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UCRL-51208

INITIAL OPERATION OF THE 2XII EXPERIMENT

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March 10, 1972

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

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TID-4500, UC-20
Controlled Thermonuclear
Processes

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LAWRENCE LIVERMORE LABORATORY

April 18, 1972

TO: Holders of UCRL-51208, "Initial Operation of the
2XII Experiment"

FROM: Technical Information Department, L-9

ERRATA

On page 23, ignore the data in the lower portion of Fig. 22
($\int n_e dx$ vs time) because it is presented in Fig. 19 in more
detail.

Technical Information Department

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Initial Operation of the 2XII Experiment

ABSTRACT

Typical examples of plasma containment observed in the first high vacuum operation of the plasma-injected, open-ended, minimum-B 2XII experiment are discussed. The density decay curves for plasmas in which the velocity function had a single maximum exhibited no periods of abrupt plasma loss or other obvious evidence of plasma turbulence (instability). For this example, the observed value of $n\tau$ at 10^{13} cm^{-3} was approximately one-third that calculated for ion-ion scattering by a two-dimensional computer code. As the density fell to 10^{12} cm^{-3} , this discrepancy approximately doubled. In examples exhibiting periods of plasma turbulence and rapid plasma loss, there is evidence that the plasma instabilities were driven by the presence of two or more maxima in the ion velocity functions.

INTRODUCTION

In this report, we discuss a limited sample of data from the first plasma containment runs in the 2XII experiment. Five representative examples are selected to illustrate the observed decay modes. Much of the original data from these runs is included, together with many of the graphs and tables developed during the initial analysis of data from the numerous simultaneous measurements, to illustrate the extent of the investigation and enable independent evaluation of our observations.

We were using, for the first time, an automatic data system for storing data from a new 11-channel analyzer which monitors the fast-atom current arising from charge exchange at the center of the plasma containment chamber. Components of this system are an analog disc, a mini-computer, and a digital tape. In future operation, the system will be extended to store and process data from several measurements.

The unapertured runs discussed here were made following replacement of an original high vacuum vessel broken during the initial pump-down of the experiment. Although base pressures in the original vessel were not low enough to ensure clean wall conditions, we used it while debugging the plasma measurements and also while conducting a preliminary scan of 2XII plasma containment. This earlier operation was discussed in our 1970 Annual Report.¹ The present high vacuum vessel is designed to reduce the mechanical stresses in the Pyroceram sections and to facilitate repair of these sections. To date, it has functioned exceptionally well; achieving base pressures in the required operating range (2×10^{-9} to 2×10^{-8} Torr) has become a routine procedure.

While fabricating and installing the second high vacuum vessel, we rewired the capacitor banks that energize the compression (Yin-Yang) magnets, connecting all capacitors in parallel rather than in series. This modification, which is easily reversible, extends the compression

time from about 200 μ sec to about 400 μ sec. The parallel configuration reduces electrical stresses in the magnets and transmission lines by a factor of 2, allowing the capacitor bank to be charged to higher potentials and later may permit operation at approximately twice the magnetic fields of the present runs.

Table 1 compares several relevant parameters of the initial 2XII operation with those of the 2X operation reported at the Novosibirsk² and Madison³ international meetings. The 2XII radial and longitudinal wells are significantly deeper; however, the magnitude of the 2XII central field is considerably less than that of the 2X. This lower central field is the result of:

- Operation of the banks at 2/3 level (as a precautionary measure) during a period in which a large range of

operating conditions is being scanned and several new plasma measurements are being developed;

- The higher mirror ratio;
- The larger volume of the containment field;
- An energy loss in the ignitron switches.

As previously noted, all field lines threading the 2XII plasma exit into the end chambers. Confirming predictions, this feature has reduced the influence of the central chamber walls on plasma containment. Furthermore, the field lines are convex toward the center at all points between the magnetic mirrors, so there is "absolute stability" rather than " $\int dl/B$ stability." Although the entire volume occupied by the closed $|B|$ surfaces extending to the mirrors is not contained within the vacuum chamber, the mirror

Table 1. Machine parameters for the 2XII and later 2X.

Parameter	2XII Initial Operation	2X Novosibirsk	2X Madison
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 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)	2 - 9	8	6
Electron temperature (eV)	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 $n_i = 10^{12}$ cm ⁻³	900	210	130

* $\omega_{pi} = 932 n_i^{1/2}$ at $n_i = 10^{12}$ and $\omega_{pi} = 9.32 \times 10^8$

point on every field line threading the contained plasma is within the vacuum chamber.

A schematic cross section of 2XII is shown in Fig. 1. The set of titanium sublimators shown here is incomplete but serves to emphasize the fact that a fresh titanium film is deposited on all interior surfaces before each containment run. Four long movable supports, such as that shown at the injector end of the vacuum vessel, carry filaments into the central chamber during the period of titanium sublimation.

Seven 2-in. injectors 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 from a single injector is proportional to the square of the potential on the capacitors which drive it and, at 10 kV, is approximately 5×10^{17} ions/pulse. The corresponding "virtual ion current" exceeds 10^5 A. When used intermittently (as in operation thus far), the injector electrodes tend to load with hydrogen from

Fig. 1. Schematic cross section of 2XII.

residual background gases. Consequently, there is a yet undetermined concentration of energetic hydrogen ions in the trapped high energy deuterium plasmas.

One of the injectors is located on the magnetic axis. The remaining six are evenly spaced around a circle 22.2 cm in diam centered on the longitudinal axis. The array is divided into three groups, for which the firing time and power supply potential can be independently selected. Group one is the central injector only. Groups two and three each consist of three injectors separated by 120 deg. By staggering the firing times of the injector groups, we deliver ions of differing translational velocities from each group to the trapping region at the same time; this results in a broader energy distribution than that obtained when all injectors are fired simultaneously.

The trapped energy distribution also depends somewhat on the magnitude, B_0 , of the dc guide field, as the more energetic ions from the injectors are not contained in weak guide fields when the angle between their velocity vectors and the magnetic field direction is sufficient for trapping. Because the compression ratio, B/B_0 , and hence ion heating are inversely proportional to the magnitude of the guide field, there is an optimum value of B_0 for each phase-space distribution of injector plasma ions.

