[1]D. R. Baker, Phys. Rev. Lett. 28, 1189 (1972).

[2]A. G. Borisenko and G. S. Kirichenko, Pis'ma Zh. Eksp. Teor. Fiz. 16, 349 (1972) [JETP Lett. 16, 247 (1972)].

[3]R. J. Taylor and F. V. Coroniti, Phys. Rev. Lett. 29, 34 (1972).

[4]R. J. Taylor, D. Baker, and H. Ikezi, Phys. Rev. Lett. 24, 206 (1970); C. N. Judice, J. F. Decker, and R. A. Stern, Phys. Rev. Lett. 30, 267 (1973).

[5]In this example an 11-eV beam with velocity spread $v_b \sim 0.035u$ and containing about 30% of the ions, $v_i < v_b$ and $v_e \sim 10^2 u$.

[6]Confirmed by time-sampled energy analysis of the beam.

[7]Independently confirmed by applying the modulation in short coherent bursts. A Langmuir probe at $x$ then picks up *two* bursts delayed in time by $\Delta t = x(k_a - k_b)/\omega$.

[8]R. J. Briggs, *Electron-Stream Interactions with Plasmas* (Massachusetts Institute of Technology Press, Cambridge, Mass., 1964),

[9]Our system is linearly stable and does not support the ion-acoustic mode, excluding theoretically predicted nonlinear instabilities such as discussed by R. E. Aamodt and M. L. Sloan, Phys. Rev. Lett. 19, 1227 (1967); C. T. Dum and E. Ott, Plasma Phys. 13, 177 (1971); P. Martin and B. D. Fried, Phys. Fluids 15, 2275 (1972).

[10]A low-level turbulent noise continuum peaked near $\frac{1}{3}\omega_{pi}$ (as a result of unstable, off-axis beam modes) is produced by the unmodulated beam (Ref. 3).

[11]The subharmonic wave numbers lie on the slow-beam dispersion curve, Fig. 1(c).

[12]Near threshold, the spectrum of subharmonic oscillations contains an appreciable fraction of broad-band, uncorrelated fluctuations at $\lessgtr \omega/2$, as shown in Figs. 2(d) and 2(e). This is *not* sensed by the monochromatic, coherent detection scheme used to produce Fig. 3. The broad-band spectrum (Fig. 2) has a smooth onset originating in the large-amplitude pump region and grows monotonically with pump power, as expected. At large $\Lambda$ the subharmonic amplitude can be locally larger than the pump mode: This is compatible with Manley-Rowe relations in cases where the pump depletes [cf. R. Z. Sagdeev and A. A. Galeev, *Nonlinear Plasma Theory* (Benjamin, New York, 1969), pp. 16–20].

[13]R. C. Davidson, *Methods in Nonlinear Plasma Theory* (Academic, New York, 1972).

[14]Retaining only lowest-order terms, and for finite values of $\eta$ only, with $k' = \vec{k}\cdot\vec{u}/|\vec{u}|$.

[15]Anti-Stokes ($\frac{3}{2}f_0$) as well as higher-order decay ($\frac{1}{4}f_0$ and $\frac{3}{4}f_0$) radiation have been observed. Typically, an anti-Stokes line emerges from noise at $\Lambda \gtrsim 1.1$, growing to 5% of the subharmonic amplitude at $\Lambda \approx 1.2$.

# Ion Energy Containment in the Oak Ridge Tokamak

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The ORMAK (Oak Ridge tokamak) experiment gives the first extensive measurement of ion transport in a collisionless plasma. We find a transition from neutral domination to a thermal-conduction limit as the ratio of central electron density to central neutral density varies by an order of magnitude. The results agree with neoclassical predictions of ion thermal transport throughout the whole range.

In presently operating tokamaks the ions are heated by collisions with Ohmically heated electrons except at low particle densities when anomalous heating has been observed.[1] The ion temperature attained is the result of a balance between this heat input and the loss processes of charge exchange, particle diffusion (convection), and ion heat conductivity.

