown in Fig. 1. For this discharge, the neutral beams were injected during the current rise. Associated with the onset of this 2.4 MW NBI discharge is a drop in surface voltage, V_{sur} , and an increased rate of rise of both the measured line-averaged density, $\bar{n}_e$, and $l_i/2 + \beta_{\text{pol}}$, where l_i is a measure of the plasma inductance, and, β_{pol} is the poloidal β value. The volume-averaged, equilibrium toroidal β , $\langle \beta_t^{\text{eq}} \rangle$, is determined from the measured $l_i/2 + \beta_{\text{pol}}$ signal and an assumed current profile based on the value of cylindrical q at the plasma edge.²⁹ From $\langle \beta_t^{\text{eq}} \rangle$, the energy confinement time, τ_E , is determined. The energy confinement time displays a drop from an ohmic value

of ~ 45 msec to a value of ~ 18 msec during the NBI portion of the discharge. Although the uncertainty in the ohmic τ_E value is large, because $L_i/2 \gg \beta_{pol}$, the value is consistent with that computed from a more sophisticated transport analysis code.²⁹ The parameter q_{ghaf} in the lower right-hand panel is the cylindrical q value at the plasma edge with toroidal corrections.²⁸ Only at low densities and high currents on TFR,³ PDX,²⁹ and PLT²⁵ was little change seen in τ_E going from the ohmic to the NBI phase, but this was due mostly to the low value of τ_E during the low density ohmic phase. These low energy confinement (L-) mode results were carried out in tokamaks whose plasmas were limited with either poloidal rail or toroidal bumper material limiters, or through use of magnetic divertors. The discharges were typically gettered with titanium.

With an increase in the neutral beam heating power, the energy confinement time was observed to deteriorate even further; however, the deterioration was found to be less than linear. Holding other parameters fixed, τ_E was seen to vary as $P^{-1/3}$ to $P^{-2/3}$ across the machines for a wide range of available heating power (~ 0.5 to ~ 8 MW). This deterioration of τ_E with power was viewed by DITE, ISX-B, JFT-2, and T-11 as resulting in a "soft" β_{pol} limit. While confinement was found² to be a moderately strong function of q in ohmic discharges ($\tau_E \propto q^{0.75}$), energy confinement for NBI discharges does not depend directly on q , but rather scales nearly linearly with I_p . While τ_E does not depend on q in NBI discharges, the electron temperature profile peakedness does, with broader T_e profiles at lower q (leading to improving τ_E with increased I_p), and more peaked profiles at higher q (leading to an almost linear scaling of central electron temperature with toroidal field). While profile peakedness depends strongly on q , it is roughly independent of beam power. An example of this, taken from PDX results, is shown in Fig. 2. This result is suggestive of a transport process that tends to restore the τ_E profiles during NBI to their ohmic shape.

Energy confinement times in NBI discharges are found to have no explicit dependence on either toroidal field, or, unlike ohmic discharges, plasma density (Fig. 3). Results from D-III²¹ indicate that plasma shaping is an important aid to confinement; at fixed q , τ_E increases by a factor of three as κ increases from 1.0 to 1.6. The improved confinement is due mostly to the increased current that the shaped plasmas are able to carry; at fixed I_p , τ_E

varied as $\kappa^{1/2}$. ASDEX NBI experiments³¹ also indicated that the plasma isotope is an important consideration, with $\tau_E \propto (m_i/m_p)^{1/2}$. This result was deduced from the difference in τ_E between $H^0 + H^+$ and $H^0 + D^+$ discharges, holding all other parameters fixed.

With 2.4 MW of neutral beam power injected in a near-tangential direction, the PLT tokamak was able to achieve record ion and electron temperatures of up to 7 keV and 4 keV, respectively.²⁶ These experiments were performed at low ($< 2 \times 10^{13} \text{ cm}^{-3}$) line-averaged densities. The question of whether near-perpendicular injection would aid heating and confinement was addressed by comparing low collisionality discharges (scattering time $>$ particle transit or bounce time) of PLT with those of PDX, a machine with comparable size and operational characteristics as PLT, but with near-perpendicular beam injection. While near-perpendicular injection could aid beam penetration and thus central heating, there was the potential of increased beam power loss due to enhanced loss of beam neutrals "shining-through" the plasma, due to enhanced loss of beam ions whose orbits take them outside the plasma. A comparison of typical PLT and PDX discharges at two different power levels is given in Table II. Note that PLT typically operated at higher q than PDX, which led to more peaked temperature profiles. It is clear from the table that higher central temperatures were observed on PLT, although at the maximum beam power available on PDX (~ 7 MW of D^0 injection) ion temperatures in excess of 6 keV were attained.²⁷ The difference in heating appears to be more dramatic at the lower than the higher power level. A good figure of merit was found to be the ion heating efficiency parameter, defined as $\bar{n}_e \Delta T_i(0)/P_{\text{abs}}$, where $\Delta T_i(0)$ is the difference between the ohmic and NBI phase central ion temperatures. Here again, the tangential injection of PLT appears to be superior to the near-perpendicular injection, especially at the lower power. On the other hand, the differences in total thermal energy confinement times, $\tau_E(a)$, do not appear to be as great, owing to the broader temperature profiles in the lower- q PDX. An analysis of a much larger data base indicated that the PLT discharges exhibited $\sim 20\%$ higher values of central ion and electron heating, and energy confinement time, than did PDX under similar operating and discharge conditions.²⁷

Other effects which potentially could influence energy confinement are beam-induced plasma rotation, and the differences between counter- and co-

injection. Rotation studies on PLT indicated that the rotation velocity was proportional to the beam momentum input.³² Similar studies on ISX-B did not corroborate this result, and further found that neither the direction nor magnitude of the rotation influenced the energy confinement scaling.³³ With counter-injection on PDX and ISX-B, beam orbit losses led to an ~ 40% loss of beam power, compared to ~ 10% with co-injection. Even with this additional loss of beam power, however, the ISX-B and PDX experiments indicated little difference between $\langle \beta_T \rangle$ attained with counter-injection and that attained with co-injection. This indicated an increase in gross (beam and thermal) energy confinement of ~ 30%, and an increase in thermal energy confinement time of ~ 50% over that achieved in co-injection discharges. Associated with counter-injection, and perhaps related to the increase in τ_E , is an observed decrease in impurity outflux,³⁴ (or, alternatively, an increase in impurity confinement time) which in turn may be related to the development of a negative potential in the plasma core with counter-injection.³³

Because the majority of the first generation NBI experiments were carried out with similar operational approaches (e.g., gettering, limiter or open divertor discharges), and because similar trends emerged from these experiments, it is possible to develop global energy confinement scalings based on the experimental results. Of particular interest for larger sized machines striving for reactor-relevant conditions is how τ_E scales with plasma size. While scalings with parameters such as I_p , B_T , etc. are straightforward, precise size-scaling is made difficult by the similar aspect ratios of all the machines involved ($R/a \approx 3.4$ to 4.2). This results in large uncertainties in the size scaling regression coefficients. Although a and it scalings will be shown, it is perhaps most useful to think about some combined length (L) scaling. In the following, discussions of various empirical and theoretical scalings will be presented along with a comparison to data where appropriate.