In the operation discussed here, there was no limiting aperture between the injectors and the central containment chamber. Thus the extent of the injected plasma was limited horizontally by the width of the near trapezoidal vacuum chamber (see Fig. 1) and vertically by the top and bottom walls of the containment

chamber's central section. This mode of operation, which maximizes the radius of the trapped plasma, also could maximize the transient increase of neutral density in the containment chamber. By comparison, it was necessary in 2X to reduce the aperture to one-third the diameter of the containment chamber in order to form long-lived plasmas in minimum-B operation.

OBSERVATIONS

Approximately 375 containment runs were made in the unapertured operation of 2XII, representing nearly 100 combinations of injector timing, injector potential, and guide field values. We encountered no difficulties in forming energetic deuterium plasmas. As judged from inspection of microwave interferograms and neutral analyzer data, the period of detectable deuterium plasma densities within the containment chamber was extended by 1-1.5 msec (to $t \approx 3.5$ msec) beyond that of the best 2X operation.

The microwave interferograms, such as shown in Fig. 2, are remarkably noise-free and, in contrast with 2X data, frequently exhibit sharp breaks corresponding to the dramatic changes in the plasma loss rate. Many events like that seen at $t \approx 1300$ μ sec in run B, Fig. 2, correspond to sudden plasma loss. Events such as that at 630 μ sec in run C, Fig. 2, correspond to a sharp decrease in the plasma loss rate. The interferogram for one of the "best containment" runs is shown as run A in Fig. 2. Only a single injector on axis was used for runs A, B, and C.

Fig. 2. 70-GHz microwave interferograms from which central density values in runs A through E were determined.

The interferograms of two seven-injector runs selected for comparison are shown as runs E and D, Fig. 2. To facilitate comparison of the "raw" data, the figures containing reproduced oscilloscope traces are grouped together. Thus

the total light signals at the center plane are shown for runs A through E in Fig. 3. The 3-cm interferograms indicating plasma line density external to the mirror at the injector end appear in Fig. 4. The 11 neutral analyzer sig-

Fig. 3. Total light signals at center for runs A through E.

nals for runs A through E appear in Figs. 5 through 9.

Figure 10 shows the estimated radial density distributions for the three com-

Fig. 4. 10-GHz microwave interferograms from which density values outside the mirror toward the plasma injectors was determined for runs A through E.

binations of guide field and delay (listed in Table 2) between plasma injection from the three groups of plasma guns and the time

Fig. 5. Neutral analyzer signals for run A.

of initiating the fast gate magnet. For these runs, all injector power supplies were charged to 12 kV. Radial distributions were obtained on the following bases:

- The radial distribution of the trapped plasma was assumed to be the same as that measured for the injected plasma burst;

- The motion of the trapped ions was assumed to be as predicted by the adiabatic theory for single particles.

Obviously, localized plasma losses invalidate these assumptions and, equally obviously, it would be desirable to monitor the radial profile. However, the derived central density values are not

Fig. 6. Neutral analyzer signals for run B.

very sensitive to the assumed radial profile; we estimate that the error in central density from this uncertainty to be less than 20 percent.

COMPARISON WITH ION-ION SCATTERING

From the radial distributions in Fig. 10 and the data in Fig. 2, we can derive the density histories shown in Figs. 11 and 12. The curves of these figures differ very slightly from $\int n dl$ vs time curves, which

are independent of the radial density distributions. Evidently, for case A, the density falls almost exponentially to nearly one-tenth its initial value. Indeed, this density history is very similar to the density histories discussed in the Madison paper.³ Even the observed $(n\tau)_E$ values are the same within experimental uncertainties for the two cases.

The measured $(n\tau)_E$ values are compared in Table 3 with $(n\tau)_C$ values calculated by the Marx-Killen code and the

Fig. 7. Neutral analyzer signals for run C.

measured energy distributions of Figs. 13, 14, and 15. In these calculations, the plasma potential was initially set at 550 eV, to be consistent with the observed low energy cutoff. T_e was set at 250 eV $\approx \phi/2$. These initial values were found to be close to the equilibrium values reached in the calculations. Any transient adjust-

ment in a calculation was short-lived ($< 50 \mu\text{sec}$). Values of the calculated life-time at equilibrium were used for the $(n\tau)_c$ values.

The values of $\bar{E}$ in Table 3 were computed in the Fokker-Planck code; and as the distribution in that calculation is adjusted to fit the loss cone boundary at

Fig. 8. Neutral analyzer signals for run D.

all angles, these mean energy values are somewhat higher than corresponding values derived from the energy distributions shown in Figs. 13 through 15. The ion energy spectra for run A in these figures were derived by measuring signal levels in the oscillograms shown in Fig. 5. The error bars, which are equal to ± 7 percent of the signal value, reflect the statistical variation found in repeated calibrations of the neutral analyzer. Although this magnitude of uncertainty is acceptable, we

are not certain that all systematic errors have been eliminated and thus are continuing to improve the calibration of this instrument.

It is seen, for run A, that the observed $n\tau$ values are quite close to the calculated values and that the discrepancy even at 1.3 msec is only a factor of 4. Thus, at late times, the agreement between $(n\tau)_E$ and $(n\tau)_C$ is apparently better for 2XII than for 2X. This improvement arises from the fact that the ion energies

Fig. 9. Neutral analyzer signals for run E.

Table 2. Injection parameters.

Run	Guide field, G	Maximum central field	Compression ratio	Delay between injection and trapping, μsec		
				G1	G2	G2
A	500	5500	11	25		
B	1500	6500	4.33	25		
C	1500	6500	4.33	30		
D	1500	6500	4.33	25	35	35
E	1500	6500	4.33	30	30	30

Fig. 10. Radial density profiles, at maximum compression.

Fig. 11. Plasma density histories for runs A, B, and C.

decreased in run A and therefore the calculated $n\tau$ value decreased in time; by comparison, a constant $(n\tau)_c$ was assumed in the 2X discussion.

Based on the evidence available at this time, $(n\tau)_E$ does not appear to depend on

Fig. 12. Plasma density histories for runs D and E.

