STATUS OF THE ORMAK EXPERIMENT

G. G. Kelley, L. A. Berry, J. F. Clarke, R. J. Colchin, P. H. Edmonds, J. R.

McNally, M. Murakami, R. V. Neidigh, M. Roberts, and W. R. Wing

OAK RIDGE NATIONAL LABORATORY*

Oak Ridge Tennessee USA

This paper describes the results from the ORMAK experiment. Particular emphasis is placed on loss processes. We conclude that 1) the ion plasma is significantly collisionless. The effective collision frequency (neglecting impurities implies an ion energy diffusion loss rate (Hinton and Rosenbluth¹) of about a factor of six less than the value predicted by Artsimovich scaling² which assumes plateau regime behavior. 2) The actual ion energy containment times are only slightly longer than predicted from Artsimovich scaling but there is strong evidence that the dominant ion energy loss mechanism is by charge exchange and the diffusion loss may well be neo-classical. 3) Electron energy loss is ultimately by charge transfer to the ion and by radiation.

The data on which these conclusions are based are presented and there will be a brief discussion of the future plans which include heating by energetic neutral particle injection now being installed and a modification of coil structure which is around operation at 50 kG.

I. Introduction ORMAK is the Oak Ridge Tokamak experiment. It is a relatively fat torus with physical characteristics given in Fig. 1. Cryogenically cooled coils are an essential feature of the design. Also shown in Fig. 1 are some typical plasma parameters.

ORMAK has operated almost continuously since June of last year. There have been a total of about 3500 experimental shots. At the time of this meeting the device is being shut down for installation of two of four energetic neutral particle

*Operated by Union Carbide Corporation for the US AEC.

injectors which are expected to double the present power input from ohmic heating.

This paper will describe the results from our experiments with particular emphasis on loss processes. Briefly we conclude that

- 1) The ion plasma is significantly collisionless. The effective collision frequency (neglecting impurities) implies an ion energy diffusion loss rate³ of about a factor of six less than the value predicted by Artsimovich scaling,⁴ which assumes plateau regime behavior.
- 2) The actual ion energy containment times are only slightly longer than predicted from Artsimovich scaling, but we have strong evidence that the dominant ion energy loss mechanism is by charge exchange and the diffusion loss may well be neo-classical.
- 3) Electron energy loss is ultimately by energy transfer to the ions and by radiation.

In the body of the paper we will describe first the data on which these conclusions are based and then we will discuss briefly our future plans including a brief statement of the plasma parameters expected from neutral particle injection and from a modification of coil structure which should allow operation at 50 kG.

II. Results Ion temperatures are measured by means of a seven-channel neutral particle charge exchange analyzer developed by Clarence Barnett. This analyzer, in conjunction with a small computer, permits time-resolved ion temperature measurements in typically 10 msec increments. Spectroscopic measurements confirm these measurements in hydrogen and give somewhat higher values in helium where charge exchange does not occur. The particles measured were emitted in the mid-plane along a line perpendicular to the major axis of the torus and at an angle of 30° in azimuth from the position of the limiter. Figure 2 shows the temperature as a function of time at a fixed current along with other parameters of the discharge. The neutral density inferred from these neutral particle measurements is quite a bit greater

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

IV
it ~~was~~ ^{you might think} ~~was~~ ^{most} ~~great everywhere~~, the ion ~~temperature~~ ^{energy loss is by charge exchange} would be much lower than is observed. We decided to use for computation the model proposed by the ST group in which relatively energetic neutral particles (~ 30 eV at typical ion temperature and proportional to ion temperature) are re-emitted from the limiter causing a local high density region. ^{Computer simulation} Calculations were made using the code developed at Oak Ridge by Widener and Dory and further developed by John Hogan. In Hogan's code the atomic processes are taken into account in detail with the simplifying assumption of slab geometry. These calculations using the model just described ~~predicted a mean neutral density in the plasma of about 10^9 particles/cm³~~ ^{energy by charge exchange} and imply ion loss rates, which account for about 80% of the total ion loss. The computer calculations also predict the observed ~~behavior~~ ^{decrease} of electron density with time. ^{See Figure 2 & Insert A} These measurements will be discussed in more detail below. ^{What must I say about density?}