Using data from PDX, D-III, and ASDEX, Singer³⁵ derived an empirical scaling for $\langle \beta_T \rangle$ which, using a relation between $\langle \beta_T \rangle$ and τ_E , can be rewritten

$$\tau_E \propto n_e^{0.35} \bar{n}_e^{0.1} I_p^{1.1} B_T^{-0.1} P_{tot}^{-0.5} a^{1.5(\pm 1.2)} \quad (1)$$

This particular expression was derived from data near the reference discharge value of $P_{\text{tot}} = 2 \text{ MW}$, $I_p = 200 \text{ kA}$, $B_T = 1.2 \text{ T}$, and $\bar{n}_e = 4 \times 10^{13} \text{ cm}^{-3}$. Since the scaling was performed at essentially fixed R/a , the a -scaling portion of the expression should more appropriately be viewed as some length (L) scaling. In addition, the length scaling coefficient was chosen by Singer to satisfy the Kadomtsev³⁶ and the Connor-Taylor³⁷ constraints in which the energy transport is independent of the ratio of the plasma Debye length to minor radius.

An insight into this type of energy confinement scaling was made by Goldston,⁷ who noted that the current and density scaling of high density ohmic plasmas was similar to that observed in L-mode beam-heated plasmas. He proposed that a useful picture of confinement scaling could be obtained by combining two separate scaling laws

$$\tau_E = \left(\frac{1}{\tau_{E,OH}} + \frac{1}{\tau_{E,AUX}} \right)^{-1/2} \quad (2a)$$

where

$$\tau_{E,OH}(\text{sec}) = 7.1 \times 10^{-22} \bar{n}_e^{1.00} (\text{cm}^{-3}) a^{1.04} (\text{cm}) R^{2.04} (\text{cm}) q^{0.50} \quad (2b)$$

and

$$\tau_{E,AUX}(\text{sec}) = 6.4 \times 10^{-8} \kappa^{0.50} I_p^{1.00} (\text{A}) P_{\text{tot}}^{-0.50} (\text{W}) a^{-0.37} (\text{cm}) R^{1.75} (\text{cm}) . \quad (2c)$$

The ohmic scaling (2b) was obtained from surveys of low density ohmic scaling experiments, and the nonsize dependent portion for NBI plasma (2c) was obtained from reported individual machine scaling results from deuterium-target L-mode plasmas (ISX-B, ASDEX, D-III, and PDX). The size scaling for the NBI portion of the expression was determined by a multiple linear

regression technique about some reference point of I_p , κ , and P_{tot} . When the two scalings (2b and 2c) are combined according to Eq. (2a), the expression seems to predict accurately the saturation in τ_E as a function of $\bar{n}_e$ observed at high density in a number of ohmic experiments. The inverse quadrature relation of τ_E to $\tau_{E,OH}$ and $\tau_{E,AUX}$ was deduced purely on the basis of the fit to the data. When $\tau_{E,AUX}$ is multiplied by a factor of two, to give a simple model of "H-mode" confinement (discussion in next section), one obtains results consistent with the recent high density pellet injection experiments on Alcator C,³⁸ and the lack of saturation with density observed on FT³⁹ and TFTR.⁴⁰

It is interesting to find the "knee" where $\tau_{E,OH} = \tau_{E,AUX}$ by equating Eqs. (2b) and (2c)

$$\frac{1.1 \times 10^{-14} P^{1/2} a^{1.41} R^{0.29} \bar{n}_e q^{0.5}}{\kappa^{0.5} I_p} = \frac{1}{2} \begin{matrix} \text{(L-mode)} \\ \text{(H-mode)} \end{matrix} \quad (2d)$$

This implies, for example, that by raising I_p to the range of 1 MA at fixed NBI power of order ~ 2 MW, one can move from the $\tau_{E,AUX}$ -dominated regime to the $\tau_{E,OH}$ -dominated regime. In this regime the increase of τ_E with I_p tends to saturate. Figure 4 shows data from a current scan on D-III by the JAERI team.⁴¹ The calculated τ_E vs. I_p , based on Eq. (2a), with an L-mode coefficient in Eq. (2c), is shown by the solid line in the figure. For this calculation, a mean density for the range shown in Fig. 4 was used. The good agreement again supports the notion that two separate τ_E scaling laws govern confinement. The saturation of τ_E at high plasma current in NBI experiments is complementary to the saturation of τ_E at high density in OH experiments.

In an even more recent scaling exercise, Kaye and Goldston⁴² collected large amounts of NBI experimental data (see Table III) in an effort to extend the previous scaling studies. The data were chosen so that only discharges with $P_{inj} \geq 2 P_{oh}$ were included in the data base in order to ensure that the scaling was performed for injection-dominated discharges. Thus, this work could be thought of as an extension of the $\tau_{E,AUX}$ scaling given in Eq. (2c). The following scaling emerged from this analysis:

$$\tau_E (\text{msec}) = 10^{-4.56} \kappa^{0.28} B_T^{-0.09} (T) I_p^{1.24} (\text{kA}) \bar{n}_e^{-0.26} (10^{13} \text{ cm}^{-3})$$

$$\cdot P_{\text{tot}}^{-0.58} (\text{MW}) a^{-0.49} (\text{cm}) R^{1.65} (\text{cm}). \quad (3)$$

The results of the fit are shown in Fig. 5 where the experimental τ_E is plotted against the τ_E derived from Eq. (3) for each data point in the data base. The correlation coefficient for this fit is $R^2 = 0.94$. In this scaling, no clear difference, due to isotope effect, could be determined between the PDX data ($D^0 \rightarrow H^+$) and data from ASDEX, DITE, D-III, ISX-B, and TFR (all $H^+ \rightarrow D^+$), all of which went into the scaling. The PLT data contained both $D^0 \rightarrow H^+$ and $H^0 \rightarrow D^+$ discharges. The most probable reason for this lack of isotope effect is that beam slowing down led to comparable thermal H^+/D^+ ratios for all machines.

In Fig. 6 the data base created by Kaye and Goldston was used to determine the goodness of fit of the Goldston² injection regime scaling. In this plot, the experimental τ_E 's are plotted versus the scaling given in Eq. (2c), with some modification of the numerical coefficient. While that determined by Goldston² is 6.4×10^{-8} (for Goldston's units), the corresponding coefficient that best fits the NBI data base is 5.8×10^{-8} (also for his units). The correlation coefficient for this fit is $R^2 = 0.93$, which is, for all practical purposes, identical to that in the Kaye-Goldston scaling. This result is not surprising since these two injection regime scalings are equivalent to within the uncertainties of the regression coefficients. It should be noted that the Goldston and the Kaye-Goldston scalings satisfy the Connor-Taylor constraints for collisionless and collisional finite- β , and resistive MHD plasma models.³⁷

Note that for both these scalings, the size dependence is approximately $L^{2.4}$. This $L^{2.4}$ dependence incorporates the assumption that I_p scales approximately linearly with plasma size for fixed $\bar{n}_e$, β_t , etc. The size scaling for the NBI dominated discharges is, consequently, slightly weaker than that described in either the INTOR or neo-Alcator ohmic scalings ($\sim L^3$).