Fig. 13. Plasma ion energy spectra at 300 and 400 μ sec in run A.

ion energy. Thus, the ratio $(n\tau)_c/(n\tau)_E$ increases as the plasma ion energy increases. However, as discussed below, different or additional instability modes possibly may have been present in the runs with higher mean ion energies.

Fig. 14. Plasma ion energy spectra at 600 and 800 μ sec in Run A.

Fig. 15. Plasma ion energy spectra at 1000 and 1200 μ sec in Run A.

Density histories were examined for evidence of periods in which $dn/dt \propto n^2$ by plotting $1/n$ vs t curve for run A (Fig. 16) can be fitted by a straight line in the 300- μ sec interval following the end of magnetic compression at 400 μ sec. Such limited evidence would be more encouraging if similar behavior were found at higher ion energies. Actually, as mentioned above, the data of Fig. 16 can be fitted to 1.2 msec with an exponential.

Table 3. Observed and calculated $n\tau$ values.

Run	Time, msec	$\bar{E}_{ion}$, keV	$(n\tau)_{E_p}$, $cm^{-3} sec$	$(n\tau)_c$, $cm^{-3} sec$
A	0.40	2.1	8×10^9	1×10^{10}
A	0.80	2.7	6×10^9	2×10^{10}
A	1.6	1.6	2.5×10^9	1×10^{10}
C	0.80	9.0	1.7×10^9	1.5×10^{11}
D	0.40	9.0	5.3×10^9	9.7×10^{10}
2X	0.4	6.0	1×10^{10}	3×10^{10}

CHARGE-EXCHANGE LOSSES IN RUN A

The observation of near-exponential density histories suggests charge exchange against a uniform, constant-density neutral background gas. For essentially the same reason, charge-exchange losses were examined in detail in the Madison paper,³ where we concluded they could not account for the observed anomalous losses in the 2X experiment. Similar convincing but indirect arguments, as well as more direct measurements, are discussed below for present 2XII operation.

For 2XII, we completed a preliminary absolute calibration of the 11-channel neutral analyzer, making it possible for us to compare the measured neutral current from the plasma surface with the charge-exchange rate that would be needed to cause the observed plasma decay rate. For an approximate comparison, the plasma is considered to occupy a long cylindrical volume of radius R . Charge exchange gives rise to a current, $I(t)$ fast atoms $cm^{-2}sec^{-1}$, from the plasma surface, leading to a charged particle loss per unit length of $dN/dt = -2RI(t)$. In this equation, $N = \int n_i(r, \theta, t) dA$ is the total number of charged particles in a 1-cm length of the plasma column. Approx-

Fig. 16. External density, charge-exchange current, and the inverse of the central plasma density for run A.

Fig. 17. Plasma line density, central density, logarithmic decay rate, total light, charge-exchange current, and 8.18-keV fast atom signal for run A.

imating the plasma density distribution by a uniform density $n_i(t)$, we obtain

$$\frac{dN}{dt} = \frac{d[n_i(t) \pi R^2]}{dt} = \frac{\pi R}{2} \frac{d[\int n_i(t) dl]}{dt} = 2\pi R I(t),$$

$$\text{so } \frac{d[\int n_i(t) dl]}{dt} = -4I(t).$$

We use line density—the observed quantity—rather than central density because it is then not necessary to estimate the plasma radius.

Values of $\int n_i(t) dl$ for run A are given in Table 4. The ratios of the values of charge exchange current, $I_c(t)$, needed to account for the plasma loss rate to the observed fast atom current, $I_0(t)$, also are shown in Table 4. The loss rates, $\dot{n}_i$, are obtained by subtracting successive observed values of line density rather than taking the slope of a smooth curve fitted to the data points. Mean values of the observed fast atom flux are taken from the exponential approximations of the charge-exchange data, in Fig. 17. Based on the present absolute calibration of the neutral analyzer, we obtain values of the charge-exchange current in particles $\text{cm}^{-2} \text{sec}^{-1}$ by multiplying the relative values shown in Figs. 17 through 21 by 0.558×10^{15} . From the values in Table 4, it is clear that charge exchange, on the average, fails to account for the loss rate by a factor near 90.

To obtain a better average of this factor, we note that the observed fast atom flux has the form $I(t) = i(200)e^{-\Delta t/\tau_1}$ from 200–800 μsec , with $\tau_1 = 2.2 \times 10^{-4}$ sec. After 800 μsec , it has the form $I(t) = I(800)e^{-\Delta t/\tau_2}$, where $\tau_2 = 7 \times 10^{-4}$ sec. Integrating the loss rate between t_1 and t_2 , we obtain

$$\int n_i(t_2) dl = \int n_i(t_1) dl - 4I(t_1)\tau_1 \times [1 - e^{-\Delta t/\tau_1}].$$

Then, substituting the values of $\int n_i(t) dl$ at 400 and 800 μsec ,

$$4.05 \times 10^{13} = 8.8 \times 10^{13} - 4 \times 2.2 \times 10^{-4} \times [1 - e^{-4/2.2}]I(400),$$

$$\text{we get } I(400) = 6.44 \times 10^{16} \text{ particles cm}^{-2} \text{sec}^{-1}.$$

$$\text{At 400 } \mu\text{sec, } I_0 = 1.2 \times 0.558 \times 10^{15} = 0.67 \times 10^{15}, \text{ indicating that, in this}$$

Table 4. Values of $\int n_i(t) dl$ and I_c/I_0 for run A.

Time, μsec	$n_i(t) dl \times 10^{-13}, \text{cm}^{-2}$	Time, μsec	I_c/I_0
370	9.75	390	68
410	8.79	440	101
470	7.58	485	107
500	6.95	550	49
600	6.12	600	79
720	5.12	760	207
800	4.05	850	66
900	3.67	950	112
1000	3.12	1065	116
1130	2.59	1165	183
1200	2.11	1250	86
1300	1.83	1350	73
1400	1.62	1450	83
1500	1.41	1550	70
1600	1.26	1650	57
1700	1.15	1750	44
1800	1.078	1850	49
1900	1.004	1950	38
2000	0.958	—	—
2100	0.895	—	—
2200	0.830	—	—

Fig. 18. Central plasma density, logarithmic decay rate, total light, charge-exchange current, scattered microwave power, and 17.5-keV fast atom signal for run B.

