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UCRL-50002-75

CONTROLLED THERMONUCLEAR RESEARCH ANNUAL REPORT

July 1974 through June 1975

Scientific Editor: M. A. Harrison
General Editor: C. K. McGregor

MASTER

October 15, 1975

Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

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Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$; Microfiche \$2.25

Page Range	Domestic Price	Page Range	Domestic Price
001-025	\$ 3.50	326-350	10.00
026-050	4.00	351-375	10.50
051-075	4.50	376-400	10.75
076-100	5.00	401-425	11.00
101-125	5.25	426-450	11.75
126-150	5.50	451-475	12.00
151-175	6.00	476-500	12.50
176-200	7.50	501-525	12.75
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LAWRENCE LIVERMORE LABORATORY
University of California Livermore, California 94550

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CONTROLLED THERMONUCLEAR RESEARCH

ANNUAL REPORT

ABSTRACT

Major experimental and theoretical results achieved by the Controlled Thermonuclear Research (CTR) program at Lawrence Livermore Laboratory during FY 1975 gave the greatest encouragement to date that the ultimate goal of a deuterium-tritium-fueled mirror reactor can be reached. In the experimental program, the year was characterized by unusually important physics results from the 2XIIB experiment and by significant steps in the plan to change the Baseball II mode of operation. The stabilization of ion-cyclotron instabilities in the 2XIIB experiment by the introduction of an auxiliary warm plasma permitted the buildup of a high-temperature, high-density plasma with an nT parameter an order of magnitude larger than the 2XII experiment. This was achieved by the use of an array of 12 neutral-beam sources and not only confirmed a theoretically predicted stabilization technique but also demonstrated that neutral-beam injection does not stimulate additional plasma losses. In the Baseball II experiment, preliminary tests and computer predictions indicated that a dense, transient, target plasma can be created by laser irradiation of a pellet in midflight through the center of the Baseball confinement zone.

Supporting research continued on a number of long-range programs. Highlights included the apparently successful use of the "bronze" method for producing multifilamentary Nb_3Sn for high-field superconducting magnets; the experimental confirmation of a technique for high-efficiency direct energy conversion; and the completion of both detailed parametric studies and conceptual system designs of fusion-fission and pure-fusion reactors. Work continued on several aspects of neutral-beam technology, including the development (in collaboration with Lawrence Berkeley Laboratory) of a 50-A, 40-kV, pulsed neutral beam. Many of the experiments designed to study the damage induced in materials subjected to 14-MeV neutrons were performed in cooperation with other laboratories. In the tritium research program, work began in two areas: development of a method for extracting tritium from the atmosphere of a reactor enclosure, and improvement of tritide targets for the RTNS-II neutron source.

Agreement between theoretical and experimental results led to increased confidence in linear and quasilinear theory. Advances during the year included a program for studying the magnetic trapping of laser-generated target plasmas, a code for the computation of finite-beta guiding-center equilibria in minimum-B geometry, and a series of Fokker-Planck codes describing classical loss processes. A quasilinear model of the drift-cyclotron loss-cone mode has been developed that agrees very well with 2XII-B data. Gas-embedded Z-pinchs initiated either by a relativistic electron beam or by exploding tubes were the subject of a small exploratory research program.

SECTION 1. CONFINEMENT SYSTEMS

INTRODUCTION AND SUMMARY

The period covered by this progress report was highlighted by unusually important physics results from the 2XIIB experiment. These results followed a major rebuilding of the 2XIIB facility that was completed during the report period. In addition, several significant steps were taken in our plan to change the mode of operation of Baseball II from a vacuum-buildup to a target-buildup mode.

The following major physics results were obtained from the 2XIIB experiment during the report period:

- Stabilization of ion cyclotron instabilities by the introduction of an auxiliary, warm-plasma component.
- Demonstration, following stabilization, of a confinement $n\tau$ factor that increased with ion energy over the range 3 to 13 keV.
- Achievement and maintenance of high plasma β -values (of order 0.4) at high plasma temperatures.

These results were achieved using the array of 12 high-current neutral-beam sources (with 20-keV, 50-A nominal design parameters) that had been installed during the rebuilding of 2XII.

The significance of these physics results was doubly enhanced because

- They were achieved by utilizing a stabilization technique that had been earlier proposed from theory, thereby giving us greater confidence in our understanding of the system behavior; and
- They were achieved during neutral beam injection at high currents, thereby demonstrating that the process of neutral beam injection did not of itself stimulate major additional plasma losses.

The achievement in 2XIIB, which operates in a pulsed mode, of a stabilized, high-temperature, high-density plasma has given additional impetus to our preparations for achieving similar plasma conditions in Baseball II, where there exists a steady magnetic field that is higher in intensity than that attainable in 2XIIB. We plan to achieve startup by creating a dense, transient, target plasma by irradiating a carefully aimed pellet in midflight through the center of the Baseball confinement zone. Beams from a large (300-J) CO_2 laser system will be used for the irradiation and subsequent ionization and heating of the pellets.