In the empirical scalings discussed above, little attention was paid to the physical process that control energy transport in the plasma. The fits were derived purely from mathematical methods. Such is the nature of an

empirical fit. The alternative method, one favored by the theoretical community, is to use some physical model of energy transport as a basis, and then to derive global τ_E scalings. One test of such models is to see how well the experimental data reflect these theoretical scalings. The following discussion will focus on three such theoretical scalings: those by Connor, Taylor, and Turner;⁴³ Perkins;⁴⁴ and; Merezhkin and Mukhovatov.⁴⁵

In recent work, Connor, Taylor, and Turner⁴³ (CTT) hypothesized that the localized onset of MHD ballooning instabilities leads to a saturation of β with increasing beam power, which results in a deterioration of energy confinement. The competing process in this instability are local values of pressure gradient (destabilizing) and local values of shear (stabilizing). A key assumption of this formulation is that the onset of ballooning does not cause a sharp reduction in energy confinement; rather there is a continual reduction with increasing β and heating power. In the CTT formulation, the threshold for instability is given by

$$\frac{-2\mu_0 R q^2}{B_0^2} \frac{dp}{dr} = f(s) \quad (4a)$$

where

$$s = \frac{r}{q} \frac{dq}{dr} . \quad (4b)$$

The global confinement scaling that emerges from this formulation is:

$$\tau_E \propto I_p^{1.44} \bar{n}_e^{0.28} p_{tot}^{-0.72} a^{-0.16} R^{1.44} . \quad (5)$$

In this work, the emphasis was on developing the parametric scaling properties of the confinement time; therefore, no numerical coefficient was derived.

How well the model explains the data may be examined on two levels. The first is a determination of whether or not the plasma is unstable to ballooning modes according to the criteria in Eq. (4a) and (4b), and the second is to use the NBI data base to steady the global scaling given in Eq. (5). This author used the PDX β -scaling dataset^{28,29} to determine if the pressure gradients were indeed large enough to cause the onset of ballooning. Using measured electron temperature and density profiles, and corresponding calculated ion and beam pressure profiles to determine total pressure gradients, the PDX data fall in the stable regime, about a factor of two to three lower than the instability threshold of CTT (Fig. 7). This result holds across the entire plasma profile. In this analysis, local cylindrical q -value with toroidal corrections was used.

In other work, Pfeiffer et al.⁴⁶ extended the CTT formulation to include a more general description of plasma heating and pressure profiles, including noncircular geometry. A test of this model with D-III data indicated that, here too, the plasma should be stable to ideal ballooning modes by a large margin.

Despite the apparent failure of the CTT model to describe local properties of the PDX and D-III high- β plasmas, the global scaling given in Eq. (5) does remarkably well in modeling the global τ_E 's contained in the NBI data base. In Fig. 6b are plotted the experimental τ_E 's as a function of the CTT parametric scaling Eq. (5). The best fit numerical coefficient for the scaling is determined to be 8.45×10^{-6} , and the correlation coefficient of the fit is $R^2 = 0.94$. Note that the CTT parametric scaling itself is not too different from either the Goldston or Kaye-Goldston scaling. It is not clear how to resolve the apparent discrepancy between the local and global comparisons. For the local comparison, using the PDX data, "smoothed" pressure profiles were used; nevertheless, examination of the unsmoothed electron temperature and density profiles indicates that the fine-scale spatial structure, not evident in the smoothed profiles, tends to cancel. On the other hand, without exact measurements of the current profile, fine-scale structure of the shear, which was calculated through a magnetic diffusion routine, is not known. Therefore, uncertainties in local values of dp/dr and $1/q \, dq/dr$ certainly do exist.

Another approach to theoretical confinement scaling was taken by Perkins.⁴⁴ This work is based on the observation that drift wave fluctuations that exist in neutral-beam-heated tokamaks appear to be in the strong turbulence regime.⁴⁷ In the Perkins confinement model, this strong drift wave turbulence is assumed to exist between the $q = 1$ and 2 surfaces; sawtooth oscillations control the energy transport within the $q = 1$ surface, and $T_e(r)$ is taken to be 0 outside of $q = 2$. The electron thermal diffusivity between $q = 1$ and 2 is attributed to toroidally induced collisionless drift instabilities. For the collisionless regime of NBI discharges, the electron heat balance equation in Perkins's formulation leads to the central electron temperature, T_0 , scaling as

$$T_0 \propto [B(\frac{P}{n})^{0.5}]^{0.8} (\frac{a}{R})^{0.2} \alpha_n^{-0.4} q^{0.1} \quad (6)$$

where α_n is a measure density profile peakedness, and q is the limiter q -value. The temperature scaling Eq. (6) agrees well with the variation in central electron temperatures observed in ISX-B, PLT, and PDX neutral beam injection experiments.⁴⁴ As in the CTT work, here too the approach was to develop a parametric scaling. Assuming a simple form for the electron temperature profile, Eq. (6) can be rewritten in terms of an electron energy confinement time:

$$\tau_{E_e} \propto I_P^{0.9} B_T^{-0.1} n_e^{0.6} P_{tot}^{-0.6} a^{0.4} R^{1.7} \quad (7)$$

The formulation from which Eq. (7) is derived assumes that all the input energy ultimately flows out of the plasma through the electron channel via thermal conduction. While for the most part this is not a bad assumption, radiation losses between $q = 1$ and 2 are typically only a fraction of the allowed losses; at least in some high toroidal field (2.2T) PDX discharges, ions were seen to carry out a significant fraction of the input energy through conduction and convection.²⁹ The scaling also assumes the plasma to be

collisionless; however, in some PDX high- $\langle\beta_T\rangle$ L-mode discharges, for instance, $v_e^* \sim 0(1)$. Collisional corrections lead to a different parametric dependence.

Nevertheless, the parametric scaling derived by Perkins appears to be consistent with the data contained in the NBI data base. A plot of experimental τ_E 's versus the scaling given in Eq. (7) is shown in Fig. 6c. Here, for simplicity, $\tau_E \propto \tau_{E_e}$, is assumed. For this fit, the best-fit numerical coefficient is 4.04×10^{-6} , and the correlation coefficient is $R^2 = 0.92$.

The last theoretical scaling to be discussed is that developed by Merezhkin and Mukhovatov.⁴⁵ While this scaling was developed primarily for low density ($\bar{n}_e \leq 2.5 \times 10^{13} \text{ cm}^{-3}$) T-11 ohmic discharges, it has recently been suggested that its applicability could be widened to include results from neutral-beam-heated experiments.⁴⁸ The Merezhkin-Mukhovatov scaling is of the form

$$\tau_{E_e} \propto \left(\frac{a}{R}\right)^{1/4} q(a) \bar{n}_e R^3 A_p^{1/2} / \langle T_e \rangle^{1/2} \quad (8)$$

where $\langle T_e \rangle$ is the volume-averaged electron temperature, and A_p is the atomic number of the plasma ionic species. For convenience, the scaling may be rewritten, assuming an additional $\kappa^{1/3}$ dependence, as

$$\tau_E \propto (R/a)^{-1/6} a^2 B_T^{2/3} R^{5/3} I_p^{-2/3} \bar{n}_e P_{\text{tot}}^{-1/3} \kappa^{5/9} \quad (9)$$

where $\langle T_e \rangle$ is eliminated in favor of heating power, and for reasons given previously, the plasma species dependence has been ignored. The scaling given above was examined in light of the NBI data base in the same fashion as with the previous theoretical scalings. The results are given in Fig. 6d. The best fit numerical coefficient is 5.01×10^{-5} , and the correlation coefficient is poor ($R^2 = 0.31$). The results clearly indicate that the Merezhkin-Mukhovatov scaling in its present form is not applicable to the NBI experiments contained in the data base.