Fig. 19. Central plasma density, logarithmic decay rate, total light, charge-exchange current, scattered microwave power, and 17.5-keV fast atom signal for run C.

Fig. 20. Central plasma density, logarithmic decay rate, total light, charge-exchange current, scattered microwave power, and 17.5-keV fast atom signal for run D.

Fig. 21. Central plasma density, logarithmic decay rate, total light, charge-exchange current, scattered microwave power, and 17.5-keV fast atom signal for run E.

time interval, charge exchange fails to account for the plasma loss by a factor ≈ 80 . Using the 800- and 1400- μsec values of $\int n_i(t) d\ell$, $I(800) = 1.51 \times 10^{16}$, compared to the observed rate 1.5×10^{14} . This is a ratio ≈ 100 . Similarly, values of line density at 1600 and 2200 μsec yield $I(1600) = 2.7 \times 10^{15}$, which is a factor of 54 larger than the observed value, 0.5×10^{14} .

The above evaluation of charge-exchange loss per unit of surface area needed to account for the observed plasma loss rate is valid whether the plasma is thin or thick: that is, whether charge exchange is distributed in plasma volume or concentrated at the plasma surface.

Obviously, if the plasma lifetime can be increased enough, charge exchange will become a dominant loss process.

The conclusion that charge exchange losses cannot account for the anomalous plasma loss rate in 2XII—based on the current absolute determination of the fast atom flux—is confirmed by the following observations made in the course of operation:

- Loss rates for plasma densities near 10^{13} cm^{-3} are essentially the same for one- or seven-injector operation and are independent of injector output. This result indicates that the plasma containment is not limited by the transient pressure rise due to untrapped, unpumped injected plasma. Nor is containment dependent upon any late streaming plasma from the injectors. This latter conclusion is confirmed by direct measurement of external plasma densities, as discussed in more detail later in this report.

- Loss rates for plasma densities near 10^{13} cm^{-3} are independent of base

pressure in the range 2×10^{-9} to 2×10^{-8} Torr and independent of the time delay between plasma injection and the termination of titanium sublimation. These observations indicate that plasma containment is independent of transient increase of the external neutral density arising from desorption of gas from the vacuum chamber walls, for the amount of gas adsorbed on the wall is proportional to both the base pressure and this time interval.

INSTABILITY-RELATED LOSSES IN RUN A

In run A, there is no evidence, like that reported in the Novosibirsk paper,² of the multicomponent instability. Furthermore, no increases of the plasma loss rate are correlated with the observed large increases of the charge-exchange rate such as those seen at 600 and 849 μsec in Figs. 16 and 17. These "spikes" result from the simultaneous increase in several neutral analyzer channels (greater than spurious noise levels) and represent real fluctuations in the total charge-exchange rate.

In other runs, such as B and C which are discussed below, observable microwave scattering, broadening of the ion energy distribution, and increased visible radiation provide direct evidence of plasma turbulence. Such direct evidence is not found in run A. The absence of microwave scattering greater than the receiver noise level places an upper limit on the peak fluctuating potential within the plasma. For fluctuations with $\omega \sim \omega_{ci}$ and $\lambda_1 \sim 2\rho_i$, our present "ball-park" estimate of this limit is 100 V. However, low or high frequency fluctuations of larger amplitude

($\omega < 0.2 \omega_{ci}$ or $\omega < 6 \omega_{ci}$), as well as short wavelength fluctuations ($\lambda_{\perp} < \rho_i$), may exist without being detected with the present microwave scattering system.

Theoretically, the drift cyclotron loss cone mode is unstable for 2XII plasmas in this energy and density range. Furthermore, the energy distributions shown in Fig. 13 through 15 do not satisfy the approximate stability criterion, $(\Delta E/E_p) > 2$, for absolute stability against the Dory-Guest-Harris (DGH) instability mode. DGH threshold densities calculated on the basis of these distributions were far below the measured plasma density at all times in run A.

INTERPRETATION OF FAST ATOM CURRENTS

The local production rate of fast atoms for a single neutral species of density n_0 in a plasma containing only one singly ionized species of density n_i is $n_0 n_i \langle \sigma_{cx} v_i \rangle$. For the 2XII plasmas, in which the velocity of the ions greatly exceeds that of the neutrals, the average is taken over the charged particle velocity distribution.

As the mean lifetime of a thermal neutral in the dense high temperature plasma is less than 1 μ sec, the neutral population within the plasma depends on the transport rate of neutrals from the surrounding volume into the trapped plasma. On the basis of considerations discussed below, we conclude that the magnitude of the fast atom current is nearly proportional to n_0 and that, for $n_i > 10^{12} \text{ cm}^{-3}$, it is essentially independent of n_i .

For thermal atomic hydrogen or deuterium, the mean free path for ionization is

$$\lambda_i = v_0 (n_i \langle \sigma_{cx} v_i \rangle + n_e \langle \sigma_{ie} v_e \rangle + n_i \langle \sigma_{ii} v_i \rangle)^{-1},$$

where v_i and v_e , respectively, are the ion and electron velocities in the plasma ($v_i \approx 10^8 \text{ cm sec}^{-1}$ in 2X and 2XII plasmas). For protons, $\langle \sigma_{cx} v_i \rangle \approx 10^{-7}$, $v_0 \approx 2 \times 10^5$, so $\lambda_{cx} \approx 2 \times 10^{12} (n_i)^{-1}$: that is, $\lambda_{cx} < 2 \text{ cm}$ for $n_i > n = 10^{12} \text{ cm}^{-3}$.

For thermal molecular deuterium which may arise from the untrapped, unpumped fraction of the injected plasma by neutralization at the walls, $v_0 \approx 10^5 \text{ cm sec}^{-1}$, $\sigma_{cx} \approx 8 \times 10^{-16} \text{ cm}^2$, and, consequently, $\lambda_{cx} \approx 1.25 \times 10^{12} (n_i)^{-1} \text{ cm}$.