During the report period, a successful pellet-launching technique was demonstrated, based on the work of Hendricks at the University of Illinois; and the guidance and control of this electrically charged pellet (frozen ammonia in these tests) to the irradiation zone using computer-controlled electrostatic steering fields was demonstrated. Although the technique needs to be refined, it appears that it can satisfy our needs. Preliminary tests and computer predictions of the irradiation process are also encouraging. According to present plans, Baseball II-T (Baseball II as modified with a target plasma and intense neutral beam source) will also follow the lead of the 2XIIB experiment by incorporating a stabilizing plasma stream.

Due to the limited size of our present facilities, we cannot adequately investigate the scaling laws for mirror confinement. However, we can go a considerable way in these experiments toward further demonstrations of the basic soundness of our understanding of mirror confinement; from this understanding, mirror fusion reactors will in time be designed.

2XIIB EXPERIMENT

Introduction

The 2XIIB experiment was brought into operation during FY 1975. There were three periods of experimentation: in January, in March, and from May until mid-July. Each experimental period showed progressive improvement in vacuum conditions, in output current of the neutral beam injectors, and in plasma diagnostics. January operation was with low-beam current, poor vacuum conditions, and minimal diagnostics. Operation in March was with higher-beam currents but with no improvement in the surface conditions of the vacuum wall. Modifications in April provided a significant improvement in vacuum. Then, during operation in May, we observed that ion cyclotron microinstability levels were enhanced by the injection of high-current neutral beams. Consequently, we attempted to prevent microinstability by various methods of plasma gun operation.

At the end of FY 1975, we achieved a major improvement in plasma confinement: we reduced ion cyclotron instabilities with the addition of an auxiliary, warm-plasma component.¹ The principal experimental results obtained with this stabilizing plasma stream were:

- Increase of ion energy from 3 to 13 keV,
- Density buildup to $4 \times 10^{13} \text{ cm}^{-3}$,

- Achievement of peak plasma β 's up to 0.4,
- Measured increasing $n\tau$ with ion energy, and
- Reduced rf turbulence.

Plasma Confinement Experiments

The 2XIIB magnet system was described in last year's Annual Report² and is similar to that of 2XII.³ Cross sections of the machine are shown in Fig. 1.

Parameters for the 2XIIB magnet are:

Central field:	0.67 T
Mirror ratio:	2:1
Distance between mirrors:	150 cm

In this minimum-B magnet system, a target plasma with the following parameters is produced:

Density:	$\leq 5 \times 10^{13} \text{ cm}^{-3}$
Mean ion energy:	2 to 5 keV
Electron temperatures:	80 to 150 eV
Plasma confinement time:	0.2 to 0.4 ms

This plasma forms an ionization target for capturing atoms from an array of 12 neutral beam injectors.⁴ In experiments during FY 1975, up to 370 A (equivalent atom current) was injected at extraction energies of 15 to 19 keV. The current was divided approximately 0.5, 0.4, and 0.1 between full-, half-, and third-energy components.⁵ Although neutral beam injection increased mean ion energies from 3 keV to 13 keV, it also increased the fluctuation level with no net improvement in particle confinement.

We improved plasma confinement by injecting warm plasma⁶ along magnetic field lines. This "streaming" plasma reduced fluctuation levels, and thus we attribute the increased confinement time to the suppression of rf fluctuations. This streaming plasma is supplied from a standard,⁷ 5-cm-diam, deuterium-loaded-titanium, washer gun operated with 1.1-ms-duration pulse line.⁸

Figure 2 compares measured line densities following neutral beam injection with the warm plasma stream on and off. For comparison, we show in Fig. 3 the peak ion cyclotron instability amplitude $\tilde{\phi}$ (in the frequency range $0.8 < \omega/\omega_{ci} < 1.2$) measured beyond the mirrors with an electrostatic probe.⁹ Since turbulent scattering rates depend on $\tilde{\phi}^2$, these reductions in instability amplitudes with streaming plasma correspond to order-of-magnitude reductions in scattering loss rates. The buildup of plasma line density (Fig. 2) is due predominantly to buildup of a hot-ion plasma, rather than of a warm component.

(a) Elevation

Fig. 1. 2XIIB assembly.

Fig. 1. Continued.

Fig. 2. Line density with and without plasma stream.

Fig. 3. Ion cyclotron instability amplitude with and without plasma stream.

Fig. 4. Density, diamagnetic-loop, and neutral measurements with plasma stream.