Of these loss processes the first two depend on the neutral-particle density within the plasma during the equilibrium stage of the discharge. Since this neutral density decreases with increasing plasma size and density, the ion energy loss in some regimes of present experiments, and in the larger experiments under construction, will be dominated by the ion heat conductivity. However, in order to determine the magnitude and scaling of this heat conductivity from present-day experiments careful account must be taken of the large competing loss processes dependent on the neutral density. As will be seen below, these competing processes depend on the plasma quality defined as the ratio of central electron density to central neutral density $N_e/N_0$. With high plasma quality, ion heat conductivity is the dominant loss process even in present-day experiments. Artsimovich[1] used this fact to determine the scaling of this energy loss. He equated the energy input to the ions from electron-ion collisions to the heat conduction loss as predicted by the best theory available at the time, the neoclassical plateau theory of Galeev and Sagdeev.[2] He then obtained a scaling of ion temperature,

$$T_i \propto (IB_tR^2N_e)^{1/3},$$

where $I$ is the plasma current, $B_t$ is the toroidal field, $R$ is the toroidal radius, and $N_e$ is the electron density. This scaling provides a reasonable fit to the data in Artsimovitch's experiments and also to the data from the ORMAK experiment and the statement has been made that therefore ion heat conductivity agrees with neoclassical theory. However, there are two difficulties with this statement. First, the neoclassical plateau theory of Galeev and Sagdeev has been replaced by a more accurate calculation by Hinton and Rosenbluth[3] which predicts an ion heat conductivity about a factor of 5 smaller than the earlier value in the range of interest. Second, some of the ORMAK data (and presumably Artsimovitch's data) which are fitted by the Artsimovich scaling were taken in the presence of high neutral density when charge exchange and diffusion are expected to play a large role in the ion losses. Since these losses are not included in the Artsimovich scaling and since this scaling is based on an inaccurate theory, the agreement of the data with this scaling is at first puzzling. The resolution of the puzzle can be found by noting that the electron density is empirically found to be proportional to the plasma current. This follows from the fact that electron particle losses decrease with increased current. This will be discussed elsewhere. For our present purposes taking $N_e \propto I$ in the Artsimovich scaling gives $T_i \propto I^{0.66}$ and, as we shall show, this is just the variation of ion temperature with current predicted by the more correct scaling based on a correct neoclassical theory including charge exchange and diffusion described in this paper. In this sense the Artsimovich scaling of the experimental data does in fact reflect neoclassical scaling. In the rest of this Letter we will present a more detailed picture of this agreement.

*Neutrals.*—Figure 1 shows the central neutral density in the ORMAK[4] experiment, obtained from an absolutely calibrated neutral spectrometer,[5] as a function of the mean plasma electron density measured with a 2-mm microwave interferometer. The data shown were taken with plasma currents ranging from 60 to 160 kA at a toroidal field of 18 kG.

The dependence of the neutral density on the electron density can be explained by a model de-

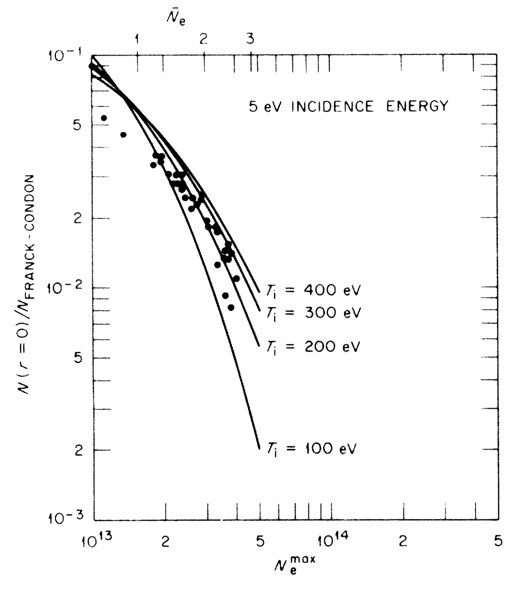


FIG. 1. Ratio of central neutral density to incident neutral density versus electron density. The data points shown represent absolute neutral densities ranging from $2\times10^8$ to $2\times10^9$ cm$^{-3}$.

scribing the neutral transport in the plasma. We assume that neutrals are incident on the plasma surface with energies such that their mean free path for ionization and charge exchange is less than one-third the plasma radius. For ORMAK this implies energies less than 100 eV. One obvious source of such neutrals is the dissociative ionization of $H_2$ molecules producing the so-called Franck-Condon neutrals with energies in the range of 1 to 10 eV. We note that our results are insensitive to the energy of these primary neutrals since the above condition is satisfied. These warm neutrals, with a density $N_{FC}$, are severely attenuated by ionization and charge exchange within a few centimenters of the plasma surface. The secondary neutrals formed by the charge exchange process in this surface layer have energies characteristic of the plasma ions and hence a longer mean free path than the primary neutrals. There results a continuous cascade toward higher neutral energy which produces the significant neutral densities seen on axis away from the limiter in all tokamaks. The neutrals have mean energies typically $\frac{1}{6}-\frac{1}{3}$ of the ion energy in the center of the plasma. The appropriate transport equation has been solved numerically to give the theoretical curves in Fig. 1. This calculation accounts for spatial variation of plasma properties and predicts the velocity-space distribution function of the neutrals and the outward-directed flux of charge-exchange particles as well as the central neutral density. The outward-directed flux is measured by the neutral-particle spectrometer to give the actual distribution of energetic neutrals for comparison with our model.

