sor, in *Plasma Physics and Controlled Nuclear Fusion Research 1976* (International Atomic Energy Agency, Vienna, 1977), Vol. II, p. 455; see also B. Coppi, Massachusetts Institute of Technology Plasma Research Report No. PRR-7527, 1975 (unpublished).

[4]F. L. Hinton and R. D. Hazeltine, Rev. Mod. Phys. 48, 239 (1976).

[5]For a general discussion of tokamak transport models, see John T. Hogan, in *Methods of Computational Physics*, edited by John Killeen (Academic, New York, 1976), Vol. 16, pp. 131–164.

[6]Keith H. Burrell, General Atomic Company Report No. GA-A14133, 1976 (to be published); see also Ref. 5, above.

[7]G. R. Hopkins and John M. Rawls, Nucl. Technol. 36, 171 (1977), and references contained therein.

[8]P. H. Rutherford, S. P. Hirshman, R. Jensen, D. E. Post, and F. G. P. Seidl, Princeton Plasma Physics Laboratory Report No. PPPL-1297, 1976 (unpublished).

[9]W. W. Pfeiffer and R. E. Waltz, General Atomic Company Report No. GA-A14727, 1978 (to be published).

[10]M. Murakami *et al.*, following Letter [Phys. Rev. Lett. 42, 655 (1979)].

Plasma Confinement Studies in the ISX-*A* Tokamak

M. Murakami, G. H. Neilson, H. C. Howe, T. C. Jernigan, S. C. Bates, C. E. Bush, R. J. Colchin, J. L. Dunlap, P. H. Edmonds, K. W. Hill,[(a)] R. C. Isler, H. E. Ketterer, P. W. King, D. W. McNeill,[(a)] J. T. Mihalczo, R. V. Neidigh, V. K. Pare, M. J. Saltmarsh, J. B. Wilgen, and B. Zurro[(b)]

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 27 September 1978)

Gross–energy-confinement times (τ_E) in the ISX-*A* (Impurity Study Experiment) tokamak exceeded predictions of the usual empirical scaling relations. We attribute this performance to reductions of impurity radiation and magnetohydrodynamically driven loss channels. The value of τ_E reached a limit as a function of plasma density. We suggest that this limit is due to a transition from electron- to ion-dominated loss regimes. Maximum attainable values of τ_E increased with discharge current, in agreement with this interpretation.

The ISX-*A* (Impurity Study Experiment) tokamak operated with major radius $R = 92$ cm, minor radius $a = 26$ cm, and relatively low toroidal magnetic field $B_T \leq 15$ kG.[1,2] Only Ohmic heating was applied. Studies of plasma confinement in this device yielded unusually favorable results in comparison with empirical scaling formulas. For example, the gross–energy-confinement times, $\tau_E = \frac{3}{2}k[\int(n_eT_e + n_iT_i)dv]/P_{\mathrm{O.H.}}$, exceeded the values expected from the scaling of Jassby *et al.*[3] by factors of 1–3 (1.6 average) and were larger than the values predicted by the Hugill-Sheffield formula[4] [with scaling 1-1] by factors of 1.5–4.5 (3.1 average). At line-average densities ($\bar{n}_e$) above 10^{13} cm^{-3}, the ISX-*A* data are closest to the scaling proposed by Mirnov,[5] $\tau_E = (3\times10^{-9})a(\mathrm{cm}) \times I(\mathrm{A})\bar{n}_e^{1/2}$ sec ($\bar{n}_e$ is given in units of 10^{13} cm^{-3}), although they still exceed the expectations by an average value of 1.2. Also, the maximum value of $\bar{n}_e$ achieved before a major disruption occurred was 7×10^{13} cm^{-3}, a factor almost 4.5 times larger than that anticipated by B_T/R_0 scaling.[6] The largest values of toroidal beta, $\beta_T(0)$ equal to 2.2% at 12 kG, were comparable to the highest published value for Ohmically heated tokamaks (2.1% at 8 kG in Doublet II[7]).

It is believed that these favorable results from the ISX-*A* were realized because of low impurity content and suppression of magnetohydrodynamic (MHD) oscillations. Metals heavier than iron were excluded from the system and values of $\langle Z_{\mathrm{eff}}\rangle$ (mainly from light impurities) less than 2 were usually achieved by discharge cleaning or by titanium gettering. Radiative losses accounted for less than 30% of the Ohmic heating power for these clean discharges, and the amplitudes of MHD oscillations were relatively low ($\tilde{B}_\theta/B_\theta < 0.1\%$ at the plasma edge). The large values of $\bar{n}_e$ were obtained by programming the gas injection[8] to suppress these oscillations almost completely. Reliable feedback control of plasma position and a relatively wide separation of the limiter and vacuum vessel (6 cm) are also believed to have contributed to low levels of impurity content and MHD activity.