We base this conclusion on the agreement, shown in Fig. 4, between magnitudes and buildup rates of density, plasma diamagnetism, and the square root of neutron production. Hot-ion densities measured by charge exchange of the neutral beam support this conclusion.

The buildup of density n is described by

$$\frac{1}{\tau} = \frac{1}{n} \frac{dn}{dt} = \frac{1}{n_h + n_w} \left(\frac{dn_h}{dt} + \frac{dn_w}{dt} \right),$$

where n_h and n_w are the hot- and warm-plasma densities. Assuming a constant warm-plasma density, n_w , the density buildup rate is

$$\frac{1}{\tau} = \frac{1}{n_h + n_w} \frac{dn_h}{dt} = \frac{Il}{eV} (\sigma_i + \alpha \sigma_x) - \frac{1 - \alpha}{\tau_L}. \quad (1)$$

Here, l and V are the plasma diameter and volume, and σ_i and σ_x are ionization and charge-exchange cross sections. An upper limit to the fraction of warm plasma $\alpha = n_w/(n_h + n_w)$ is estimated from line-density measurements to be ~ 0.2 .

Equation (1) includes inputs due to ionization on both hot and warm components as well as charge exchange on the streaming component. The loss time, τ_L , includes Coulomb scattering, electron drag, charge exchange on background gas, instabilities, and any residual particle input due to trapping of the streaming plasma by processes other than charge exchange with the neutral beam, e.g., trapping by rf electric fields. Charge-exchange losses from background gas and wave-scattering losses, though strongly suppressed by gettering and streaming plasma, are not negligible on the long confinement time scales of the present experiments.

Figure 5 shows, as a function of injected beam current, experimental τ^{-1}

Fig. 5. Density buildup rate vs neutral beam current.

values obtained from microwave interferometer measurements during periods when fluctuations were suppressed. The zero-current intercept of Fig. 5 determines that the lifetime τ_L is ~ 10 ms for $\alpha = 0.2$ with a 5-ms lower standard deviation limit. The upper limit is indeterminate, because statistically the τ^{-1} intercept could be positive.

Of particular importance are measurements of τ_L versus average ion energy for stabilized plasma. Figure 6 shows solid circles for τ_L values determined from the intercept of line-density curves (Fig. 2) and open circles for measurements obtained by switching off the neutral beam input and measuring the plasma density decay rate (Fig. 7). These data, taken at a density of $1.5 \times 10^{13} \text{ cm}^{-3}$, show confinement time increasing with ion energy. For comparison, a curve is shown in Fig. 6 for $n\tau = 2 \times 10^9 E_i^{3/2}$. The coefficient of this curve is about one third that found in Fokker-Planck calculations¹⁰ without the streaming

Fig. 6. Measured $n\tau$ vs average ion energy.

Fig. 7. Line density decay after neutral beam turnoff with plasma stream.

plasma. Since our measurements were obtained in the presence of residual charge-exchange and fluctuation losses and during periods of a few hundred microseconds when the stabilizing plasma stream was on, one would not expect agreement with steady-state Fokker-Planck calculations. Rather, this comparison demonstrates that the fluctuation losses have been significantly reduced.

To summarize, recent experiments on 2XIIB have demonstrated a means of suppressing microinstability amplitudes so that losses associated with these waves are reduced. Although there are no direct measurements to identify a specific mechanism, filling of the loss cone is a plausible theoretical explanation¹¹ for the observed stability.

Operation of 12 Neutral Beam Sources

The installation of 12 neutral beam power supplies and modules on 2XIIB was completed in FY 1975. The power supplies were debugged, and cross-talk problems between power supplies were reduced. Source operation delivered up to 370 A (equivalent) into the 2XIIB plasma at an average extraction energy of 17 keV. We are continuing to increase the current and energy by more precise control of beam operating parameters, by improvements in the electronics, and by rebuilding out-of-tolerance grids in beam modules.

At present, two to three technicians can operate the entire 12-beam system. However, because optimum operation requires a very highly sustained level of concentration, we are developing a computer control system that will assist and eventually take over the control functions.

A Lawrence Berkeley Laboratory (LBL) 50-A (equivalent) module is designed to inject 50 A of neutral atoms at 20 keV into the 2XIIB plasma. So that many modules could be placed near the plasma, compactness was a major design criterion. The source (including the magnetic shielding) measures 22.9 by 69 cm, and the grid measures 7 by 35 cm; therefore, the modules have a 15% area efficiency. As shown in Fig. 8, six modules can then be installed in a relatively small area on 2XIIB.

During FY 1974 and early FY 1975, the Duffy grid described in last year's Annual Report² attained reliable 20-keV operation. This design holds wires of refractory metals (Mo and W) in grooves that allow the wires to expand without changing their shape or location. The Duffy grid was a great advance over the machined-Cu grids used originally because it

- Is cheaper to build,
- Is much more rugged,
- Attains high-voltage operation more quickly, and
- Is curved to focus the beam.