Another auxiliary heating mechanism that is presently being used is RF heating, and in particular, ion cyclotron heating. While parameter space is filled with results from NBI experiments, the dataset for confinement studies from RF heating experiments is relatively sparse. Nevertheless, recent ICRF results from JFT-2M (up to 1.6 MW RF power)⁴⁹ and PLT (up to 2.6 MW RF power)⁵⁰ do indicate behavior of energy confinement similar to that in NBI discharges. For instance, in both experiments, τ_E was found to degrade with increasing total heating power, although on PLT, τ_E , once degraded from its ohmic level, remained constant at the highest powers (1.9 to 2.6 MW). The confinement values themselves were quantitatively similar to those obtained in NBI discharges under similar operating conditions. A problem noted by both experimental groups was the uncertainty in both the total heating power and the RF power deposition profile.

Experiments with electron cyclotron heating with powers up to 0.7 MW have recently been performed on D-III.⁵¹ The experiments were done in divertor discharges with the ECH resonance in the plasma center. In discharges with $P_{ECH} \geq 2 P_{OH}$, the results were strikingly similar to those of NBI discharges, with a linear dependence of confinement time on plasma current, in the range $I_p = 200$ to 650 kA, and no density dependence. The ECH power levels were too low to extract any definitive power scaling, although at these low powers the ECH and NBI plasmas showed similar stored energies.

III. SECOND GENERATION EXPERIMENTS (H-, Z-, AND P-MODES)

The second generation of NBI experiments was marked by a more creative approach to tokamak operation, and an appreciation of some subtle, yet controllable effects that could influence energy confinement significantly. One such effect was due to "closed" divertor operation. Early experiments on ASDEX,⁵² D-III,⁵³ and PDX,⁵⁴ along with modeling results,⁵⁵ pointed to improved power handling for a divertor configuration in which the recombined neutrals from the divertor region could reach the main chamber only by first passing through a dense divertor scrapeoff. What was not expected in these types of discharges was the factor of approximately two improvement in energy confinement, over the L-mode expectation, discovered first by ASDEX in this mode of operation.^{31,56} While only L-mode energy confinement times were achieved in the open divertor configuration of PDX, the H-mode was attained on that machine shortly after the divertor was modified to a closed

configuration.^{57,58} For ASDEX and PDX, the transition of a discharge from L- to H-mode occurred during NBI and was signaled by a sharp drop in divertor H_α/D_α emission. While the sharp drop in divertor H_α/D_α emission was a necessary precursor to high energy confinement times, it was not sufficient, as evidenced by PDX open divertor results. What was also needed for high τ_E was a significant reduction of the thermal neutral density in the main plasma. Therefore, to use the drop in H_α/D_α emission alone as a signal of the transition into an H-regime is misleading, especially if "H-Mode" is meant to signify high τ_E .

In their expanded boundary configuration, both the JAERI and GA teams on D-III attained the H-mode,^{41,59-61} but their details differed from those of ASDEX and PDX. For instance, no sharp transition into the H-mode was observed during NBI; improved energy confinement was observed from the outset of NBI, and even, in some cases, in the ohmic plasma. Differences between D-III and ASDEX or PDX are not surprising because of differences in divertor configurations. In D-III, the x-point was in a region open to the entire bottom chamber of the vacuum vessel, while in PDX and ASDEX, the region outside the x-point led through a narrow chamber into the divertor dome region. The JAERI D-III team operated in a configuration with the x-point closer to the inside wall than the GA D-III team, resulting in a larger access region to the plasma chamber for neutrals from the lower portion of the vessel. The divertor configurations for the ASDEX, PDX, and D-III machines are shown in Fig. 8.

Most noticeable in the ASDEX and PDX discharges is the fact that the increase in energy confinement was due in some large part to the development of a pedestal of several hundred eV in the measured electron temperature profiles. In addition, density profiles became flatter after the transition to the H-mode, also aiding the improved confinement. Examples of the differences in T_e and n_e profiles for the L- and H-phase in PDX are shown in Fig. 9. The top portion of Fig. 9 shows the electron temperature and density profiles in the main plasma as measured by the multipoint Thomson scattering system. A single-point Thomson scattering system was used to study the gradients near the plasma edge outside $R = 180$ cm (lower portion of the figure). The shaded portions in the lower figures indicate the combined range and uncertainties of the separatrix locations, as calculated by an MHD

equilibrium code. Note that for these PDX discharges the large gradients in both the temperature and density occur inside the plasma, not beyond the separatrix.

The GA team on D-III observed $\sim 50\%$ higher central electron temperatures in their expanded boundary (H-) discharge than in their limiter (L-) discharge, with the difference being of order ~ 700 eV, but with nearly identical profile shapes. They conclude that it is this increase in stored energy in the core region of the plasma that led to the improvement in energy confinement. However, because of the sparse diagnostic coverage at the plasma edge, they did not rule out the presence of pedestals in the electron temperature profile. An example of the GA D-III L- and H-mode temperature profile is shown in Fig. 10.

The confinement times for ASDEX, PDX, and GA (D-III) H-modes followed scalings similar to those in the L-mode, with nearly linear current dependencies and little toroidal field or density dependence. An interesting dichotomy emerged from the D-III results in that the JAERI team found that τ_E was proportional to $\bar{n}_e$ in the H-mode, and they attributed little confinement scaling to I_p . By contrast, the GA team found a strong I_p and weak $\bar{n}_e$ dependence, as also observed on ASDEX and PDX. The JAERI group inferred from observations of H_α light at the limiter, that changes in recycling, leading to an improvement of particle confinement with increasing density, was associated with the improvement in energy confinement. The improvement in particle confinement during the H-mode was also reported by the ASDEX and PDX groups. This observation may be related to the claim by both D-III groups and the ASDEX group that plasma decoupling from the limiter is crucial to good H-mode confinement. For plasma-limiter separations of $\lesssim 2$ cm on D-III and $\lesssim 1.5$ cm on ASDEX, good confinement is lost.

Several factors were found to lead to a deterioration in energy confinement at fixed discharge parameters. One such phenomenon was the rapid loss of stored energy in the outer half of the plasma associated with short bursts of H_α/D_α emission. The loss of stored energy was related to both an expulsion of plasma and reduction in plasma temperature near the plasma edge. The relative amount of confinement deterioration was proportional to the severity of the H_α/D_α spikes, the spikes themselves becoming more severe with higher absorbed power. H_α/D_α spikes were observed on all H-mode devices

in at least some of the H-mode discharges, and this led to a new round of phenomenon naming. The H_{α}/D_{α} spikes were called ERP's (Edge Relaxation Phenomena) by the PDX group, ELM's (Edge Localized Modes) by the ASDEX group, and SI's (Surface Instabilities) by the JAERI D-III group. The GA D-III group took the most enlightened approach: when H_{α}/D_{α} spikes were observed, they were called H_{α}/D_{α} spikes.