The ion temperatures observed imply a relatively high degree of collisionlessness in the ORMAK device due to its low aspect ratio. Figure 5 shows a comparison of the ~~effective collision frequency ν^*~~ ^(the ratio of collision frequency to trapped collisional parameter) in various devices. It is seen that ORMAK and the compressed ATC plasma ^{assuming similar magnetic content in all plasmas ($\nu^* \sim 0.1$ to 10 in various devices)} have the lowest value of ν^* (~ 0.4). At this value of ν^* the neoclassically expected energy diffusion coefficient is about $1/6$ of the plateau value. In a typical computer calculation using Hogan's code 20% of the energy deep in the plasma is lost by this means. If charge exchange losses were not present and if all losses were by diffusion, a

... ⁱⁿ than we had expected, and if ^{of the ion energy loss is by charge exchange} ~~were this great everywhere, the ion temperature would be much lower~~ ^{is observed.} We decided to use for computation ~~the model proposed~~
~~the ST group in which relatively energetic neutral particles~~
~~30 eV at typical ion temperature and proportional to ion temperature)~~
~~re-emitted from the limiter causing a local high density region,~~
calculations were made using the code developed at Oak Ridge by Widener
Dory and further developed by John Hogan. In Hogan's code the
mic processes are taken into account in detail with the simplifying
assumption of slab geometry. These calculations using ~~the model just~~
~~described predicted a mean neutral density in the plasma of about 10^{20}~~ ^{by charge exchange} ~~particles/cm³~~ and imply ion loss rates, which account for about 80%
of the total ion loss. The computer calculations also predict the ob-
served ^{decrease} behavior of electron density with time. ^{See Figure 2 * Insert A} These measurements will
be discussed in more detail below. ^{What must be said about density}

The ion temperatures observed imply a relatively high degree of
ionizationlessness in the ORMAK device due to its low aspect ratio.
Figure 5 shows a comparison of the ^(the ratio of collision frequency to trapped particle frequency) effective collision frequency ν^* in
various devices. It is seen that ORMAK and the compressed ATC plasma
have the lowest value of ν^* ^{assuming similar magnetic confinement in all plasmas ($\nu^* = 0.4$ to 1.0)} ~~($\nu^* = 0.4$)~~. At this value of ν^* the neo-
classically expected energy diffusion coefficient is about $1/6$ of the
Spitzer value. In a typical computer calculation using Hogan's code
of the energy deep in the plasma is lost by this means. If charge
exchange losses were not present and if all losses were by diffusion, a

-11-

diffusion coefficient just slightly smaller than the plateau value would be inferred. We conclude that all ion losses are accounted for by classical effects, i.e., principally by charge exchange, and that in spite of the small value of v^* and of the large toroidal curvature, anomalous losses have appeared.

A new viewpoint into the ultimate loss processes is being provided by experiments using a movable probe.
~~There is further evidence that the loss of energy through the ion channel is at least ultimately by charge exchange.~~ Measurements were made of the floating potential^{of} and energy flux to a tungsten probe inserted beyond the shadow of the limiter in the equatorial plane. Measurements were made also of the total heat flux to the thin stainless steel liner at a point far from the limiter. These measurements implied

- 1) that the electron temperature at large radius in the plasma (but inside the limiter radius) was no more than a few eV; 2) the heat flux to the limiter inferred from the heat flux to the probe is approximately 3 kJ assuming that the flux is uniform around the circumference of the limiter and extends over its full radial depth; 3) *The charge exchange flux observed at a point close to the limiter did not change in spite of the flux were uniform and had the value measured at a point 120 degrees azimuth from the limiter, about 8 kJ would be accounted for.* 4) *The was inserted 4 cm beyond the limiter shadow. We infer that the total energy to be accounted for in a typical case is about 45 kJ. This over the function of the limiter but that the average neutral density this energy does not go to the limiter and is not a uniform flux to the liner, it must occur locally.* If one calculates the particle flux to the limiter and assumes that these particles are re-emitted and can penetrate deeply into the plasma, the resulting energy flux from charge exchange is compatible with the calculations of Hogan. 5) A further conclusion from these measurements is that the ultimate electron loss mechanism is by radiation, since ^{the inferred rate of} particle diffusion would be expected to be uniform over the surface of the liner and since the electrons at the limiter ^{transport} ~~are too cold to transfer~~ ^{very little} ~~a significant amount of~~ energy to the limiter by direct bombardment.