Fig. 8. Six injectors located in one neutral beam injection tank.

All but one of the original Cu grids have now been converted to Duffy grids.

The timing chassis and power supplies for each neutral beam source are independently controlled to allow full flexibility. A master control system permits simultaneous turn-on and turn-off of some or all beams as desired during a 2XIIB shot. Each neutral beam requires four power supplies:

- An 80-A, +20-keV supply for the accelerating grid,
- A 15-A, -2-kV supply for the decelerating grid,
- A 4-kA, 150-V, 16-ms pulse line for the arc, and
- A 2500-A, 15-V, 12-phase rectified power supply for the filaments.

These supplies were debugged by January 1975. To accelerate the break-in process, in March we installed pulse transformers to allow multiple recoveries from breakdowns of a source on each shot.

Figure 9 shows how the source extraction energies improved over the months of operation. In December, electronics problems prevented beams from reaching high energies. In January, the electronics problems were solved, and most extractors reached 15 kV. However, one extractor became shorted and several arc chambers lost all their filaments. The damaged extractor was repaired, filament monitors were installed, and efforts were made to minimize the number of shots. Thus, by May all of the beams were operating, and most were near the 20-keV design level. Individual source operation had improved to the point where a spark or interrupt in one source involved enough energy

Fig. 9. Summary of improved performance of neutral beam injection system.

current is the relevant current for our experiments because we must know the total number of energetic particles that must be injected into a plasma in order to sustain the density.

The time dependence and magnitude of the neutral beam injected during a data shot is conveniently monitored by summing all 12 extracted ion currents and multiplying each by an individual, calorimetrically determined ratio of atom current to extracted current. This sum is checked calorimetrically at the end of each day's run.

to trigger an interrupt in some of the other five sources on the same side of 2XIIB. With a few weeks of intensive engineering effort, minor modifications decreased the crosstalk in the system.

The neutral beam current is measured by a retractable calorimeter at the plasma position. This measurement is necessary because, with large-area sources and variable beam divergence, measurements at intermediate points between the source and the plasma do not reliably determine the current delivered to the plasma.

From the calorimetrically measured beam energy, the extraction potential, and the beam duration, we can determine the equivalent current of neutrals (assuming all to be at the extraction energy). However, we know that there are components of the beam at half and third energies.

Therefore, to include these and obtain the atom current, we use data from LBL⁵ and multiply by a correction factor (1.3 at 20 keV). The atom

Plasma Diagnostics

Plasma diagnostics from 2XII are being used on 2XIIB, often with considerable improvement. In addition, during the past year we began taking a number of new measurements. These new measurements include charge-exchange measurements; digital spectral analysis of rf fluctuation data; measurements of plasma size; and measurements of angular energy distributions, diamagnetic loop, and x-ray diagnostics.

Charge-Exchange Measurements

Charge-exchange measurements on the 2XIIB are being made by means of

- an 11-channel neutral analyzer, and
- a movable, neutral analyzer.

The 11-channel neutral analyzer remains unchanged from the 2XII experiment. It is located in the center plane of the machine, where it observes charge-exchange neutrals emitted from the central region of the plasma, perpendicular to the magnetic axis. The important improvements have been to the software, which now allows on-line data reduction and which can produce plots of total flux and average energy versus time with a 10- μ s resolution and plots of energy distribution at any desired time.

Without neutral beam injection, the total flux is a measure of the flux of cold neutrals onto the plasma surface, and as such is a measure of the gas density external to the plasma. Analysis of these flux signals under fully gettered operation has led to the conclusion that charge exchange is a minor contributor to the loss of the plasma.

The introduction of high-current beam injection has further enhanced the versatility of the 11-channel analyzer. Charge exchange on the beam produces signals one to two orders of magnitude higher than the no-beam case. We now measure energy distributions characteristic to the central region of the plasma rather than to the surface. Analysis of the change in the total flux signals when beams are switched on or off furnishes information on the fraction of the plasma that is hot, while the residual flux level after all beams are off gives information on the increase in background pressure during the beam injection.

Besides the changes in the energy distribution of the plasma due to instabilities, the neutral analyzer also can furnish information concerning changes in the angular distribution of the plasma and radius when the total flux signal is properly combined with microwave density and beam density measurements.

A new diagnostic on 2XIIB is a movable, neutral analyzer used to examine the charge-exchange flux. This analyzer complements the 11-channel analyzer that looks at a fixed position with a fixed schedule of energy windows that become rather widely spaced at high energy. The movable analyzer, shown schematically in Fig. 10, can be swept in the horizontal plasma midplane from $x \approx -15$ cm to $x \approx +15$ cm and from $z = 0.3$ cm to $z = -25$ cm. The analyzer field of view at the midplane is an approximate ellipse with semi-minor axis $a_x = 3.5$ cm and semi-major axis $a_z = 5.0$ cm. Charge-exchange flux can be analyzed up to and exceeding

$E = 40$ keV with 10% energy resolution. The analyzer is equipped with a high-voltage sweep generator so that a continuous range of energies can be detected, although at present most data have been taken with the analyzer at a fixed bias.