Figure 11 shows a portion of a PDX H-mode discharge in which H_{α}/D_{α} spikes first appeared, then disappeared (lower panel). As seen in the figure, a reduction in the rate of rise of line-averaged density and total $\langle \beta_t \rangle$ implying a reduction in energy confinement time, is associated with the onset of these spikes. For some as yet unknown reason, the spikes disappeared some time later, and this is associated with an increase in the rate of rise of both $\bar{n}_e$ and $\langle \beta_t \rangle$, and thus an increased τ_E . Theoretical work suggests that the H_{α}/D_{α} spikes may be the result of destabilization of the external kink mode due to large temperature (current) gradients at the plasma edge,⁶² or the result of ballooning.⁶³

From studies in D-III and PDX, it was clear that the way to achieve good confinement in H-mode plasmas was to adopt an operating scenario that led to a minimum of neutral recycling in the main chamber. The PDX Thomson scattering optics were used to study the position of the fueling source. High energy confinement discharges were attained when the fueling source was localized to the divertor throat. A deterioration of confinement to L-mode levels was seen in discharges where the fueling source was delocalized, such as in discharges with large gas feed rates. These large gas feed rates were necessary in higher power discharges (> 2.5 MW) to reduce the metallic impurity influx that could lead to disruptions. Therefore, in PDX for $P_{\text{heat}} \leq 2.5$ MW, confinement times ranging from L-mode values to ~ 2.5 times these values were achieved in H-mode discharges (noting that H-mode is taken to mean the time after the drop in the divertor H_{α}/D_{α} emission), while τ_E was little higher than L-mode values above the ~ 3 MW level. ASDEX discharges exhibited no deterioration in τ_E at higher powers, but at the time of their last report, results were available only up to 3.4 MW injected power. The GA D-III team found $\tau_E \propto P_D^{-1/3}$, while the JAERI team found little scaling with P_D ; only an $\sim 10\%$ deterioration in H-mode τ_E 's was found going from 3 to 7 MW of absorbed power.⁶¹ In these JAERI experiments, both the central electron and ion

temperatures were in excess of 5 keV at the highest powers. A comparison of discharge quality factor, defined as $\tau_E/\kappa^{1/2}I_p$, is shown in Fig. 12 for PDX, GA D-III, and ASDEX results. The confinement times were normalized by the quantity $\kappa^{1/2}I_p$ to suppress the elongation and current dependence of the energy confinement time. For PDX and ASDEX, $\kappa \approx 1.0$. Both L- and H-mode discharges are shown in the figure; the improvement in $\tau_E/\kappa^{1/2}I_p$ is clearly seen in the H-phase for each machine. In addition, the ASDEX H-mode discharges appear to exhibit greater discharge quality factors for a given P_{tot} than either PDX or D-III. The reason for this is not known. But, if neutral recycling is a crucial issue for good confinement, it should be noted that the relative size of the divertor throat region to plasma size in ASDEX is smaller than in the other two devices.

Divertor operation is not the only mode in which an improvement in NBI energy confinement over the L-mode value could be achieved. Control of fueling and neutral recycling were also critical issues for scoop limiter NBI experiments on PDX.^{58,64} Observations of fast neutral efflux in these discharges indicated that main chamber neutral densities reached levels even lower than those in H-mode discharges, and observations of plasma light suggested that the fueling seemed to be confined to a region near the scoop limiter blades. No sharp transition into an H-regime during NBI was seen in these discharges. But at moderate power (≈ 2.5 MW), values of τ_E 's approaching those in the good H-mode discharges were attained. Above 3 MW, τ_E deteriorated to near L-mode values. A nearly linear current dependence and no density dependence were deduced from the scoop limiter τ_E values.

ISX-B L-mode experiments were carried out with titanium gettering. It was noticed early on, and then later studied in more detail, that for similar operating conditions, discharges without gettering exhibited higher particle and energy confinement values than those with gettering.⁶⁵ The τ_E values were $\sim 80\%$ higher at $\bar{n}_e = 6 \times 10^{13} \text{ cm}^{-3}$, and were due primarily to a broadening and increase of the electron temperature profile. These ungettered discharge confinement times scaled with I_p and P_{tot} as in the L-mode; without gettering, a positive density dependence was recovered (see Fig. 13). Similar results were subsequently observed in DITE ungettered discharges.⁶⁶

Quantitatively similar to the ungettered discharges are those ISX-B discharges in which trace amounts of neon were injected.⁶⁷ τ_E was found to

increase nearly linearly with $\bar{n}_e$ in these discharges, although above a critical $\bar{n}_e$ value (dependent on ratio of injected neon to gas puffed deuterium), the density dependence disappeared (but at τ_E levels $\sim 80\%$ higher than those in the L-mode).⁶⁸ Too much neon injection led to disruptions. In these ungettered and neon injection "Z-mode" plasmas, Z_{eff} increased only marginally. Fueling of these Z-mode discharges by impurities was apparently insignificant.

In Alcator-C ohmic discharges, pellet injection to aid in plasma fueling was found to result in a peaking of the density profile and a factor of two improvement in energy confinement time over that deduced from gas-fueled discharges. Even more dramatic was the factor of three to four improvement in the Lawson number, $n_e(0) \tau_E$, over gas-fueled discharges. At line-averaged densities of $\sim 8 \times 10^{14} \text{ cm}^{-3}$, the Lawson number reached $8 \times 10^{13} \text{ cm}^{-3} \text{ -sec}$, approximately 30% greater than that value required for thermalized breakeven.³⁸

An experiment to determine the effects of pellet fueling in NBI discharges was undertaken by the JAERI and GA D-III groups with a continuous pellet injector supplied by Oak Ridge National Laboratory.⁶⁹ These experiments were carried out in both limiter and divertor discharges, with both continuous and interrupted neutral beam injection. The pellet injection increased the central density by a factor of two over that with gas fueling, to a value of $2.0 \times 10^{14} \text{ cm}^{-3}$. With 2.4 MW of continuous NBI into an $I_p = 620 \text{ kA}$, $\bar{n}_e = 1 \times 10^{14} \text{ cm}^{-3}$ limiter discharge, the energy confinement was determined to be 70 msec; for a comparable gas fueled discharge, τ_E was only 45 msec (Fig. 14). The energy confinement time for the pellet-fueled discharges (P-mode) decreased with both time after the first pellet injection (the pellets were injected at a rate of 32 sec^{-1}) and with increased beam power. At 5 MW, the pellet-fueled discharge confinement time was comparable to that of the similar gas-fueled discharge. The high confinement of the P-mode could be sustained with interrupted beams; short, 20 msec, beam pulses separated by 5 to 20 msec. The motivation for the latter experimental scenario was based on the fast slowing-down time of the fast beam ions and the dependence of the pellet ablation on the fast ion population. These experiments were carried out also in divertor H-mode configurations. While confinement times were not improved over the gas-fueled H-mode values, the

density of the pellet-fueled discharges was maintained at a high level.

It is clear that a global τ_E scaling for these H-, Z-, and P-mode scenarios could be misleading because of the large variations in confinement even in what would have been considered a fixed discharge condition (I_p , $\bar{n}_e$, B_T , etc.). The effects of gettering, impurity injection, and neutral recycling are critical, but as yet unquantifiable. Thus the different scaling results observed on the different machines may be in part attributable to variations in these conditions. Some qualitative scaling of these high confinement operating modes can nevertheless be attempted. A summary is given in Table IV.

An alternative, or additional, explanation for the different scalings of some of the results presented in Table IV can be obtained by examining Eq. (2d). Note that the transition to $\tau_{E,Aux}$ scaling occurs at four times higher beam power for H-mode plasmas than for L-mode (if the H-mode $\tau_{E,Aux}$ is taken to be simply two times that of the L-mode). Also, the transition power (from OH to Aux scaling) is proportional to I_p^2 . Therefore, while the recent JAERI (D-III) results at 900 kA would be expected to show largely $\tau_{E,OH}$ scalings, the GA (D-III) scans at ~ 500 kA show $\tau_{E,Aux}$ scaling. ISX-B Z-mode scans at 150-200 kA and ~ 1 MW injected power could be expected to show a mixture of scaling results. This quantitative agreement with experimental results suggests that H-mode confinement can indeed be reasonably well modeled as a simple doubling of $\tau_{E,Aux}$. However, while Goldston's two component confinement scaling laws help clarify the experimental situation in different regions of parameter space, it does not explain the factor of approximately two enhancement of $\tau_{E,Aux}$ from L- to H-mode.