diffusion coefficient just slightly smaller than the plateau value would be inferred. We conclude that all ion losses are accounted for by classical effects, i.e., principally by charge exchange, and that in spite of the small value of v^* and of the large toroidal curvature, no anomalous losses have appeared.

~~A mechanism is being~~ There is further evidence that the loss of energy through the ion channel is at least ultimately by charge exchange. Measurements were made of the floating potential^{of} and energy flux to a tungsten probe inserted beyond the shadow of the limiter in the equatorial plane. Measurements were made also of the total heat flux to the thin stainless steel liner at a point far from the limiter. These measurements implied that the electron temperature at large radius in the plasma (but outside the limiter radius) was no more than a few eV; 2) the heat flux to the limiter inferred from the heat flux to the probe is approximately 8 kJ assuming that the flux is uniform around the circumference of the limiter and extends over its full radial depth; 3) ~~if heat flux to the~~ ^{3) The charge exchange neutral} flux observed at a point close to the limiter did not change in spite of the fact that the flux from the region was decreased by a factor of 6 when the probe was inserted 4 cm beyond the limiter shadow. We infer that the probe energy to be accounted for in a typical case is about 45 kJ. Since the energy does not go to the limiter and is not a uniform flux to the liner, it must occur locally. If one calculates the particle flux to the plasma is not changed.

limiter and assumes that these particles are re-emitted and can penetrate deeply into the plasma, the resulting energy flux from charge exchange is compatible with the calculations of Hogan. 4) A further conclusion from these measurements is that the ultimate electron loss mechanism is by radiation, since particle diffusion would be expected to be uniform over the surface of the liner and since the electrons at the limiter are too cold to transfer a significant amount of energy to the limiter by direct bombardment.

Ion temperatures also are measured spectroscopically. The neutral temperature evaluations are supported by Doppler spectroscopic data, except for radiating hydrogen atoms which are frequently a factor of two ^{cooler} lower than neutral particle spectrometer data. Hydrogen atoms formed by a charge exchange capture give a Doppler temperature 100-200 eV using either λ 6563 Å (H_{α}) or λ 4861 Å (H_{β}). Helium discharges show He^{+} ions to a Doppler temperature of 200 eV, but sometimes rising to 600 eV in the plasma decay, based on the λ 4686 Å line. Carbon and oxygen impurity lines in hydrogen discharges give about 200 eV from C^{2+} (λ 4647 Å) and from O^{4+} the latter ion showing ions of about 500 eV temperature during plasma decay. The unusually high ion temperatures observed during plasma decay at $t > 5$ msec suggests that ions in the core may be quite hot since recombination spectra would be expected to dominate the plasma decay period. Rotational velocities of the plasma have been measured both in the poloidal and toroidal directions. The Doppler shift of an H_{α} (6563 line, at a minor radius > 10 cm, was used. It was found that the rotation is poloidal during the early and late phases when the ions are cold, and becomes toroidal as ions are heated. Both peak velocities are roughly 5×10^6 cm/sec. Both the magnitude and direction of rotation are correlated with magnetic probe fluctuations. This result supports the interpretation that the stripped ions at $r < 10$ cm are collisionless, since the theory predicts an absence of poloidal rotation in this case.