The principal new results obtained with the movable analyzer are measurements of the radius of the density distribution of the ion guiding center. Typical results are shown in Fig. 11 for data taken with ~ 240 A (equivalent) D^0 injection. In Fig. 11, the analyzer signal is plotted vs radial position x (see Fig. 1) 2200 μ s after the beginning of the shot. The radius of the ion guiding-center distribution is 8.8 cm, consistent with microwave measurements described later. Because the analyzer only detects charge-exchange products that leave the plasma in the downward direction, the recorded intensity profile is expected to be shifted one ion Larmor radius from the plasma center. For the data in Fig. 11, the analyzer energy was set at 17 keV, corresponding to Larmor radius $a_i = 3.8$ cm. The peak of the profile is shifted about 1 cm further from the plasma origin.

Fig. 10. Movable, neutral analyzer system.

Fig. 11. 17-keV radial charge-exchange profiles.

Fig. 12. Microwave line-density measurements with central, radially offset, and axially offset 4-mm interferometers.

Microwave Measurements of Plasma Shape and Angular Distribution of Ions

Three 4-mm microwave interferometers are used to determine the plasma shape. One interferometer passes through the midplane; a second passes through a chord that is offset radially 7 cm and used to estimate plasma radius. A third interferometer is moved along the axis between 15 and 148 cm from the machine midplane (mirrors at 75 cm). The axial density profile is constructed from measurements at different positions during a series of shots under identical experimental conditions.

For a neutral-beam-sustained plasma stabilized by streaming plasma, Fig. 12 shows a typical line-density time history for the central interferometer at $z = 7.5$ cm and for the movable interferometer at $z = 39$ cm. Beams and streaming plasma are turned on at 1100 μ s. The normalized profiles at several times are shown in Fig. 13 for 200 A neutral atom injection. The rapid decrease of density away from the midplane shown in the 750- and 900- μ s profile reflects the change of the injected plasma distribution, which initially "leans"

Fig. 13. Measured normalized axial-density profiles.

against the mirrors, to one more collisional. The Holdren distribution¹² is shown for comparison. The time to reach equilibrium in the axial profile is determined by the charge-exchange lifetime of ions on the neutral beams. The data show that near-equilibrium is reached in about 300 μ s and that the plasma length is [assuming $n(0)/n(7.5) = 1.4$]

$$\bar{L} = \frac{\int n dz}{n_0 \pi R_0^2} = \int \frac{n(z)}{n(7.5)} \frac{n(7.5)}{n(0)} \frac{B_0}{B(z)} dz = 35 \text{ cm.}$$

The angular distribution of ions at the midplane is obtained from Hall's¹³ inversion formula. Figure 14 compares the measured angular distribution and the Holdren distribution. Half the ions are contained within an angle of 85°. From the measured density profile, the calculated field line fanning the line density decreases by a factor of 2 from the midplane value at the beam edge ($z = 20$ cm). Using the line density variation and assuming a beam divergence of $\pm 2^\circ$, an estimate of the angular spread of trapped ions is $\theta_{1/2} \geq 83^\circ$, in agreement with measured value.

Fig. 14. Measured angular distribution function. $M(\mu)$ is normalized $\int_{-1}^{+1} M(\mu) d\mu = 1$, and $\theta_{1/2}$ is defined as $\int_{\theta_{1/2}}^{\pi/2} M(\mu) d\mu = 1/2$.

Measurements of Ion Cyclotron Fluctuation

In 2XIIB, fluctuations spanning the first four ion cyclotron harmonics (0.1 to 24 MHz) are monitored using techniques similar to those used in 2XII.⁹ Density fluctuations at the center of the confinement region are observed as phase modulation of the 4-mm microwave interferometer signal, and electrostatic fluctuations are recorded on a floating, double-tipped probe located on magnetic field lines that pass through the confinement region. The important new addition is that detailed spectral analysis is facilitated because each of these signals is fed into fast digital transient recorders. Spectral analysis of the rf probe data allows the determination of ω and k for each wave that is present. Comparison of the microwave phase modulation with probe spectra provides some confidence that signals detected by the probe are representative of waves in the confined plasma region.

A schematic of the double-tipped rf probe is shown in Fig. 15. The two probe tips are electrically independent of each other. Wave propagation is detected by measuring the phase delay of signals recorded on the two tips. The amplitude and coarse-grained frequency spectrum of rf activity is monitored over the total length of a shot with filter networks and oscilloscopes.