For thermal methane (CH_4), which is the residual background gas in the gettered system, $v_0 \approx 5 \times 10^4 \text{ cm sec}^{-1}$ and $\sigma_{cx} \approx 2 \times 10^{-15} \text{ cm}^2$ in the energy range 100 eV-20 keV, so $\lambda_{cx} \approx 2.5 \times 10^{11} n_i^{-1} \text{ cm}$.

When the impact terms are included, the mean free paths for ionization are found to be approximately half the λ_{cx} values. Thus, for plasmas in the 2X and 2XII experiments, the mean free path is always less than the plasma radius, and essentially all neutrals entering the plasma are ionized. Clearly, if the background gas were atomic hydrogen, the resulting fast atom flux would be independent of n_i and proportional to n_0 . For this case, a constant fast atom current from the plasma would indicate a constant neutral density external to the plasma.

The situation is more complicated for molecular neutrals, which frequently produce energetic neutral fragments upon dissociation (the Franck-Condon effect). For example, dissociation of H_2 yields H

atoms with energies up to 9 eV, for which $\lambda_1 \leq 2 \times 10^{13} n_1^{-1} \text{ cm}$ in the 2XII plasma. The maximum energy of the dissociation fragments from other molecular constituents is less than 9 eV. Thus, in 2XII, λ_1 for Franck-Condon neutrals is less than the plasma radius, r_p , for $n_1 > 10^{13} \text{ cm}^{-3}$; but as the plasma density decreases, λ_1 eventually equals and then exceeds r_p .

To estimate the dependence of the fast atom current on plasma density resulting from the Franck-Condon neutrals, consider a dense cylindrical plasma in which $\lambda_1 \ll r_p$ for thermal neutrals. A fraction f_1 of the incident thermal flux $1/4 n_0 \bar{v}_0$ charge-exchanges and a fraction f_2 dissociates, producing a fast neutral flux $n_F = 1/4 n_0 \bar{v}_0 f_2$. About half the Franck-Condon neutrals formed in the boundary layer are directed out of the plasma and do not contribute to the charge-exchange current $I(t)$. The attenuation of those dissociation fragments directed into the plasma is

$$V_F (dn_F/dy) = - n_F n_1 \sum \langle \sigma v \rangle,$$

where V_F is the velocity of the Franck-Condon neutral. If the fractional contribution of charge exchange to the attenuation of Franck-Condon neutrals is f_3 , then the total charge-exchange current per unit surface area is

$$I(t) = \frac{1}{4} n_0 \bar{v}_0 \left[f_1 + \frac{f_2 f_3}{2} \times \left(1 - \exp - \frac{\sum \langle \sigma v \rangle}{V_F} \int n_1 dy \right) \right].$$

Let $\Lambda_F = \bar{v}_F / \sum \langle \sigma v \rangle$. The term $\int n_1 dy$ is the average plasma line density

along the flight direction of the dissociation products.

Fast neutrals which escape do not return to the plasma as energetic particles after striking the vacuum chamber walls.

If the background gas is H_2 , the mean energy of the Franck-Condon neutrals is about 2.2 eV, so $\bar{v}_F \approx 2.1 \times 10^6 \text{ cm sec}^{-1}$ and $\Lambda_F \approx 10^{13} \text{ cm}^{-2}$. In this case, $f_3 = f_1$, and values for the term in square brackets are shown in Table 5 for the observed line densities of run A. ($\int n_1 dy$ was taken to be equal to $\int n_1 dl$ and f_2 was assumed to be unity.)

It is seen that the charge-exchange current would decrease about 17 percent due to an order of magnitude decrease of n_1 if n_0 remained constant.

The dissociation of methane, which is more complicated, is being reviewed by J. R. Hiskes. He finds that a significant number of H atoms of mean energy $\approx 1 \text{ eV}$ and H_2 molecules of mean energy $\approx 3 \text{ eV}$ are produced. The H atoms lead to a smaller dependence on n_1 than the H_2 molecules. The velocity of 3-eV H_2 molecules $\approx 10^6 \text{ cm sec}^{-1}$, so for the 2XII plasma $\Lambda_F \approx 0.63 \times 10^{13}$, which is also somewhat less than the value for Franck-Condon neutrals from H_2 dissociation. Thus we conclude that the

Table 5. Relative dependence of charge-exchange current on line density in run A.

Time, μsec	$10^{13} \int n_1 dl, \text{ cm}^{-2}$	$1 + \frac{1}{2} \left[1 - \exp - \left(\int n_1 dl / \Lambda_F \right) \right]$ Value	Normalized value
400	8.8	1.5	1.00
800	4.2	1.49	0.99
1200	2.1	1.44	0.96
1600	1.28	1.36	0.91
2000	0.96	1.31	0.87
2400	0.71	1.25	0.83

charge-exchange current is proportional to the neutral background density and only slightly dependent on the plasma density in the 2XII experiments. However, we also find that for a H_2 background (see Table 5), as much as one-third of the fast atom current may arise from charge exchange with dissociation fragments and thus can provide a significant contribution from the plasma interior to the energy spectra measured by means of the 11-channel neutral analyzer.

EVIDENCE OF PLASMA INSTABILITIES AND MODE IDENTIFICATION

Based on the microwave interferograms, the data from the unapertured single-injector operation can be divided into three modes:

- Smooth decays such as run A;
- Late plasma dumps;
- Early plasma dumps.

From inspection of the data, we see that late dumps, such as that at $t \approx 1300 \mu\text{sec}$ in run B, were always accompanied by increases in all of the following: (a) the total light emission (see Fig. 3), (b) H_α radiation, (c) the relative number of high energy atoms in the charge-exchange current (see the 17.5- and 11.5-keV signals in Fig. 6), and (d) scattered microwave power. The same correlations are also found for all early plasma dumps, such as that in run C between 400 and 630 μsec (Fig. 11); but as all signals are rapidly decreasing early in time, the evidence is not as readily distinguished here as in run B.

The temporal relations between these and other data are shown in Figs. 18 and 19, where plasma density, logarithmic loss

rate ($n^{-1}\dot{n}$), scattered microwave power, charge-exchange current, visible radiation, and the normalized 17.5-keV neutral analyzer signal are shown as a function of time for runs B and C.