IV. LOCAL TRANSPORT: COMPARISON OF THEORY AND EXPERIMENT

Comparisons of local transport theory (e.g., expressions for electron thermal diffusivity) with experimental results are much more difficult to make than for global scalings. Although in many instances the particular theory being tested is not relevant to the experiment being performed, much difficulty also lies with the experimental side, with large uncertainties in data as well as incomplete datasets. This is not meant as criticism of the scientific method of the experimentalists. It is merely a statement of the difficulties and realities of experimental physics. For instance, one

experimental shortcoming is the general lack of ion temperature profile measurements. While central ion temperatures can be measured with some accuracy by several means (charge exchange, neutron intensity, Doppler broadening), and are generally consistent with classical electron-ion coupling and thermal conduction of order 0.5 to 3 times that given by neoclassical theory,⁷⁰ only sparse measurements of the rest of the profile are available. This results in some difficulty in modeling local transport in the plasma. Typically, the neoclassical multiplier used to model the central ion temperature is assumed to be constant across the plasma. This assumption has, for the most part, led to an almost universal conclusion that the bulk of the plasma energy loss in NBI discharges is through some anomalous electron process usually attributed to electron thermal conduction. This is because radiative losses are small except just at the edge, the neoclassical ion thermal conductivity is relatively flat, and calculated ion losses are small compared to the input power. The dominance of the electron conduction loss channel could be called into question should the ion conduction loss, for some reason, be more important in the outer portion of the discharge. Chang and Harvey,⁷¹ for instance, suggested an enhancement in ion conduction due to the presence of poloidal electric fields. Nevertheless, in the cases where ion temperature profiles are available, and believable, the assumption of an approximately constant neoclassical multiplier across the plasma is not unreasonable^{29,72} but, also, is not always the case.⁷³

Most theoretical effort, therefore, has concentrated on relating energy transport losses to the value and form of the electron thermal diffusivity, χ_e . Experimentally, χ_e is difficult to deduce and can be done so meaningfully only if a full complement of diagnostics, especially those giving high spatial resolution T_e profile information, is available. The reason for this latter necessity is that the local χ_e values deduced from experimental results through transport analyses depend on the calculated volume-integrated electron conduction loss at that radius as well as measured values of n_e and dT_e/dr . One recent experimental technique to overcome these difficulties is the determination of χ_e through heat pulse propagation during sawteeth,^{74,75} while meeting with some success,⁷⁵ this technique is still in the development stage.

Using transport analysis as the primary means of calculating χ_e , a coordinated effort was undertaken by several groups to determine what

magnitude of uncertainty could be attached to the χ_e values.⁷⁶ The different data handling techniques, as well as uncertainties in $T_e(r)$, $n_e(r)$, $T_i(r)$, and radiated power led to the conclusion that χ_e was known best at $r = a/2$, where the electron temperature gradients are the largest. At this radius the calculated χ_e is "certain" to within a factor of ~ 1.7 . The uncertainty is larger at the plasma edge where n_e , T_e , and the radiative loss profile are not well known. It was also concluded that without any sort of sawtooth model, χ_e values deduced for the core region of the plasma could be misleading because of uncertainties in the heating profile and because of direct sawtooth losses.

A variety of theories have been developed in an attempt to explain the electron transport, including those based on micro-tearing theory^{77,78}, strong turbulence saturation⁷⁹, finite- β universal modes,⁸⁰ drift wave turbulence⁸¹ and nonlinear trapped electron modes.⁸² None of these theories have had success in predicting either the shape or magnitude of the deduced L-mode χ_e 's.²⁹ A recent semiempirical χ_e model based on kinetic drift wave turbulence has achieved good success in matching the χ_e 's deduced from a representative set of ohmic discharges.⁸³ The key assumptions in this model are that the region that determines the thermal confinement lies between the $q = 1$ and $q = 2$ surfaces, that the current profile is related to the temperature profile by a form of Ohm's law, and that the radial dependence of χ_e is determined by "profile consistency," that is, current and temperature profiles are maintained by the anomalous transport processes.

A transport scaling developed specifically for ISX-B observations was that by Carreras *et al.*⁸⁴ based on pressure-driven resistive ballooning mode theory. This last theory was reported to achieve some success with ISX-B results, perhaps because of the relatively low temperature ISX-B discharges, but not with results from PD χ ²⁹ and D-III (JAERI),⁸⁵ even at high β_{pol} .

Simple empirical scalings of χ_e (e.g., $INTOR$, $1/nT$) yield some agreement with the shape of the experimentally deduced χ_e (typically sharply rising towards the outside of the plasma), but do not give good agreement in magnitude. Another empirical scaling has come from simple power balance arguments including auxiliary heating,⁸⁶ and is also based on the assumption that electron conduction will vary in order to relax the electron temperature profiles during auxiliary heating to their ohmic profile shape. In this scaling, χ_e depends most strongly on $1/T_e$, thus yielding the correct profile

shape for χ_e . But the portion of the scaling that reflects the "profile consistency principle" contains a number of adjustable parameters. Therefore, agreement with experiment can be obtained by a judicious choice of numerical coefficient. However, the underlying scaling with key parameters such as power is not uniquely determined.

An ambitious attempt to formulate an empirical model of χ_e was undertaken by Singer.³⁵ In this model, χ_e was composed of a sawtooth model for the $q < 1$ region, an empirical ohmic diffusivity, based on the Pfeiffer and Waltz¹⁵ global scalings, and an empirical auxiliary heating χ_a term. This local scaling model leads to the global scaling given in Eq. (1). Singer stressed that local profile effects should be considered in addition to the global dependencies. For instance, the ohmic χ_e term includes a density gradient influence to reflect destabilization of micro-instabilities at low β . For the χ_e^{aux} term, pressure gradients reflect the destabilizing influence of kinetic ballooning, and shear gradients provide a stabilizing influence. In Singer's transport model,

$$\chi_e^{\text{OH}} \propto n_e^{-0.9} r^{-1} \epsilon^{1.9} z_{\text{eff}}^{-0.1} \left| \frac{d \ln n_e}{d \ln r} \right| \quad (10)$$

and

$$\chi_e^{\text{aux}} \propto \kappa^{-2.2} n_e^{-0.2} r^{0.4} q^{2.2} B^{-2.0} \left(\frac{M_i}{M_p} \right)^{-0.3} \epsilon^{1.4} p^{-1.0}$$

$$\left| \frac{d \ln p}{d \ln r} \right|^{1.5} \left| \frac{d \ln q}{d \ln r} \right|^{-1.5} \quad (11)$$

where, here, p is pressure, and $\epsilon = r/R$. Work is presently underway to use this scaling to model ASDEX and PDX L- and H-mode plasmas. Regressions on the deduced χ_e dataset from PDX, however, suggest that the pressure and shear gradient terms are not as important as indicated in Eq. (11).

Because of the general disagreement between theory and experiment for local transport coefficients, the experimental groups themselves have

attempted to define the discharge parameters which best order their respective $\chi_e(r)$ results. Both GA (JAERI)⁸⁵ and ISX-B⁸⁷ groups reported that χ_e was found to scale as $1/n_e T_e^{1/2}$ for L-, H-, and Z-mode plasmas. An example of how well the $1/n_e T_e^{1/2}$ scaling fits GA (JAERI) χ_e data is shown in Fig. 15.