Figure 16 is an example of the spectral data obtained with the rf probe and transient recorders. The data were obtained during an instability that occurs at high density in 2XIIB and that may be associated with the relaxation of a narrow angular distribution of the ions that is created by the intense neutral beam injection. Evidence indicating a broadening angular distribution of the ions comes from axial interferometer data that show a lengthening of the plasma during instability and 90° charge-exchange flux. The bottom trace is the amplitude of the cross power spectrum of the two probe tips that is obtained by fast Fourier transform of the probe data. The top trace is the phase of the cross-power spectrum. The amplitude spectrum indicates a narrow spectral component with a maximum intensity centered at the first ion cyclotron harmonic at the center of the finite- β plasma. The phase spectrum oscillates randomly between $\pm\pi$ radians in a manner characteristic of a noise spectrum, except near the ion cyclotron frequency where it has a well defined value that indicates a wave-phase velocity of 9.1×10^6 cm/s. Uncorrected for possible Doppler shift due to $E \times B$ motion of the plasma, this wave phase velocity is in the same direction as and equal in magnitude to the ion diamagnetic drift velocity. The wavelength at the plasma center, 4.4 cm, corresponds to

Fig. 15. Schematic of rf probe. The elliptical flux tube (semi-minor axis = 1.6 cm; semi-major axis = 3.7 cm) is the boundary of a 5-cm-radius circle at the plasma midplane.

$ka_1 \approx 5.0$. The magnitudes of such fluctuations are observed to be correlated with the ion scattering rate.

Diamagnetic Loop Measurements of Plasma Pressure

Plasma diamagnetic signals in 2XII B have been measured from a loop of wire that encircles the vacuum chamber. Non-plasma flux changes in the loop that are caused by induction from the compression and gate-pulsed coils are initially cancelled out in the absence of plasma by the addition of Rogowski coil signals obtained from the current feeds to each coil. The residual loop

signals obtained after balancing with first and second derivatives of the coil currents are about 10^{-3} of the unbalanced loop signals. Plasma diamagnetic signals $\Delta\phi$ measured with target plasma alone after subtraction of residual signals are typically also of order 10^{-3} of the pulsed field ϕ in the loop, but decay in about 400 μ s because of plasma loss. With neutral beam injection, we have measured plasma diamagnetic signals $\Delta\phi/\phi$ ranging from 0.2 to 1×10^{-3} . These signals increase with beam current and persist as long as the plasma is stabilized with streaming plasma. The time behavior and magnitude of the plasma pressure calculated from $\Delta\phi/\phi$ agree well with the density and ion energies measured by the microwave interferometer and charge-exchange analyzer, thereby confirming achievement of plasma β 's of about 0.3 with neutral beams.

X-Ray Measurements

A four-channel, soft-x-ray detector has been installed on 2XIIB to measure x rays between 100 and 1000 eV. X rays from the plasma pass through various thin ($\sim 1\text{-}\mu\text{m}$ -thick) foil attenuators that transmit different portions of the x-ray spectrum to plastic scintillator-photomultiplier tube detectors. Measured signal amplitudes and ratios of x-ray power transmitted through different foils are then compared with computer-calculated amplitudes and ratios for various plasma models. Plasma electron temperatures deduced from x-ray measurements are generally within the range measured by Thomson scattering, if an ambipolar cutoff and small amounts ($\sim 2\%$) of carbon and oxygen impurity are assumed. These results are sufficiently encouraging that we plan to upgrade the x-ray detection system to 8 channels for improved x-ray energy resolution.

Fig. 16. Amplitude and phase of cross-power spectrum.

Engineering Support

During FY 1975, engineering-support emphasis was on completing the neutral beam injection system and on upgrading 2XIIB operation and diagnostics.

Neutral Beam Injection System

During FY 1975, we completed the vacuum system for the neutral beam injection system. Two sets of apertures were installed to impede the flow of cold gas from the 12 neutral beam injectors into the plasma containment region. Mechanical shutters were mounted on one set of apertures to stop wall bombardment and to reduce gas input to the containment region during beam warmup. To further reduce gas flow to the containment region, we began designing surfaces cooled by liquid nitrogen (LN_2) in the neutral beam tanks. The higher sticking probability and sorption limit of Ti on 77 K surfaces, compared to present room temperature surfaces, will allow experiments under high-vacuum conditions for 10 ms.

The 2XIIB neutral beam injection system was continually up-graded to improve reliability and to reduce crosstalk from other beams and from operation of the 2XIIB magnet. In preparation for the conversion of some 2XIIB beams to 40 keV, the power supply for the neutral beam test facility was converted from 20 kV to an LBL 40-kV design. At the end of the report period, this power supply and the extractor assemblies were being tested.