Electron temperatures are measured in three ways: by Thomson scattering using a ^{Q switched} 10 Joule ruby laser, by ^{direct} Bremsstrahlung spectrum measurement, and by a two-absorber measurement of the Bremsstrahlung spectrum. The principal tool is the laser. It permits a 3 point radial profile to be gotten ^{at 100 ns} 4 points in time and at 3 radial positions. The electron temperature profiles at several values of discharge current are shown in the next figure. For comparison, profiles are shown also for several other tokamaks. The rather peaked profile at 150 kA was obtained in

Ion temperatures also are measured spectroscopically. The neutral temperature evaluations are supported by Doppler spectroscopic data, except for radiating hydrogen atoms which are frequently a factor of two or more than neutral particle spectrometer data. Hydrogen atoms formed by a charge exchange capture give a Doppler temperature 100-200 eV using either λ 6563 Å (H_{α}) or λ 4861 Å (H_{β}). Helium discharges show He^+ ions to have a Doppler temperature of 200 eV, but sometimes rising to 600 eV in the plasma decay, based on the λ 4686 Å line. Carbon and oxygen impurity lines in hydrogen discharges give about 200 eV from C^{2+} (λ 4647 Å) and from O^{4+} (λ 2781 Å), the latter ion showing ions of about 500 eV temperature during plasma decay. The unusually high ion temperatures observed during plasma decay at $t > 5$ msec suggests that ions in the core may be quite hot since recombination spectra would be expected to dominate the plasma decay spectra. Rotational velocities of the plasma have been measured both in poloidal and toroidal directions. The Doppler shift of an H_{α} (6563 Å) line, at a minor radius > 10 cm, was used. It was found that the rotation is poloidal during the early and late phases when the ions are cold, and becomes toroidal as ions are heated. Both peak velocities are roughly 10^6 cm/sec. Both the magnitude and direction of rotation are correlated with magnetic probe fluctuations. This result supports the interpretation that the stripped ions at $r < 10$ cm are collisionless, since the theory predicts an absence of poloidal rotation in this case.

Electron temperatures are measured in three ways: by Thomson scattering using a ^{Q switched} 10 joule ruby laser, by ^{direct} Bremsstrahlung spectrum measurement, and by a two-absorber measurement of the Bremsstrahlung spectrum. The principal tool is the laser. It permits a 3 point radial profile to be taken at 4 points in time and at 3 radial positions. The electron temperature profiles at several values of discharge current are shown in the next figure. For comparison, profiles are shown also for several other tokamaks. The rather peaked profile at 150 kA was obtained in

discharges which were intermittently unstable. The value of q at the limiter in this case was 4.

Electron temperatures inferred from Bremsstrahlung measurements are in agreement with the values obtained by Thomson scattering.

We can infer β_{poloidal} from these electron profiles ^{density} and using an parabolic shape for the ion temperature profiles. Values of β_{poloidal} are typical for values of limiter $q \gtrsim 5$. We now are making direct measurement of β_p from the change in toroidal flux. Values of β_p ~~data~~ obtained from these measurements are typically constant within ~~5~~ 5% during any one shot and lie between 0.47 and 0.52 for stable discharge.

Thus in the sense that $\beta_{\text{poloidal}} = 0.5$ ^{implies} ~~finds~~ pseudo-classical scaling. This scaling is observed in ORMAK. A typical result of simulation calculations show 44% of the electron energy going to the ions. Most of the rest of the energy must be lost ultimately by radiation but more work is required to understand the loss processes in detail.

Electron line density is measured using a 2mm microwave interferometer. Looking vertically through the major axis of the torus.

Future Plans

The neutral particle injectors which are being installed at this time are the subject of another paper at this meeting. An important consideration is the implication of the greater-than-expected density of charge exchange centers in the plasma for injection. The next figure shows results using Hogan's ^{simulation} code in this case. The heating is less than was predicted when charge exchange losses were expected to be less important but ~~nevertheless~~ ^{should} the temperatures ~~expected~~ ^{will} push the plasma far into the collisionless regime. In particular, in the High-Field case, ^{the} calculation predicts that synchrotron radiation will become a significant loss process.

The dominance of charge exchange losses seriously effect the predicted plasma parameters in large machines being built or proposed, in calculation of the expected plasma parameters in ATC were based on

charges which were intermittently unstable. The value of q at the center in this case was 4.