Figure 1 shows τ_E as a function of $\bar{n}_e$ for both

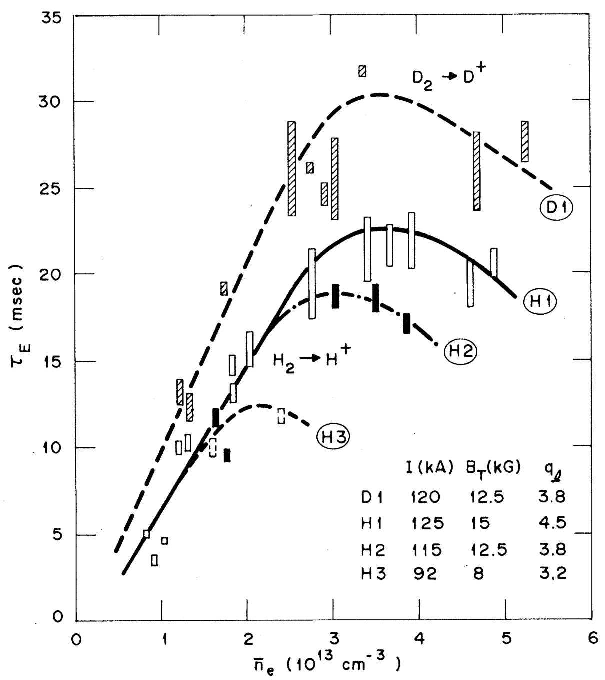

FIG. 1. Gross–energy-confinement time (τ_E) as a function of line-averaged electron density ($\bar{n}_e$) in deuterium and hydrogen discharges. Results are shown for assumed profiles $T_i(r) \sim \bar{n}_e(r)$ (upper bounds) and $T_i(r) \sim T_e(r)$ (lower bounds).

hydrogen and deuterium plasmas. The points were obtained during quasi-steady-state conditions so that the temporal variation of the total energy constitutes a negligible correction to our definition of τ_E. Radial profiles of n_e and T_e required for calculating τ_E were obtained by Thomson scattering. The central ion temperature, $T_i(0)$, was deduced from analysis of the charge-exchanged neutral hydrogen atoms, by assuming that the T_i profile was parabolic. Hydrogenic ion densities were chosen to be consistent with the values of Z_{eff} inferred from the resistivity by assuming oxygen to be the only impurity. The linear rise of τ_E, evident at small values of $\bar{n}_e$, tends to reach a plateau (or to decrease slightly) at large values of $\bar{n}_e$. At given values of $\bar{n}_e$, I, and B_T, values of τ_E are larger in deuterium plasmas than in hydrogen plasmas, as observed in many tokamak experiments.[4]

The usual result of confinement studies has been that $\tau_E \approx \tau_{Ee} \sim \bar{n}_e$ (where τ_{Ee} is the electron energy confinement time),[9,10] but the scaling $\tau_E \sim \bar{n}_e$ clearly fails at larger $\bar{n}_e$ in the ISX–A. In the remainder of this Letter, we concentrate on an explanation for this behavior. We examine the possibility that $\tau_{Ee} \sim \bar{n}_e$ while the failure of τ_E to increase with $\bar{n}_e$ is the result of ion losses.

To calculate τ_{Ee}, defined us

$$\tau_{Ee} = W_e/(P_{\text{O.H.}} - P_{ei} - \dot{W}_e),$$

we first need to calculate P_{ei} (the power transferred to the ions by collisions). We do so by computing a one-dimensional ion power balance which uses measured electron parameters [$n_e(r)$, $T_e(r)$, and Z_{eff}] along with the classical electron-ion energy-transfer rate. The charge-exchange rate and convection loss are estimated from a neutral-transport model for which the neutral density level is given by the measured charge-exchange flux. We adjust the ion thermal conductivity (χ_i) such that the resulting $T_i(0)$ brackets measured values from the deuterium density scan, which is summarized in Fig. 2. As shown in Fig. 3, this bracketing occurs with χ_i equal to 1 and 2 times the neoclassical value[11] ($\chi_{i\text{NC}}$).

We then calculate τ_{Ee} by using the volume-integrated electron-energy (W_e), Ohmic heating power ($P_{\text{O.H.}}$), and electron-ion heat transfer (P_{ei}) based on the theoretically calculated ion temperature profile. The integrations are carried out for $0 \leq r \leq 2a/3$ because this volume contains 80% of the stored energy and is dominated by heat conduction, since it excludes most of the radiation, convection, and charge-exchange losses. As shown in Fig. 4, $\tau_{Ee}(\bar{n}_e)$ rises more slowly than $\tau_E \sim \bar{n}_e$ for $\chi_i = \chi_{i\text{NC}}$ but improves faster than $\tau_{Ee} \sim \bar{n}_e$ for $\chi_i = 2\chi_{i\text{NC}}$. An experimental scaling $\tau_{Ee} \sim \bar{n}_e$ is suggested since the $T_i(0)$ data in Fig. 3 are best fitted with $\chi_{i\text{NC}} < \chi_i < 2\chi_{i\text{NC}}$. The limit on $\tau_E(\bar{n}_e)$ is then understood to result from an increase of the ion conductivity as a function of density ($\chi_{i\text{NC}} \sim \bar{n}_e$).