The central ion temperature is determined by calculating the slope of the measured neutral energy spectrum. The central neutral density is obtained by matching the measured neutral flux in each energy channel with the flux predicted by our model using the independent measurement of the electron density and temperature profile obtained by laser Thomson scattering and microwave interferometry.

There is some uncertainty in the spatial ion temperature profile, therefore the theoretical curves are calculated under the assumption of a parabolic profile which closely approximates the predictions of our plasma simulation calculations.[6] Since, in the model, a relatively larger ion temperature near the boundary will enhance the cascade process, the scatter in Fig. 1 may well be a result of deviations from the assumed profile, especially at high currents. Nonetheless the agreement is quite good. Central ion temperatures are found to be in the range 150–370 eV, and the points lie within the bounds provided by theory.

The theoretical calculation gives the ratio of central neutral density to the density of incoming warm neutrals. While there is no independent measurement of this external density, we find that the assumption of a linear dependence in initial filling pressures, $N = (3.5\times10^{13}\ \text{Torr}^{-1}\ \text{cm}^{-3})P_0$, produces good statistical agreement over the pressure range $7.3\times10^{-4}$ to $1.2\times10^{-3}$ Torr. The ratio of theoretically predicted spectrometer counting rates to measured counting rates has a standard deviation from 1 of 10%.

*Ion Energy Balance.*—As Artsimovich has noted,[7] the energy input to the ions is very nearly independent of the electron temperature for the measured ratios of $T_e/T_i$. Thus, we have $Q_{ei} = Kn_e^2/\sqrt{T_i}$. This energy input must be balanced by the ion loss processes. The ion energy balance is dominated at low plasma density by charge exchange and convection and at high density by thermal conduction.

Since the ions flow out of the core of the discharge there is a separate question to be considered regarding the physical origin of the ion convection loss and this will be addressed elsewhere. For our discussion of the ion energy balance, we need only know that the convection ion energy loss is simply the product of flow rate and ion energy. Since the flow rate must equal the birth rate of particles, we have

$$Q_{\text{conv}} \propto N_0 N_e \langle\sigma v\rangle_{\text{ion}} T_i.$$

The thermal conduction loss is given by the neoclassical calculation of Hinton and Rosenbluth.[3] This calculation is valid in the so-called "banana-plateau" regime of our experiment. The conduction loss is

$$Q_{\text{cond}} \propto \frac{1}{r}\frac{1}{dr}\left(rK_iN_i\frac{dT_i}{dr}\right)$$

with $K_i = \hat{\rho}_i^2\nu_{ii}f(\nu_i^*)\sqrt{\epsilon}$. $\hat{\rho}_i$ is the ion poloidal gyroradius, $\nu_{ii}$ the ion-ion collision frequency, $\epsilon \equiv r/R$ with $r$ the minor and $R$ the major radius, $\nu_i^*$ is the ratio of ion-ion effective collision frequency to ion bounce frequency, and $f(\nu_i^*)$ is a function describing the continuous transition from the banana regime (where all ions are collisionless) to the plateau regime (where only the toroidally circulating ions are collisionless).

Equating each of these loss processes in turn to the ion energy input gives limiting ion temperatures which would result if that process were the only one occurring. To demonstrate the transition from neutral domination to classical transport, we chose $x \equiv (N_e/N_0)^{1/2}$ as the plasma quality variable. The value of $T_i$ assuming only charge-exchange loss is linear in $x$, the convection-limited $T_i \propto x^{4/3}$, and the conduction limit which is independent of $x$ gives a horizontal asymptote. The conduction limit depends strongly on the current and collisionality of the plasma which is determined by the parameter $\nu_i^*$. This parameter can be written as

$$\nu_i^* \propto \frac{Z_{\text{eff}}}{M_i}\left(\frac{rB_T}{B_p}\right)\frac{N_e}{T_i^2}\left(\frac{R_0}{r}\right)^{3/2},$$

where $B_T$ is the toroidal field, $B_p$ the poloidal field, and $R_0$ and $r$ the major and minor radii of the plasma, respectively. Clearly the effective charge due to impurity ions $Z_{\text{eff}}$ and the radius in the plasma at which $\nu_i^*$ is evaluated will determine its exact value. The ion temperature and density have only a small variation for a given plasma current. Therefore we will evaluate $\nu_i^*$ for each plasma current by using the mean value of density and ion temperature for that current at $\frac{1}{2}$ of the limiter radius. The exact value of $Z_{\text{eff}}$ is uncertain. Soft-x-ray brems-