It is noted that the logarithmic decay rate during the plasma dumps in runs B and C exceeds, by factors of 2 and 5, that of the "early unstable" periods in the runs discussed in the Novosibirsk paper. This comparison is pointed out because the evidence of instability in runs B and C is quite similar to that in the 2X operation, and the difference of loss rates in the two experiments could be related to the greater distance between the trapped plasma and the vacuum chamber walls in 2XII.

Data relevant to this and other questions about the plasma density external to the magnetic mirrors was obtained by means of a 10-GHz microwave interferometer which monitored the plasma density outside the mirror at the injection end. Rather than indicating that the external plasma has a stabilizing influence, the data of Fig. 4 suggest a destabilizing influence. For example, the plasma loss rate in run C decreased abruptly at the same time the external density became too low to observe; and in run A, which did not exhibit a plasma dump, the external plasma density disappeared before the end of the magnetic compression. However, this simple correlation was not confirmed in a comprehensive examination of the data from all runs in this series. We conclude that the measurements to date provide neither evidence of a simple stabilizing or destabilizing influence of the external plasma density near the axis at the injection end.

In addition to temporal correlations between the logarithmic loss rates and the increase or decrease of scattered microwave power, the magnitude of these two quantities are related. For example, compare the run A loss rate at 400 μsec where no microwave scattering was observed, to runs B and C. In run C, where intense microwave scattering was present from time of plasma trapping until 680 μsec , $n^{-1} dn/dt$ was 2.6 times greater than in run A. Similarly, in run B, where the scattered signals were weaker than in run C and did not reach observable levels until 420 μsec , $n^{-1} dn/dt$ was 1.7 times greater than in run A. Furthermore, in a given run, such as shown in Fig. 19, the decay rate and the scattered microwave signal fall together; and when the scattered power reaches the received noise level, $n^{-1} dn/dt$ is at its minimum. Later in run C, when the decay rate again increases, the scattered microwave signal reappears (see Fig. 22 at 1700 μsec).

Again, good correlation is found between the early rise of the scattered microwave signal and an increase of the loss rate at 400 μsec in run B (see Fig. 18). Also, in run B, this correlation reappears during the plasma dump at 1300 μsec . Unfortunately, in run B the amplifier in the microwave detector was saturated between 600 and 1200 μsec , so there is no scattered microwave information for that period.

A similar correlation is found between $n^{-1} \dot{n}$ and the normalized 17.5-keV neutral analyzer signal (normalized by dividing the charge-exchange current). In run B, for example, the normalized 17.5-keV signal provides evidence that plasma

turbulence is associated with the accelerated plasma losses early in time, as well as later during the plasma dump at 1300 μsec .

Final reduction of electrical noise pickup in the microwave scattering receiver had not been completed at the time of the earlier seven-injector runs D and E. Although there is evidence of scattering in these runs, the data are insufficient to estimate the scattered microwave power. Based on the normalized 17.5-keV signals (Figs. 20 and 21), runs D and E appear to have been strongly turbulent in the intervals 400-500 μsec and 400-650 μsec , respectively.

The intensity of line radiation from neutral atoms (e.g., 6563 Å H_α radiation), as well as the charge-exchange current, depend on the transport rate of neutrals into the trapped plasma. The total light signal, monitored by an RCA 8575 photomultiplier, has been found to follow the H_α signal closely (see Figs. 17 through 21). The light signals generally follow the charge-exchange current, though deviations are observed (such as at 620 μsec in run C, where no transient increase of charge exchange accompanies the light signal). Such light peaks are coincident with rf activity (e.g., in Fig. 22) in the frequency range $0.25 < \omega/\omega_{ci} < 0.8$.

In our analysis of data from several runs (Figs. 17 through 21), we have found no simple correlation between the fluctuation or magnitude of the neutral density (as indicated by either light or charge-exchange signals) and the plasma loss rate or any other evidence of instability. For example, from the data in Table 6, there is no consistent correspondence between loss rate and either the magnitude of $I(t)$ or the ratio

Fig. 22. Intensity of scattered microwave signals for run C.

Table 6. Loss rate, charge-exchange current, and line density for several runs.

Time, μsec	Run	$10^{-13} \int n_i d\ell$	$I(t)$	$10^{14} I(t) / \int n_i d\ell$	$n^{-1} \dot{n} \times 10^{-3}$
400	A	8.8	1.3	1.5	-2.3
	B	6.8	0.58	0.85	-3.9
	C	7.2	0.85	0.12	-6.1
1200	B	0.96	0.18	1.9	-1.07
1325	B	0.58	0.261	3.67	-9.2
1500	B	0.24	0.122	5.11	-2.43
450	C	5.1	0.72	1.42	-7.16
470	C	1.8	0.62	3.33	-22.5
700	C	0.75	0.55	7.0	-0.57

of charge-exchange current to line density, $I(t)/\int n_i d\ell$. If decay rate of the charge-exchange current in run A can be taken as the upper limit for the characteristic pump-down time of a transient increase of neutral density in the containment chamber, the interruption of the exponential decay of $I(t)$ at $t \approx 420 \mu\text{sec}$ in run C indicates an increase in production of neutrals. This increased production follows a period of strong microwave scattering, energy spreading, and rapid plasma loss, and hence appears to be an effect rather than a factor leading to instability. Similarly, in run B, the early scattered microwave signal precedes evidence of enhanced neutral production, but later in time the neutral density obviously increases before evidence of instabilities appears.

Sequences of ion energy spectra separated by $20 \mu\text{sec}$ were constructed for runs A through E from data stored on magnetic tape. Those of run A agree with the spectra in Figs. 13 through 15, which were obtained by reading the photographed

oscilloscope traces. Throughout run A, the ion energy spectrum had a single maximum lying close to the low energy cutoff. The average ion energy in run A, which remained in the range 1.5-2.1 keV, was lower than that of the other four runs by a factor of 3 to 5.

The striking difference of the ion energy spectra in runs A and C, as shown by the comparisons at 350, 420, and 500 μsec in Figs. 23 and 24, is due primarily to differences in timing (see Table 2) and, to a lesser extent, to differences of the magnitude of the guide field.