A regression analysis of PDX L-mode χ_e 's indicates that $\chi_e(r)$ is well described by the expression $\chi_e \propto r^{1.65} B_p^{-1.20} n_e^{-0.37}$, where B_{pol} is the local poloidal magnetic field, reflecting the nearly linear dependence of τ_E on I_p for the PDX L-mode.²⁹ This fit is shown in Fig. 16; the correlation coefficient for the fit is $R^2 = 0.77$. While the $1/n_e T_e^{1/2}$ scaling is not inconsistent with the PDX χ_e results, it was determined that the $T_e^{1/2}$ dependence reflected primarily the broadening of the T_e profile with increasing I_p , holding all other parameters fixed.

Because of parameter-space-limited data, as well as the unquantifiable nature of many of the parameters in the PDX H-mode experiments, no systematic scalings of χ_e are possible from this set of experiments. However, the PDX group pointed out the χ_e in H-mode discharges was approximately a factor two less than that in the L-phase.²⁹ This was also noted by the GA D-III,⁵⁷ and the ASDEX⁸⁸ groups. The ISX-B group also reported a similar quantitative reduction in χ_e during Z-mode discharges. Note that the drift wave turbulence theory⁴ predicts improved confinement with broader density profile, in accord with the observation of broader density profiles in PDX,^{57,58} ASDEX,⁸⁸ and D-III⁶⁰ H-mode discharges.

V. CONCLUSIONS

The first generation of NBI tokamak experiments are in almost universal agreement as to how the global energy confinement scales with discharge parameters. As such, empirical scaling laws, based on these results, can easily be formulated to describe well the confinement variation. A far more difficult and as yet unsolved problem, is to identify the underlying physical process or processes that control energy confinement. This involves, in part, relating local transport deduced from experiment to that predicted by theory. Because of experimental shortcomings, and the inadequacy of numerous proposed theoretical models, this process is difficult and, to date, not definitive. For instance, the global τ_E scaling determined from experiments

agrees with the theoretical scalings derived by either Perkins or Connor, Taylor, and Turner, despite the fact that the two theories are based on quite different physics.

To resolve this and other dilemmas, experimentalists would be served by theories that predict not only global scalings, but local (χ_e and, perhaps, temperature) scalings as well. While further development of theoretical scalings is steadfastly encouraged, a more general service by the theory community could also be offered. This service, which would be a generic breakdown of the classes of instabilities, would provide the experimentalists with a clearer picture of where to look. A specific example might be for the theorists to identify the key parameters governing different classes of instabilities (e.g., drift wave versus ideal ballooning). While these parameter sets may intersect over some parameters, others, such as density scale length, pressure scale length, and shear, would serve to distinguish the classes of instabilities. While the difficulty of determining these parameters experimentally would not be obviated, at least the experimentalists would have a more focused way of classifying their results.

What we have to date, though, is a set of empirical scalings that describes the existing data. This last point is one to stress, for it underscores the very nature of what an "empirical scaling law" is. While it is tempting to use these scaling trends to extrapolate to larger machines and assess their *pohaehtib uanprnjieoaW* to do so without a proper understanding of the underlying physics is obviously dangerous. Clearly, the L-mode scalings given by Eqs. (2) and (3) result in quite discouraging predictions of τ_E for machines such as TFTR, JET, and, potentially, INTOR. Such scalings may, in fact, be valid for these machines, but such a conclusion is premature. Assumptions that have gone into the development of these scaling trends may not be applicable for the operating parameters of the larger machines. For instance, it was assumed in the empirical scaling τ_E scales as P^α . However, results from D-III (GA)⁸⁹ indicate that either a P^α or an $(a + b/P_{tot})$ dependence could explain the behavior of τ_E with P_{tot} . The latter dependence leads to much more optimistic predictions of τ_E for reactor-sized machines. Another facet of NBI that can be examined with this new generation of larger machines is whether it is total power or power density that is important to confinement.

In addition, the second generation of NBI experiments has indicated that the L-mode is just one alternative. The H- and Z-mode, scoop limiter, and NBI pellet injection discharges have led to energy confinement times that can be at least a factor of two greater than that in the L-mode. Unfortunately, the underlying physics of these modes, as well as their applicability to reactor design, is not known. Expanding on the latter of these two unknowns, the doubling of τ_E in the PDX and ASDEX H-mode, for instance, results in large part from the addition of a pedestal of several hundred eV to the electron temperature profile. Should this be an upper limit to the temperature pedestal, it would be inconsequential at central T_e values of ~ 10 keV. However, a ~ 2 keV pedestal, or a $\Delta T_e(0)$ of 5 keV would have a significant effect on the energy confinement of a test reactor.

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NEUTRAL BEAM HEATED TOKAMAKS

Device	a(cm)	R(cm)	I _p (kA)	B _T	$\bar{n}_e (10^{13} \text{cm}^{-3})$	P _{inj} (MW)	Injection $\angle^*$	Comments
ASDEX	40	165	500	2.8	≤ 7	3.5	58°	Divertor, Limiter
ATC	17	90	80	1.5	≤ 2.5	0.23	near-tangential, near-perpendicular	uncompressed plasma characteristics
CLEO	18	90	80	2.0	≤ 3	0.05	near-tangential	
D-III	37-44	143-147	1000	2.4	≤ 9	~8	27°	Expanded boundary divertor, limiter, $\kappa > 1$
DITE	18-27	110-125	260	2.7	10	1.2	near-tangential	Bundle Divertor, Limiter
ISX-B	25-27	92-95	230	1.5	12	2.5	53°	$\kappa > 1$
JFT-2	28	90	170	1.6	12	2.0	near-tangential	
OPNAK	23	80	175	2.5	≤ 2.5	0.36	near-tangential	
PDX	36-44	140-144	500	2.2	≤ 8	7	14°	Divertor, Limiter
PLT	40	134	600	3.5	≤ 10	2.5	71°	
T-11	13-20	70	~125	1.2	≤ 5	0.6	near-tangential	
TFR	16-20	96-98	400	6.0	13	1.0	~10°	

*From perpendicular at the magnetic axis.

TABLE I

COMPARISON OF TANGENTIAL (PLT) AND NEAR-PERPENDICULAR

(PDX) NEUTRAL BEAM INJECTION RESULTS

	<u>PLT</u>	<u>PDX</u>	<u>PLT</u>	<u>PDX</u>
B_T	3.2	2.2	3.2	2.2
I_P (kA)	475	510	530	480
$\bar{n}_e$ (10^{13}cm^{-3})	2.5	2.4	3.4	2.6
P_{inj} (MW)	1.9	1.7	3.1	3.1
P_{abs} (MW)	1.9	1.4	3.0	2.5
$n_e(o)$ (10^{13}cm^{-3})	5.4	3.5	6.2	3.5
$T_e(o)$ (keV)	2.8	1.7	2.5	1.8
$T_i(o)$ (keV)	5.8	3.1	5.0	4.4
$\Delta T_i(o)$ (keV)	4.6	2.4	3.8	3.6
$\bar{n}_e \Delta T_i(o) / P_{abs}$	6.0	4.1	4.3	3.7
$\tau_E(a)$ (msec)	28	27	34	27
$\tau_{Ee}(z)$ (msec)	18	15	21	14
$e(1a/3)$ (cm^2/sec)	$4 \cdot 10^4$	$5 \cdot 10^4$	$3 \cdot 10^4$	$7 \cdot 10^4$