The conclusion is reinforced by examining the maximum value of $\tau_E(\bar{n}_e)$ obtained in density scans with different values of discharge current (I). The maximum confinement time achievable at a given current should scale as $\tau_E^{\max} \sim I$, nearly independent of the toroidal field, if the electron confinement improves with density ($\tau_{Ee} \sim \bar{n}_e$) and the limit of τ_E is due to ion conductivity (which follows primarily collisional scaling with some plateau enhancement). In Fig. 1, we observe such a dependence in the three hydrogen sequences, and the results of several more experiments showing an approximately linear dependence are given in Fig. 5.

Recently Waltz and Guest have reached the same conclusion as ours, based on a transport simulation of these ISX–A data by assuming *a priori*

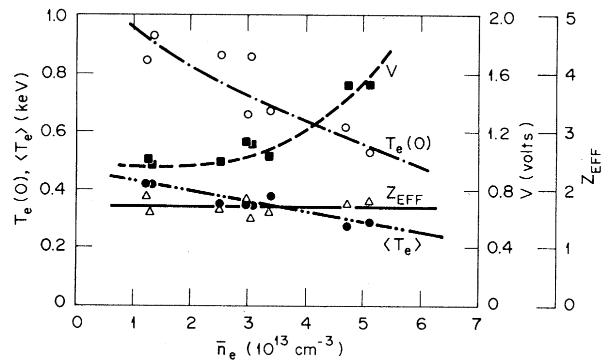

FIG. 2. Variation of plasma parameters with $\bar{n}_e$ for deuterium discharges. Data are from laser-profiled sequences at 110 and 130 msec.

that the anomalous electron heat conductivity χ_e is inversely proportional to density.[12] Furthermore, recent results from the Alcator takomak[10,13] indicate that the central energy-confinement time, τ_{E0}, increases less than linearly as a function of

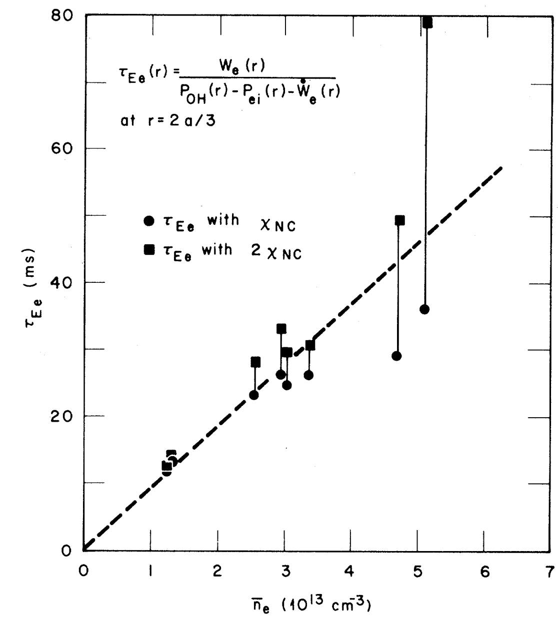

FIG. 4. Electron energy confinement time (τ_{Ee}) within radius $2a/3$ as a function of $\bar{n}_e$ for deuterium discharges.

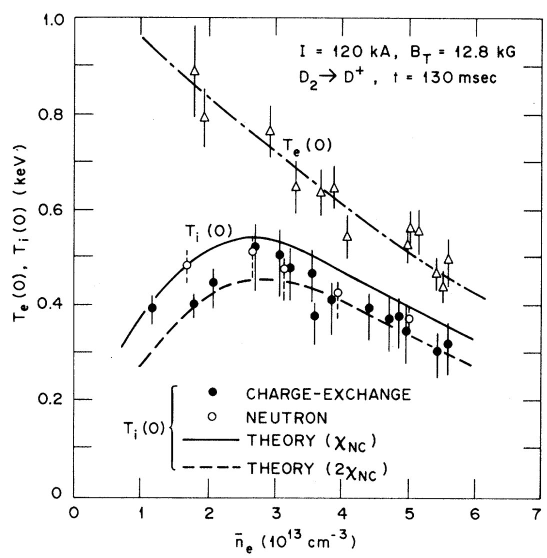

FIG. 3. Central electron temperatures from Thomson scattering and a comparison of measured central ion temperatures with the theoretical values calculated using 1 and 2 times neoclassical ion heat conduction. The 130-msec data set of Fig. 2 is augmented by some nonprofiled sequences. The charge-exchange–derived values of $T_i(0)$ are those which produced the best fit between measured spectra and spectra calculated from assumed T_i profile shape functions, usually parabolic. Sensitivity to the choice of the shape function is reflected as uncertainty in the inferred $T_i(0)$. The uncertainty is larger at higher $\bar{n}_e$ because the plasma is becoming opaque to neutrals.