Operation and Diagnostics

Several modifications to upgrade 2XIIB operations were completed during FY 1975. These included installation of new fire and crowbar ignitrons in the fast-trapping power supply of the magnet capacitor bank and construction of power supplies for the streaming plasma gun. To decrease the failure rate of the Ti getter wire, a new technique was developed for installing Ti getter wires with small bends so that axial tension during thermal cycling would be relieved.

Considerable mechanical and electrical engineering effort was directed toward the construction of plasma diagnostic equipment. This effort included expansion of the central data-handling computer system¹⁴ and its connection to the machine and to the satellite computers that monitor the neutral beams. The machine central computer now sets currents for the 54 Ti getter wires, logs the running time of the wires, and indicates the location of any wire failures.

The neutral beam minicomputer¹⁵ was brought into operation with four monitored signals per beam. The collected data are presented in both graphic

and tabular form. The design of a new, expanded system to perform full neutral beam control was completed. The new system will also continue beam monitoring but will provide more signals and improved time resolution.

The flat-topping power supply¹⁶ shown in Fig. 17 will hold the current of the compression magnet constant for 10 ms. Once the current has been quickly established by the existing high-voltage bank, it can be kept at a constant level by supplying only the I^2R losses of the system. A low-voltage electrolytic capacitor bank is sufficient for this task. The low-voltage electrolytic banks are isolated from the high-voltage banks by Si diodes that also act as crowbars either at the end of the 10-ms flat-topping or in the event that the electrolytic banks are not utilized. The 10-ms pulse is obtained by sequentially discharging 10 subsections, each supplying a 1-ms pulse. We are now testing the flat-topping modules.

Fig. 17. Equivalent circuit of flat-topping power supply.

BASEBALL II EXPERIMENT

Introduction

This has been a year of preparatory activity for the Baseball II-T experiment, with most of the effort being aimed at the development of a "startup" target plasma in the Baseball steady-state magnetic field. At the beginning of this period, we had chosen laser irradiation of a solid peller as the most promising method for obtaining a target plasma suitable for buildup with neutral beam injection.

The system planned for assembly on Baseball II during the first quarter of FY 1976 is shown in Fig. 18. The laser is a transversely excited atmospheric (TEA) CO_2 laser rated at a 300-J output at a 10.6- μm wavelength in a

Fig. 18. Artist's sketch of Baseball II-T target plasma buildup experiment.

50-ns (FWHM^{*}) pulse. To reduce rocketing effects, the laser beam is split so that the pellet is irradiated from two directions. The pellet generator projects frozen NH_3 pellets to the laser focus. A 50-A, 20-keV, pulsed neutral beam helps diagnose the target plasma and also provides a first indication of hot-plasma buildup.

Our estimates indicate that a 50-A beam is not adequate to ensure buildup with the target-plasma quality we shall probably achieve with the laser-pellet system. We are therefore planning to inject up to 250 A into Baseball II-T from a multibeam injector line. Construction of this injector, planned for FY 1976, includes provision for a 40-keV, 25-A beam of long duration (≥ 100 ms). Use of this injector following a successful buildup would allow us to examine many of the features of a mirror reactor as presently conceived, i.e., a high-temperature plasma maintained in steady state.

In addition to the laser-pellet development, we continued work on plasma diagnostic preparations, on data-handling improvements, on buildup calculations, on particle adiabaticity, and on the "vacuum" buildup results of previous years.

^{*} Full width, half-maximum.

Laser-Pellet Plasma-Target Production

Formation of a suitable startup plasma target is one of the major needs for neutral beam injection and plasma-buildup experiments in a steady-state magnetic well such as that in Baseball II.¹⁷ One of the best approaches to plasma-target production appears to be the use of an intense laser pulse to heat a low-Z-material pellet that is in free flight.¹⁸ The initial properties desired for the hot-plasma target are:

- An expanded plasma with a diameter ≥ 6 cm that matches available beam focal sizes;
- An $n\lambda \geq 10^{14}/\text{cm}^2$ that permits efficient trapping, and
- An $n\tau \geq 10^{10}$ (requiring ≥ 1 -keV ion temperatures) that persists long enough for plasma buildup using presently available neutral beam source intensities.

Allowing for expected losses, achieving these properties will require pellets ≥ 100 μm in diameter.

The use of laser irradiation of a pellet to form an expanded, hot-plasma target is an application somewhat in contrast to the more common laser-fusion goal that requires relatively rapid and extreme compression. The "similarity" model that involves an assumption that conductivity is sufficiently high to permit spherical symmetry has been widely applied to small (≤ 80 - μm -diam) pellets. This approach requires a laser oscillator-amplifier chain that produces first a carefully programmed, preheating pulse to assure relatively uniform energy absorption and/or conduction; and then a short (few-nanosecond), intense, heating pulse. For larger pellets, the thermal structure due to limited thermal conductivity appears to allow (if not require) a much longer laser-heating pulse.