Electron temperatures inferred from Bremsstrahlung measurements in agreement with the values obtained by Thomson scattering. We can infer β_{poloidal} from these electron profiles ^{density} and using an assumed poloidal shape for the ion temperature profiles. Values of $\beta_{\text{poloidal}} \approx 0.5$ typical for values of limiter $q \approx 5$. We now are making direct measurement of β_p from the change in toroidal flux. Values of β_p obtained from these measurements are typically constant within a few percent during any one shot and lie between 0.47 and 0.52 for stable discharge.

Thus in the sense that $\beta_{\text{poloidal}} = 0.5$ ^{implies} ~~finds~~ pseudo-classical scaling, scaling is observed in ORMAK. A typical result of simulation calculations show 44% of the electron energy going to the ions. Most the rest of the energy must be lost ultimately by radiation but work is required to understand the loss processes in detail.

Electron line density is measured using a 2mm microwave interferometer, scanning vertically through the major axis of the torus.

Future Plans

The neutral particle injectors which are being installed at this time are the subject of another paper at this meeting. An important consideration is the implication of the greater-than-expected density large exchange centers in the plasma for injection. The next figure shows results using ^{simulation} Hogan's code in this case. The heating is less than was predicted when charge exchange losses were expected to be less important but ^{nevertheless} the temperatures ^{should} ~~expected~~ will push the plasma far into the collisionless regime. In particular, in the high- q case, ^(see below) the calculation predicts that synchrotron radiation will be a significant loss process.

The dominance of charge exchange losses seriously effects the predicted plasma parameters in large machines being built or proposed, i.e., calculation of the expected plasma parameters in ATC were based on classical ion loss rates and are therefore optimistic.

One possible solution to the problem ^{of} enhanced charge exchange loss is the use of a divertor. We intend to build a divertor which will take the place of the present limiter and will be ^{added} installed at the time of the installation of the third and fourth injectors, scheduled now for January 1974. In essence, the present limiter is ^{to be} replaced by a contact liquid-helium-cooled ^{copper} coil having several hundred thousand ampere turns. Lines of force at the surface of the plasma will be moved outward where they will strike the coil housing at a point shadowed from the plasma. ~~Some of the particles will be pumped out of the system.~~ Others will re-enter the plasma volume as thermal particles.

The High-Field modification is based on a suggestion by W. F. Gauster that copper could be ^{added} matted to the coils ^{asymmetrically in a radial direction,} without interfering with access and without reducing the area available for iron core. By this means we find that it will be possible to double the number of turns in the coils and at the same time achieve a lower resistance than the present coils.

Conclusions:

The @ PRRK experiment: see dictation

One possible solution to the problem ~~to~~ enhanced charge exchange loss is the use of a divertor. We intend to build a divertor which will take the place of the present limiter and will be ^{added} ~~installed~~ at the time of the installation of the third and fourth injectors, scheduled now for January 1974. In essence, the present limiter is ^{to be} replaced by a compact, liquid-helium-cooled ^{copper} coil having several hundred thousand ampere turns. Lines of force at the surface of the plasma will be moved outward where they will strike the coil housing at a point shadowed from the plasma. ~~Some of the particles will be pumped out of the system.~~
~~Others will re-enter the plasma volume as thermal particles.~~

The High-Field modification is based on a suggestion by W. F. ^{added} ~~maister~~ ^{asymmetry in a radial direction} that copper could be ~~matted~~ to the coils, without interfering with access and without reducing the area available for iron core. By this means we find that it will be possible to double the number of turns in the coils and at the same time achieve a lower resistance than the present coils.

Conclusion:

The @ PRANK experiment: see dictation

Conclusions

The ORMAK experiment has achieved its initial goal -- to determine the effective high toroidal curvature on a tokamak discharge. The predicted advantages of low aspect ratio and large bore for penetration into the collisionless regime have been realized. Anomalous losses from trapped particle effects or from possible unforeseen effects of high toroidal curvature have not been observed.

The ion transport has been reduced to a level where charge exchange clearly dominates the loss processes. Diffusive transport may be neo-classical.

These results put the prediction of the effect of our future neutral particle injection experiment on a firmer basis. The expectation is a deep penetration into the collisionless regime with kilovolt ion temperatures.