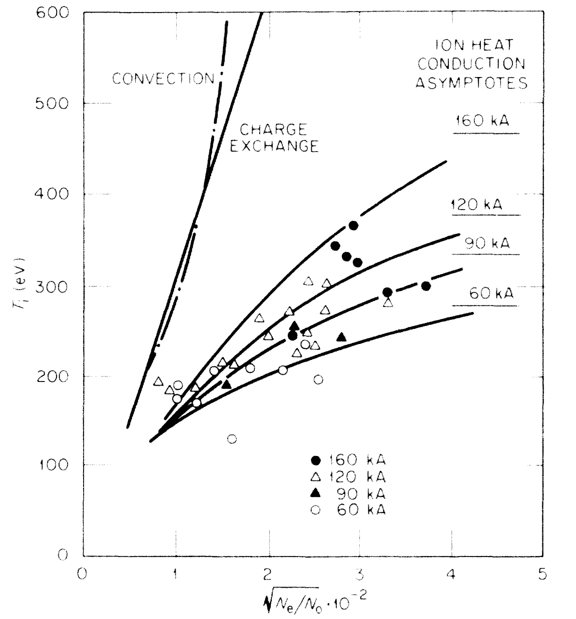


FIG. 2. Ion energy balance: $T_i$ as a function of the ratio of central electron density to central neutral density.

strahlung measurements put a rough limit of $Z < 3$ and our computer simulations of the total plasma behavior give good fits with $Z \sim 3$. We choose $Z_{eff} = 3$. If $Z_{eff}$ remains constant with plasma current, our scaling will not be affected by this assumption. It is quite possible that some of the scatter of our experimental points is due to $Z_{eff}$ variation. We calculate $\bar{\nu}_i^* = 10.6$, 4.7, 2.4, and 0.5 for the cases of $I = 60$, 90, 120, and 160 kA, respectively. The ion heat-conduction asymptotes shown in Fig. 2 indicate the ion temperature which would be attained at this collisionality in the absence of neutral particles. From these asymptotes one finds that the current dependence of $T_i$ due to the neoclassical ion heat conductivity is $T_i \propto I^{0.6}$. This dependence is also apparent in computer simulations of tokamak plasmas and is the dependence revealed by the Artsimovich scaling. The solid curves running through the data points show the predicted ion temperatures when all three loss processes act simultaneously.

We find good general agreement, but note a tendency toward lower ion temperatures at the highest values of $N_e/N_0$ for each current. This may reflect the additional loss produced by the lack of magnetohydrodynamic (MHD) stability seen in tokamak plasmas as the density is raised at a fixed current.[1] The data indicate that when the current is increased at a fixed value of $x$ and MHD stability is regained, the ion temperatures once again agree with theory.

*Conclusions.*—Transport theory predicts a smooth transition from plateau to collisionless losses in tokamak plasmas. Effects of neutral atoms in the plasma are predicted to decrease as the plasma quality $x$ is improved. We observe both effects and see ion thermal transport scaling consistent with neoclassical predictions when the plasma is MHD stable. Further experiments are necessary to determine if this agreement persists for the values of collisionality ($\nu_i^* \leq 0.1$) needed for reactor operation.

Results obtained on large experiments are always the product of the dedicated efforts of many people. The members of the ORMAK group are too numerous to mention individually but thanks are due them all. We also want to acknowledge the contributions of C. F. Barnett and J. A. Ray of the Atomic and Molecular Physics Group who not only developed the charge-exchange analyzer but made it work on the experiment.

[1]L. A. Artsimovich, Nucl. Fusion 12, 215 (1972).
[2]A. A. Galeev and R. Z. Sagdeev, Dokl. Akad. Nauk SSSR 189, 1204 (1969) [Sov. Phys. Dokl. 14, 1198 (1970)].
[3]F. L. Hinton and M. N. Rosenbluth, Phys. Fluids 16, 836 (1973).
[4]C. F. Barnett *et al.*, in *Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971* (International Atomic Energy Agency, Vienna, Austria, 1972), Vol. 1.
[5]C. F. Barnett and J. A. Ray, Nucl. Fusion 12, 65 (1972).
[6]G. G. Kelley *et al.*, in Proceedings of the Third International Symposium on Toroidal Plasma Confinement, Garching, Germany, 26–30 March 1973 (to be published).
[7]L. A. Artsimovich *et al.*, in *Proceedings of the Fourth European Conference on Controlled Fusion and Plasma Physics* (Comitato Nazionale per l'Energia Nucleare, Ufficio Edizioni Scientifiche, Roma, Italy, 1970).