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UCRL - 74087
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CONF-720804--8

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MASTER

CONFINEMENT STUDIES IN 2XII

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August 18, 1972

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This paper was prepared for "Fifth European Conference on Controlled Fusion and Plasma Physics, August 21 - 25, Grenoble, France

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CONFINEMENT STUDIES IN 2XII*

by

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Abstract: The containment of deuterium plasmas in a magnetic mirror well has been investigated for mean plasma ion energies in the range from 1 to 10 keV. Evidence indicates that detectable plasma turbulence in this experiment arises primarily from instabilities driven by the presence of two or more maxima in the ion velocity function. Plasmas with no detectable turbulence have been formed with mean energies in the range from 1.2 to 2.7 keV. The ion velocity functions of all quiescent plasmas have a single maximum. For these plasmas neither the magnitude nor the density dependence of the loss rate was noticeably different for runs which were theoretically stable for the Dory-Guest-Harris mode and those that were unstable. In both cases n_T at high densities was below that calculated for collisional losses by a factor of two to three and decreased as the density fell. Although losses induced by other instabilities (e.g., drift-cyclotron, loss-cone mode) cannot be ruled out, the high density data from quiescent decays appear to be in agreement with the Baldwin-Callen^[1] theory of "collective scattering".

EXPERIMENT - The 2XII experiment at the Lawrence Livermore Laboratory was constructed to further investigation of plasma containment in magnetic minimum-B wells. As in the earlier 2X experiments, an energetic plasma is formed in the well by trapping and subsequently compressing a portion of a plasma burst which is injected along a uniform steady magnetic field. Trapping is achieved through the use of an appropriately programmed set of pulsed magnets. These pulsed magnets are short circuited at time of peak discharge current and plasma behavior is followed during the exponential

decline of the magnetic field. As the lifetime of the plasma is much less than that of the magnetic field the contribution of the field decay to plasma loss is assumed to be limited to the density change calculated for adiabatic plasma expansion. Characteristic field and plasma parameters of the initial 2XII experiments are compared in Table I with those of the previously reported^{[2][3]} 2X experiments.

TABLE I
Magnetic Field and Plasma Parameters for 2XII and 2X

Parameter	2XII Initial Operation	2X Ref. 3	2X Ref. 2
Maximum dc guide field (kG)	2	2	2
Maximum central magnetic field (kG)	6.5	13.2	16.3
Longitudinal mirror ratio	2	1.33	1.33
Radial well depth measured at wall (%)	21	2.5	2.5
Plasma to wall distance along magnetic field lines (cm)	300	20	20
Pulsed magnetic field rise time (μ sec)	400	160	160
Magnetic field decay time (msec)	8	8	8
Distance between mirror points (cm)	100	160	160
Plasma diameter (FWHM cm)	12	6	6
Maximum plasma density	6×10^{13}	5×10^{13}	3×10^{13}
Maximum mean ion energy (keV)	1 - 10	8	6
Electron temperature (eV)	80 - 250	200	200
ω_{ci} (sec^{-1})	3.1×10^7	6.4×10^7	7.9×10^7
$(\omega_{pi}/\omega_{ci})^2$ at $n_i = 10^{12} \text{ cm}^{-3}$	900	210	130

All field lines which thread the 2XII plasma exit into the 1.5 meter diameter end chambers where adequate pumping is provided for non-trapped injected plasma and for plasma lost through the mirrors. As predicted, this feature has reduced the influence of the central chamber walls on plasma

containment. The field lines are convex toward the center at all points between the magnetic mirrors, so there is absolute hydromagnetic stability rather than " $\int d\ell/B$ stability". Adiabaticity is assessed by calculating particle orbits^[4] through 50 or more mirror reflections. Deuterium ions up to 100 keV are found to behave adiabatically for the 6.5 kG central magnetic field level. Stability against interchange instabilities in the fully developed magnetic well is predicted for all values of β by the Cordey-Watson criterion^[5].

Seven 2-inch washer-type plasma guns are located 340 cm from the center of the containment chamber. When driven by a low inductance 30 μ f capacitor bank, each injector provides an energetic deuterium plasma of approximately 2.5 keV mean ion energy. The output of a single injector is proportional to the square of the capacitor bank potential and at 10 kV, is approximately 5×10^{17} ions/pulse. The equivalent total injected ion current exceeds 10^5 A. When used intermittently (as in operation thus far) the injector electrodes tend to load with hydrogen from the residual background gases. Consequently the concentration of hydrogen ions in the energetic plasma is in the range from 30 to 50%. Although the velocity ranges of the hydrogen and deuterium ions are nearly the same, the velocity distribution of the hydrogen component is not necessarily the same as that of the deuterium component. The mean energy of the trapped and compressed plasma can be varied in the range from approximately 1 to 10 keV. Limited control of the plasma ion velocity distribution is achieved by firing groups of the plasma gun array at different times.