The fact that the ion energy distribution in run C had three distinct maxima early in time (Fig. 23) suggests that the "double-humped" instability may account for the difference of early loss rates in runs A and C. In agreement with this hypothesis of a "double-humped" instability, the loss rate in run C dramatically decreased by $t \approx 700 \mu\text{sec}$ when, within the uncertainties of the data, both low energy peaks had disappeared (see Figs. 18

Fig. 23. Energy spectra at 360, 380, and 400 μ sec (run C) and 350 μ sec (run A).

Fig. 24. Energy spectra at 420, 500, and 600 μ sec (run C) and 420 and 500 μ sec (run A).

and 25). As mentioned above, microwave scattering and energy spreading, which indicate plasma turbulence, also disappeared at the time the loss rate changed.

No substantial correlation of plasma loss, energy spreading, etc., has been found with low energy peaks (i.e. $E < 2$ keV), such as seen at 500, 940, and 1000 μ sec in run C (Fig. 25). As these second peaks do not precipitate an instability, perhaps they are associated with a local concentration of low energy ions in the plasma boundary.

Formation of the 3-keV peak in run C, which was timed to trap a high energy plasma, possibly can be attributed to ions entering the containment region after the fast gate field was applied. A few of the late ions will be trapped by the rising magnetic compression field; but as they must enter with relatively low perpendicular energies, they will be heated less by the compression and could thus form a lower energy group.

Selected ion energy spectra from run B are shown in Figs. 26 through 28. Again, a single peaked energy distribution evolves from an initial double-humped distribution during a period of rapid plasma loss (compare the spectrum at 1200 μ sec, Fig. 28, with that at 1400 μ sec, Fig. 29). However, for the greater part of run B and during runs D and E (Figs. 30 through 32), the energy distributions had two or more maxima. Thus, although the loss rates of these plasmas exceed that of run A (or run C following the plasma dump), multi-maxima distributions can be seen to persist for hundreds of microseconds without causing catastrophic plasma dumps. The difference in plasma loss rate for apparently similar multi-maxima distributions can be reconciled by postulating that in the examples of lower loss rate, the double-humped distribution is characteristic of successive small

Fig. 25. Energy spectra for run C at 660, 720, 800, 880, 940, 1000, and 1100 μ sec.

Fig. 27. Energy spectra for run B at 600, 700, 800, 900, and 1000 μ sec.

Fig. 26. Energy spectra at 400, 450, and 550 μ sec (run B) and 550 μ sec (run C).

Fig. 28. Energy spectra at 1100, 1180, 1200, and 1300 μ sec (run B) and 560 μ sec (run C).

Fig. 29. Energy spectra for run B at 1320, 1340, 1360, 1380, and 1400 μ sec.

Fig. 31. Energy spectra for runs D and E at 700, 800, 900, and 1000 μ sec.

Fig. 30. Energy spectra for runs D and E at 400, 500, and 600 μ sec.

Fig. 32. Energy spectra for runs D and E at 1200, 1400, and 1500 μ sec.

volume regions (e.g., the plasma boundary), whereas in a plasma dump a large fraction of the plasma volume is involved.

If the late plasma dumps and accelerated plasma losses do arise from double-humped distributions, then some mechanism must produce the second energy group. Direct evidence of the formation of low energy ions is provided by the reoccurrence of a second peak near the low energy cutoff in runs B, C, D, and E. Even in run A, there is fluctuation in the relative magnitude of the maximum near the low energy cutoff.

As cooling of the energetic plasma ions would be expected to yield a smooth distribution, we are led to examine the possibility that ions formed from the neutral background gas are trapped and heated. Charge-exchange products are deposited into the plasma either by thermal atoms with 0.03-eV energy or by Franck-Condon neutrals with 1-10 eV energies. The rate of cold ion formation in the plasma boundary by ionization of the incident neutral flux is

$$\begin{aligned} dn_c/dt &= n_0 [n_i \langle \sigma_{cx} v_i \rangle + n_e \langle \sigma_{ie} v_e \rangle \\ &+ n_i \langle \sigma_{ii} v_i \rangle] = n_0 n_i \Sigma \langle \sigma v \rangle \end{aligned}$$

for a hydrogen plasma. The neutral density, n_0 , can be estimated from the observed fast atom current

$$I(t) = \frac{1}{4} n_0 v_0 \frac{\langle \sigma_{cx} v_i \rangle}{\Sigma \langle \sigma v \rangle}.$$

Thus, the ratio of cold to hot ions accumulated in a time Δt in the plasma boundary is

$$\frac{\Delta n_c}{n_i} = \frac{4I(t)}{v_0} \frac{\Sigma \langle \sigma v \rangle^2}{\langle \sigma v \rangle} \Delta t,$$

where Δt is the average transit time of cold ions to a magnetic mirror. If the plasma potential is uniformly distributed, forming a constant electric field along the magnetic lines from the plasma center to the mirrors, then, for protons, Δt will be in the range 2-4 μsec for plasma potentials corresponding to the observed values (0.4-1 kV) of the low energy cutoff in the fast atom spectra. However, if the plasma potential is concentrated in sheaths near the mirrors, the transit time of cold ions to the mirrors could be much longer than 2 μsec . A lower limit of the cold ion concentration in the boundary can be estimated assuming a background of atomic hydrogen for which $\Sigma \langle \sigma v \rangle \approx 2 \langle \sigma_{cx} v \rangle \approx 2(10^{-7})$. Then

$$\Delta n_c/n_i = 8 \times 10^{-12} I(t) \Delta t.$$

For run A at 500 μsec , $I(t) = 5 \times 10^{14}$ fast atoms $\text{cm}^{-2} \text{sec}^{-1}$ and $\phi = 0.75$ kV. Assuming the plasma potential is uniformly distributed, $\Delta n_c/n_i = 8 \times 10^{-3}$. If the plasma potential is concentrated in a sheath, this concentration could be much greater.