TABLE II

NUMBER OF DATA POINTS IN NEUTRAL BEAM INJECTION DATABASE

<u>MACHINE</u>	<u># DATA POINTS</u>
ASDEX	32
DITE	205
D-III	212
ISX-B	108
PDX	46
PLT	70
TFR	4

TABLE III

SECOND GENERATION EXPERIMENTS

<u>EXPERIMENT</u>	<u>SCALING</u>	<u>COMMENTS</u>
ASDEX H-MODE	$\tau_E \bar{n}_e^0 I_p P_{tot}^0$	deterioration in τ_E caused by H_α/D_α spikes, large gas feed
PDX H-MODE	$\bar{n}_e^0 I_p P_{tot}^?$	deterioration in τ_E caused by H_α/D_α spikes, large gas feed, fishbones
D-III (GA)	$\bar{n}_e^0 I_p P_{tot}^{-1/3}$	different geometries, parameter scans
D-III (JAERI)	$\bar{n}_e I_p^0 P_{tot}^0$	
PDX (SCOOP)	$\bar{n}_e^0 I_p P_{tot}^{<0}$	insufficient data to estimate coefficients
ISX-B (ungettered, Z-mode)	$\bar{n}_e^{>0} I_p^{>0} P_{tot}^{<0}$	
D-III (P-MODE)	$\bar{n}_e^0 P_{tot}^{<0}$	insufficient data to estimate coefficients

TABLE IV

FIGURE CAPTIONS

- FIG. 1 Output from a O-D, between shots analysis program for a PDX NBI discharge. The energy confinement time, τ_E (lower right) is determined from the measured $I_1/2 + \beta_{pol}$ signal, an assumed current profile, and the total heating power (ohmic and absorbed beam power). Note the sharp drop of τ_E with the onset of NBI ($t = 400$ msec).
- FIG. 2 Temperature profile peakedness $T_e(o)/\langle T_e \rangle$ as a function of q_{cyl} for $B_T = 0.7$ to 2.2 T, $I_p = 200$ to 480 kA, and for OH, two, and four beam discharges.
- FIG. 3 Dependence of energy confinement time on line-averaged density (top panel) taken from a D-III (GA) parameter scan, and on toroidal field taken from an ISX-B, parameter scan (bottom panel).
- FIG. 4 Energy confinement time as a function of plasma current for JAERI (D-III) L-mode discharges taken from Nagami et al. (1984).⁴¹ The curve through the points is the τ_E calculated from the Goldston scaling for the D-III (JAERI) parameters.
- FIG. 5 Experimental energy confinement times, τ_E , EXP, plotted versus the associated Kaye-Goldston scaling values, τ_E^{FIT} [Eq. (3)], for all the data contained in the NBI dataset described in the text. The correlation coefficient for the fit is $R^2 = 0.94$.
- FIG. 6a Same as Fig. 5 for the Goldston scaling [Eq. (2a-c)]. The best fit numerical coefficient for the data is 6.4×10^{-8} , and the correlation coefficient is $R^2 = 0.93$.
- FIG. 6b Same as Fig. 5 for CTF scaling [Eq. (5)]. The best fit numerical coefficient is 8.45×10^{-6} , and the correlation coefficient is $R^2 = 0.94$.

- FIG. 6c Same as Fig. 5 for the Perkins scaling [Eq. (7)]. The best fit numerical coefficient is 4.04×10^{-7} , and the correlation coefficient is $R^2 = 0.92$.
- FIG. 6d Same as Fig. 5 for the Merezhkin-Mukhovatov scaling [Eq. (9)]. The best fit numerical coefficient is 5.01×10^{-5} , and the correlation coefficient is $R^2 = 0.31$.
- FIG. 7 Connor-Taylor-Turner pressure gradient parameter, plotted as a function of shear, for a series of PDX discharges. Cylindrical ζ is used. Each solid line represents the radial profile of one discharge (e.g., values taken every 5 cm from $r = 5$ to 35 cm for $a = 40$ -42 cm PDX discharges. The dashed curve is the ideal ballooning mode instability threshold as determined by CTT⁴³; to the right of the dashed line has the unstable region. The PDX discharges fall well within the stable regime.
- FIG. 8 Divertor configurations for ASDEX, PDX, D-III (GA), and D-III (JAERI). The D-III (GA) configuration is referred to as an expanded boundary (XB) divertor.
- FIG. 9 (Top panel) Electron temperature and density profiles measured by the multipoint Thomson scattering diagnostic on PDX during the pretransition and the H-phase of a divertor discharge. (Bottom panel) Edge electron temperature and density profiles during the H-mode. The points outside $R = 180$ cm were measured by the single-point Thomson scattering system. The shaded region represents the range of possible separatrix locations.
- FIG. 10 D-III (GA) temperature profiles for limiter and expanded boundary (XB) divertor configurations.
- FIG. 11 Portion of a PDX discharge with the appearance and subsequent disappearance of H_α/D_α spikes (edge relaxation phenomena). Associated with the appearance of these spikes is a decrease in the rate of rise of $\bar{n}_e$ and $\langle \beta_T \rangle$, and a drop in τ_E . With the

disappearance of these spikes, the rate of rise of $\bar{n}_e$ and $\langle\beta_T\rangle$, and thus τ_E , recovers.

FIG. 12 (Top panel) Discharge quality factor, defined as τ_E/I_P , as a function of total heating power for ASDEX L- and H-mode discharges. (Middle panel) Discharge quality factor, $\tau_E/(I_P \kappa^{1/2})$, plotted as a function of total heating power for limiter and expanded boundary (XB) D-III (GA) discharges. (Bottom panel) Discharge quality factor, τ_E/I_P , plotted as a function of total power for PDX D^o+ D⁺ divertor discharges. The shaded region is the envelope of τ_E/I_P values for previously measured D^o+ H⁺ limiter discharges without ion loss due to fishbone oscillations. $\kappa = 1.0$ for ASDEX and PDX.

FIG. 13 Global energy confinement time in ISX-B, normalized to a phenomenological scaling law in gettered and nongettered discharges as a function of beam power and plasma density. The confinement time is inferred from equilibrium poloidal magnetic measurements.

FIG. 14 Energy confinement time, τ_E , versus line-averaged density ($\bar{n}_e$) for pellet- and gas-fueled discharges from D-III limiter and divertor configurations. The upper envelope of open circles corresponds to JAERI D-III H-mode discharges. For the gas-fueled discharges, τ_E was calculated during the equilibrium phase of the discharge.

FIG. 15 The quantity $\chi_e T_e^{1/2}$ plotted as a function of n_e (at $r = 0.45a$) for D-III (JAERI) divertor and limiter discharges.

FIG. 16 Results of a regression fit to PDX L-mode χ_e values from $r = a/2$ to $7a/8$. The χ_e values are well modeled by the relation $\chi_e \propto r^{1.65} B_{pol}^{-1.20} n_e^{-0.37}$ ($R^2 = 0.77$).

#84X0068

Figure 1

Figure 3

Figure 4

figure 5

Figure 6

Figure 7

#84X1350

Figure 8

Figure 9

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Figure 10

Figure 11

Figure 12

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Figure 13

#85X0011

Figure 14

Figure 15

Figure 16

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