Base pressures are in the range of 2×10^{-9} to 10^{-8} torr. To insure clean, "active-pumping-surfaces", titanium is deposited on all interior surfaces just before each plasma containment run.

MEASUREMENTS - The central electron density is measured with a 70 GHz stabilized wave interferometer and a second 4 mm interferometer is occasionally

used to determine the density 5.7 cm off axis. The ratio of these two agrees with the radial distribution estimated by assuming that the radial distribution of the trapped plasma ions was the same as that measured for the injected plasma burst and that the motion of the trapped ions is adiabatic during magnetic compression. Longitudinal density scans are made with a moveable 35 GHz μ wave interferometer. Two 10 GHz μ wave interferometers are used to monitor plasma densities external to the magnetic mirrors.

The magnitude and frequency spectra of the fluctuating electric fields during periods of plasma turbulence are determined from forward angle scattering of 4 mm μ waves.

The intensity and radial distribution of line radiation from heavy ions is monitored through the use of a dual-channel, grazing-incidence, vacuum ultra-violet monochromator. Time dependent intensities of radiation in the visible range and the H_{α} line are also recorded.

For the operation discussed here we have no direct measurement of electron temperature. A Thomson scattering measurement is now installed and evidence from initial operation indicates that it is possible to determine T_e at least early in the decay.

Time dependent energy spectra of the transverse fast atom current at the center of the plasma containment chamber are determined by allowing neutral particles to pass through a nitrogen gas cell ($n_L = 2 \times 10^{14}$ atoms cm^{-2}) then through an 11-channel tandem mass analyzer. Particles which are ionized in the gas cell are deflected in the magnetic field of the analyzer and those in the proper momentum ranges enter one of the eleven separate electrostatic energy analyzers. An automatic data system comprised of an analog disc, a mini-computer, a digital tape and a high-speed printer is used to store and process the data.

Plasma ion energy spectra are derived from the neutral analyzer signals assuming that plasma ions charge exchange with thermal neutral methane (i.e.

the residual gas) flowing into the plasma volume. Both atomic and molecular hydrogen may be formed through neutralization of part of the injected plasma and contribute to a transient increase of neutral density external to the trapped plasma. Atomic hydrogen would not appreciably alter the derived spectra but the relative charge exchange cross-sections fall off at low energies for molecular hydrogen so if it forms an appreciable component of the background gas the relative magnitude of low energies in the spectra have been underestimated.

We estimate that less than one-third of the fast atom current is formed in the plasma interior by charge exchange with the flux of relatively energetic neutrals (Franck-Condon neutrals) resulting from dissociation of the thermal molecules in the plasma boundary. Since the mean free path for ionization of thermal particles is $\leq n_i^{-1} \times 10^{12}$ cm, fast atom energy spectra are dominated by conditions in a shallow low density boundary where interaction with the cold background gas is greatest. Plasma potentials derived from the low energy cutoff of the energy distributions are characteristic of the plasma boundary.

Except for low densities late in time the diameters of 2XII plasmas are greater than the mean free path for the ionization of Franck-Condon neutrals. Consequently the fast atom current is proportional to the neutral density external to plasma rather than the plasma density. Based on absolute calibration of the neutral analyzer the charge exchange rate is found to be a factor of 10 to 100 too low to account for the lowest observed plasma loss rates. J. R. Hiskes^[6] in an independent evaluation of the data has also concluded that charge exchange is not a significant loss in 2XII.

OBSERVATIONS AND DISCUSSION - As judged from the density histories and the energetic deuterium content of the fast atom flux the period of detectable deuterium plasma densities in 2XII is frequently longer than 3.5 msec and exceeds by about 1.5 ms that of the best 2X operation.

In contrast with 2X data, short periods of very rapid plasma loss are observed for some modes of operation. Typical examples of these "plasma dumps" are shown in Fig. 1 at $t \approx 1300$ μsec in the run B density history and 630 μsec in run C. However, such obvious plasma catastrophies before 2 msec are the exception and the density decay of the trapped plasma is usually similar to that of run A in Fig. 1.