A cold ion will be trapped in the magnetic well only if it can acquire a rotational energy exceeding the plasma potential, $\phi \sim 2.5 T_e$, in one transit time. Since Coulomb scattering times for 2XII plasma parameters are much longer than 1 μsec , the possibility of acceleration due to fluctuating electric fields in the plasma is considered. The electric field required to accelerate a deuterium ion to the plasma potential $\phi = 2.5 T_e = 750$ V is calculated by

$$\sqrt{(V)_{\text{final}}^2} = (e/M) \sqrt{t \cdot \tau},$$

where t is the transit time ($\sim 2 \mu\text{sec}$) and τ is the electric field correlation time which we take to be one cyclotron period ($\sim 0.2 \mu\text{sec}$). For $V_{\text{final}} = 2.7 \times 10^7 \text{ cm/sec}$, we calculate

$$E = 84 \text{ V/cm.}$$

For comparison, we estimate the electric field associated with ion-cyclotron instabilities by assuming that $k_{\perp} \approx \pi/a_i$ and that $\tilde{\phi}$ is limited by nonlinear mechanisms to $\tilde{\phi} = T_e$; thus, $\tilde{E} = k_{\perp} \approx \pi/a_i$. For 2XII, we take $T_e = 300 \text{ eV}$ and $a_i = 2 \text{ cm}$ ($T_i = 5 \text{ keV}$, $B_0 = 7 \text{ kG}$), and calculate $\tilde{E} = 438 \text{ V/cm}$.

It is seen that relatively modest electric fields $\sim 100 \text{ V/cm}$, which are low enough to have escaped detection, are sufficient to heat deuterons to high enough energies in one transit time so they are not expelled by the plasma potential $\sim 750 \text{ eV}$. This mechanism could explain the accumulation of the low energy ion component as well as providing means whereby other constituents, such as hydrogen, could be accumulated in the plasma.

Fluctuating electric fields of sufficient intensity could be generated due to the presence of one or more instability modes. The concentration of thermal ions calculated above, for example, may be high enough to produce the double-humped mode in the plasma boundary. Also, as mentioned in our discussion of run A, both the Dory-Guest-Harris and drift cyclotron loss cone instability modes may be present.

We conclude that there is sufficient neutral flux and possibly also an adequate heating mechanism to account for the observed reappearance of the secondary

peaks near the low energy cutoff in the fast atom spectra. In time, this energy group will extend beyond the shallow plasma boundary, due in part to the expanded size of the gyroradii when the ions are heated and also to the continuing accumulation of ionization products deeper within the plasma volume. When the concentration of the ion group near the cutoff energy becomes great enough, a double-humped instability should be excited. As observed during the period of plasma turbulence, the double-humped feature is eliminated. Repetition of this cycle could account for the frequently observed sudden decreases of plasma density.

SUMMARY

We summarize our conclusions and suggest possible directions for future work as follows:

- Diversion of the magnetic field lines into the large end tanks has reduced the effect of the containment chamber walls on plasma formation and containment.
- Charge-exchange losses were negligibly small.
- For 2XII experiments, the total charge-exchange current, $I(t)$, is essentially proportional to the density, n_0 , of the external neutral gas and only slightly dependent upon the plasma density, n_1 .
- The maximum fractional contribution to the charge-exchange current from the plasma interior is near 0.35, so the measured ion energy spectra were heavily weighted by the ion energy distribution in the plasma boundary.

- No simple correlation was observed between magnitude or fluctuations of the external neutral density and plasma turbulence, instability, or loss rate.
- No simple correlation was observed between late streaming plasma (near the axis) and plasma turbulence, instability, or loss rate.
- Tentatively, we attribute the occurrence of brief periods of very rapid plasma loss to effects of the double-humped instability.
- The accelerated but less than catastrophic plasma loss rates in distributions which appear to have two or more maxima for long periods of time could arise from local rather than a volume-distributed effect of the double-humped instability.
- The loss rate of a 2-keV plasma, which had a single maximum with $\Delta E/E_p < 2$, was 2 to 4 times the loss rate calculated for collisional scattering at a density of 10^{13} cm^{-3} . The ratio of observed to calculated loss rates increased about a factor of 2 during an order of magnitude drop in density.
- On the basis of run A and the loss rate following the run C plasma dump ($t = 800 \mu\text{sec}$), n_T does not appear to be energy-sensitive. In both plasmas, $\Delta E/E_p < 2$. This conclusion may be unduly pessimistic, as the run C maximum at this time is considerably greater than the value of the low energy

cutoff and lower energy maximum tend to reoccur. Thus, the double-humped instability may also be a contributor to losses in this case.

- The tendency of maxima to form near the low energy cutoff indicates the presence of fluctuating electric fields not detected by the present microwave scattering measurement.
- As illustrated by the differences in runs A and C, the trapped ion energy distribution can be grossly changed by varying the injection timing. Similar data were obtained for the peripheral injectors.

In the next series of runs, Dory-Guest-Harris (DGH) stable distributions will be formed through the use of three or more injector groups capable of being charged and timed independently. Based on the observations reported above, we will locate the peak of the distribution near the low energy cutoff to avoid formation of double-humped ion energy distributions. Using similar stable distributions, we will investigate the energy dependence of n_T .

As the present measured energy distribution may be strongly weighted by conditions in the plasma boundary rather than representing the plasma interior, we are installing a modulated, high-energy, high-density, neutral beam to generate charge-exchange signals from the plasma interior.

REFERENCES

1. F. H. Coensgen, W. F. Cummins, V. A. Finlayson, and W. E. Nexsen Jr., "2X-2XII," in Controlled Thermonuclear Research Annual Report July 1969 through June 1970, Lawrence Livermore Laboratory Rept. UCRL-50002-70 (1970).
2. F. H. Coensgen, W. F. Cummins, R. E. Ellis, and W. E. Nexsen Jr., "Decay Modes of a Dense Plasma in a Magnetic Well," in Proc. 3rd International Conference on Plasma Physics and Controlled Thermonuclear Research, Novosibirsk, USSR, 1968 (Vienna, International Atomic Energy Agency, 1969), Vol. II, pp. 225-238.
3. F. H. Coensgen, W. F. Cummins, W. E. Nexsen Jr., V. A. Finlayson, and T. C. Simonen, "Plasma Containment in the LRL-2X Experiment," in Proc. 4th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wi., USA, 1971 (Vienna, International Atomic Energy Agency, 1971), Vol. 2, pp. 721-734.