$n_e(0)$ at high densities even though τ_E appears to increase linearly with $\bar{n}_e$ over a wide range of electron concentrations. This result has also been interpreted as a transition from electron-dominated to ion-dominated confinement.

The fact that we have been able to observe a limit to τ_E occurring at relatively low electron concentrations is due primarily to two aspects of

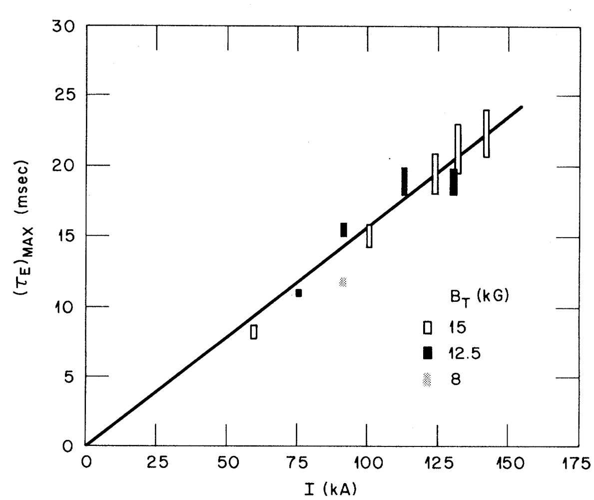

FIG. 5. Maximum gross–energy-confinement time as a function of current in hydrogen discharges with three different toroidal field values.

the operation of the machine: (1) Low impurity and MHD levels produced very favorable electron confinement so that τ_{Ee} increased strongly as a function of $\bar{n}_e$ (Fig. 3). (2) At the low Ohmic-heating currents and toroidal fields which were employed, ion heat conduction could become large enough at some value of $\bar{n}_e$ to dominate the energy losses. In ISX-*B*, a modification of ISX-*A* that adds neutral-injection heating, improvements in gross confinement at high $\bar{n}_e$ should result from supplementary heating of the ions, which will reduce the ion heat conduction by raising the ion temperature.

We thank our many colleagues within the Tokamak Experimental and Plasma Theory Sections, and K. H. Burrell, J. C. DeBoo, and E. S. Ensberg of the General Atomic Company for their contributions to this work. We are grateful for the support given by L. A. Berry, O. B. Morgan, Jr., T. Ohkawa, and J. Sheffield. The research was sponsored by the Division of Magnetic Confinement Systems, U. S. Department of Energy, under Contract No. W-7405-eng-26 with the Union Carbide Corporation.

[(a)]Current address: Princeton Plasma Physics Laboratory, Princeton, N. J. 08540.

[(b)]Permanent address: Junta de Energía Nuclear, Madrid, Spain.

[1]R. J. Colchin and T. C. Jernigan, J. Nucl. Mater. 63, 83 (1976).

[2]M. Murakami *et al.*, in Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978 (International Atomic Energy Agency, Vienna, to be published), Paper IAEA-CN-37-N-4.

[3]D. L. Jassby *et al.*, Nucl. Fusion 16, 1045 (1976).

[4]J. Hugill and J. Sheffield, Nucl. Fusion 18, 15 (1978).

[5]S. V. Mirnov, in Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978 (International Atomic Energy Agency, Vienna, to be published), Paper IAEA-CN-37 F-1-2.

[6]M. Murakami, J. D. Callen, and L. A. Berry, Nucl. Fusion 16, 347 (1976).

[7]T. H. Jensen *et al.*, Phys. Rev. Lett. 34, 257 (1975).

[8]K. H. Burrell *et al.*, General Atomic Company Report No. GA-A14918 (to be published).

[9]L. A. Berry *et al.*, in *Proceedings of the Sixth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, West Germany, 1976* (International Atomic Energy Agency, Vienna, 1977), Vol. 1, p. 46.

[10]M. Gaudreau *et al.*, Phys. Rev. Lett. 39, 1266 (1977).

[11]F. L. Hinton and R. D. Hazeltine, Rev. Mod. Phys. 48, 239 (1976).

[12]R. E. Waltz and G. E. Guest, preceding Letter [Phys. Rev. Lett. 42, 651 (1979).

[13]A. Gondhalekar *et al.*, in Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978 (International Atomic Energy Agency, Vienna, to be published), Paper IAEA-CN-37-C-4.