From inspection of the data we see that the plasma dumps are always accompanied by increases in all of the following: a) scattered μwave power, b) the relative number of high energy atoms in the charge exchange current, c) total light, and d) H_{α} radiation. The H_{α} signal is very similar to the total light signal and is not included in Fig. 2

where data from run C are reproduced to illustrate the time correlations of these data. In addition to temporal correlations the magnitudes of the logarithmic decay rate and the scattered μwave power are found to be directly related. A similar correlation is found between the logarithmic decay rate and the normalized 17.5 keV neutral analyzer signal (normalized by dividing by the total

FIG. I DENSITY HISTORIES

FIG. II RUN (C) DATA

charge exchange current). In fact, broadening of the energy distribution as indicated by relative increase of energetic particles in the charge exchange current has been found to be our most sensitive indicator of plasma turbulence.

No correlation has yet been established between the plasma decay rate or the occurrence of plasma dumps and the magnitude or time dependence of plasma external to the magnetic mirrors.

If the sequence of operation is timed to trap low energy plasma the trapped ion energy spectra usually have a single maximum lying near the low energy cutoff similar to that in the 420 μ sec run A spectrum shown in Fig. III. As predicted shorter delays between injection and trapping increases the relative number of high energy ions but a lower energy group is also formed resulting in two and even three maxima in the trapped ion velocity functions; e.g., the 420 μ sec run C spectrum shown in Fig. III.

Frequently, as in run C, during periods of rapid plasma loss the low energy maximum disappears and evidence of plasma turbulence is no longer detectable. This transition is accompanied by an abrupt decrease of the loss rate (see Fig. II).

In run B the charge exchange current rises before evidence of plasma turbulence (at $t \approx 1300 \mu$ sec) suggesting that this particular plasma dump is triggered by the influx of cold gas. Run B energy spectra have two or more maxima and the evidence from this run as well as that from run C suggests

FIG. III ENERGY SPECTRA

plasma losses resulting from double-humped^[7] instability.

The correlation of detectable plasma turbulence with double-humped velocity functions is not restricted to the case of obvious plasma dumps, but rather such evidence is found in all runs where the velocity function has more than one maximum. In weakly turbulent runs where only a single maximum is evident, a second peak could escape detection due to the large separation between analyzer channels or because the observed spectra are representative of the plasma boundary rather than its interior.

The mechanisms leading to the formation of the lower energy maxima have not been identified. However, intense r. f. fluctuations occur in every run during trapping and into the magnetic compression. Thus when the cycle is adjusted to trap high energy ions lower energy ions streaming along the field lines will be trapped in the magnetic well if they can acquire sufficient rotational energy in one transit time. The fluctuating electric field $\tilde{E}$ necessary to provide one keV rotational energy to a one keV deuterium ion which is moving directly along a field line may be estimated by

$\sqrt{v_{final}^2} = (e/M) \tilde{E} \sqrt{t\tau}$ where t is the transit time ($\sim 3 \mu\text{sec}$) and τ is the electric field correlation time which we take to be one cyclotron period ($\sim 0.2 \mu\text{sec}$). The required field, $E \sim 90\text{V/cm}$, is much less than the values deduced from the intensity of the μ wave scattering during plasma trapping. Fluctuations at this level, which may escape detection, provide a mechanism for accumulating low energy ions. Since the ionization mean free paths are much less than the plasma radius this mechanism could lead to double-humped instability losses localized in the plasma boundary. This mechanism may account for the observed variation of loss rates in runs in which the energy spectra are quite similar.

Infinite medium $k_{||} = 0$ stability analysis^[8] of the 420 μsec run C energy spectrum shows unstable frequencies around $1.1\omega_{ci}$ for the densities above $6 \times 10^{11} \text{ cm}^{-3}$. As suggested by the appearance of the spectrum the

instability results from the presence of two maxima in the velocity function. Following the plasma dump when there is no detectable μ wave scattering or energy spreading, unstable frequencies were found in analysis of run C spectra due to the limited spread of ion velocities; i.e. Dory-Guest-Harris mode^[9].

With the exceptions of the occasional appearance of a component in the frequency band about $\omega_{ci}/2$ the scattered μ wave frequency spectra associated with these plasma dumps are consistent with the double-humped instability. The lower frequency component may indicate a secondary effect due to an influx of cold heavy ions which drive a lower frequency double-humped instability.

On the basis of limited analysis of data from runs with double-humped energy distributions we observe that the n_T values at 425 μ sec decrease with increasing relative depth of depression between the two maxima. From instability analysis the bandwidth of unstable frequencies and wavelengths are found to increase with increasing slope of velocity function between the maxima. We conjecture that marginally unstable cases would be stabilized after flute averaging the dispersion relation and including stabilizing electromagnetic corrections. These results may also contribute to the observed variation of n_T from a value less than 10^8 during plasma dumps to $5 \times 10^9 \text{ cm}^{-3}$ sec in weakly turbulent runs.

Quiescent plasmas such as that of run A have been generated with mean ion energies in the range from 1.2 to 2.7 keV. The velocity functions of these plasmas are all single peaked. Observed n_T values in the turbulence-free plasmas at the end of magnetic compression are only a factor of two to three less than the n_T values calculated (through the use of Fokker-Planck codes) for coulomb collisions. However the plasma decay in these "best" cases is in obvious disagreement with collisional losses as n_T decreases by about a factor of ten during the density decay from 2×10^{13} to $2 \times 10^{12} \text{ cm}^{-3}$.

In an earlier discussion^[1] of plasma containment similar to that of run A we advanced arguments that the anomalous loss rate resulted from either the Dory-Guest-Harris^[9] or the drift-cyclotron loss-cone instability mode^[8]. Infinite medium $k_{||} = 0$ stability analysis of run A spectra shows instability for the zero frequency DGH mode. Inclusion of the hydrogen term in the dispersion relation shifts the predicted threshold density to higher values in this example and in other cases leads to predicted absolute stability for the DGH mode. Deuterium velocity functions in two turbulence-free runs were found to be DGH stable. Thus, in the absence of recent theory of "collective scattering" for loss-cone particle distributions we would have been inclined to attribute the anomalous losses to the drift-cone mode. However, as shown in paper 91^[10] of this Conference, it appears necessary to add to the classical ion-ion scattering loss rate a correction. Such a correction has the right functional form to fit the observed dependence of n_T with density and indeed the initial comparison of experimental data^[10] with theory suggests that the anomalous loss rate could arise solely from this process.

In comparison of 2XII data with theory it is convenient to rewrite Eq. (2) of Ref. 10 in the form

$$\frac{1}{n^2} \frac{dn}{dt} = \left(\frac{1}{n^2} \frac{dn}{dt} \right)_{\text{classical}} + \frac{A}{[1 + \omega_{pe}^2 / \omega_{ce}^2]^2} \exp \int d\alpha \left(\frac{\omega_{pe}^2 / \omega_{ce}^2}{1 + \omega_{pe}^2 / \omega_{ce}^2} \right)^{1/2}$$

where dependence upon the ion velocity function is included in the factor A and A is inversely proportional to the $3/2$ power of electron temperature. If the density is expressed in units of 10^{13} and magnetic field in units of 10^4 gauss then $\omega_{pe}^2 / \omega_{ce}^2 = \frac{n}{B^2}$. For large values of $(\omega_{pe}^2 / \omega_{ce}^2)$ where the exponential is independent of density (provided that the velocity function is time invariant) the curve $n^{-2} dn/dt$ vs $(1 + n/B^2)^{-2}$ should be a straight line which intercepts the axis at the classical value of $(n_T)^{-1}$. High density data from low energy (1 to 2.7 keV) plasmas lie close to straight lines

and n_T values derived from the intercepts show an $E^{3/2}$ dependence within the accuracy of experimental uncertainties. In runs with higher energy plasmas the velocity functions are found to change with time so that the comparison with theory is more difficult and has not been completed.

CONCLUSIONS

- Turbulence in 2XII appears to arise primarily from double-humped instabilities.
- Plasma loss rate resulting from the double-humped instability appears to increase with increasing relative depth between maxima in the velocity function.
- Plasma losses from quiescent plasmas are greater than predicted for coulomb scattering and do not have an n^2 dependence.
- Charge exchange effects are negligible.
- It is unlikely that Dory-Guest-Harris instability mode contributes to the anomalous loss rate.
- Theoretically 2XII is unstable to the drift-cyclotron loss-cone mode but other than the anomalous loss rate there is no direct evidence suggesting its existence.
- The data from low energy quiescent plasma decays is consistent with the Baldwin-Callen theory of collective scattering.

ACKNOWLEDGEMENTS: We wish to thank R. F. Post and W. M. Tang for the numerical procedures utilized in the 2XII stability analysis. D. E. Baldwin has participated in the comparison of the experimental results with collective scattering theory.

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*Work performed under the auspices of the U.S. Atomic Energy Commission