One of the simplest available theories that includes such a thermal structure is Puell's¹⁹ plane-target, ablative-burn-through model. Qualitatively, Puell's theory predicts a typical burn-through time (before becoming under-dense) of 50 ns for pellets in the 100- to 200- μm -diam range of interest here. This burn-through time allows use of a CO_2 laser operated in a relatively inexpensive gain-switched mode; however, it ultimately also requires a symmetric, two-sided irradiation to prevent pellet remnants from rocketing out of the laser focal zone. A discussion of the general features of Puell's theory is given in Ref. 20, together with supporting calculations using the LASNEX²¹ code and the detailed results of the one-sided irradiation experiments that are summarized below.

Calculated Laser Performance

To support Puell's qualitative theory, we used the LASNEX code to predict the specific performance expected from the irradiation of a 100- μ m-diam pellet by an 18-J, 45-ns, FWHM CO_2 laser. One-dimensional calculations (assuming spherical symmetry) were performed for D_2 , NH_3 , and polystyrene $(\text{CH})_n$ pellets; and two-dimensional calculations were performed for D_2 pellets receiving either one-sided or two-sided irradiation. Major predicted features for a Gaussian-shaped (in space and time) 400-MW, 18-J, CO_2 laser pulse with 200- μ m focal spot included the following:

- Major heating at an electron density near the critical value of $\sim 10^{19}/\text{cm}^3$ that yields peak electron temperatures approaching 200 eV,
- Escaping radial ion velocities of a few times 10^7 cm/s, and
- Typical, one-sided, irradiation pellet burn-through times of 35 to 65 ns (ablative recoil of the pellet remnants was ignored).

Fig. 19. Two-dimensional LASNEX calculation of selected mesh zone boundaries at 13 ns after laser turn-on (laser pulse shape as given in Fig. 4). This plot includes a ray trace of laser beams into the absorption zone and also the reflected and refracted rays (only 41% absorption indicated). Note the different vertical and horizontal scales of the computer-adjusted printout.

Figure 19 shows a computer output plot of representative Lagrangian mesh points at the end of 13 ns of one-sided irradiation. It includes an overlay ray trace of entrant and reflected laser beamlets. If possible pellet loss from the focal zone due to recoil is ignored, typical predicted absorption efficiency from two-dimensional LASNEX calculations for 10.6- μ m radiation on $(\text{CH})_n$ is only 41%.

To test the above predictions in experimental pellet-heating studies, in June 1974 we procured a relatively small TEA CO_2 laser. We operated this laser in the gain-switched mode with unstable resonator optics in order to yield an ~ 50 -ns output pulse with the needed very low-beam

Fig. 20. Schematic view of the experimental apparatus used for the studies of laser-pellet heating.

divergence. The measured performance for this 10.6- μm laser included a 10-cm-diam annular laser beam that contained a total energy of 28 to 30 J (with the He:CO₂:N₂ mixture optimized for an initial 50-ns pulse yield) and an intrinsic divergence of ≤ 0.2 mrad.

Experimental Verification

Figure 20 shows the experimental test stand used to proof laser performance, explore focal-zone properties, study alignment problems, and apply various diagnostic techniques. The time history of the gain-switched CO₂ laser pulse as measured by a fast pyroelectric detector is shown in Fig. 21. Only about half of the total calorimetric energy contained in the initial 50-ns pulse is of interest here.

50 ns/div.

Fig. 21. Time history of CO_2 laser pulse.

The focal point in space was determined by a parameter study of attenuated beam-damage patterns on Mylar.* The laser beam was focused by a polished-Cu mirror with a 50-cm focal length. Measurements made on a narrow, 0.002-in.-thick Mylar target (a strip of recording tape) with the beam attenuated by $\sim 10^4$ showed an essentially diffraction-limited damage pattern with a central-spot diameter of 80 μm . This pattern is consistent with over 60% of the energy being

within the 250- μm -diam, first diffraction ring. Two nearly orthogonal laser beams (one He-Ne red and one He-Cd blue) were then focused to intersect through the center of the small damaged spot. This intersection defined the point in space so that the Mylar foil target could be removed and the pellet could subsequently be aligned visually.

In the series of full-beam, one-sided tests, two types of material were studied: plane targets of carbon and thin Mylar, and standard 100- μm -diam polystyrene, $(\text{CH})_n$, pellets suspended on a 6- μm -diam glass fiber. The diagnostics (Fig. 20) typically included up to five time-of-flight ion detectors, a single-channel magnetic analyzer with time-of-flight detectors for species identification, various optical signals, and x-ray detectors with thin Be or Al windows.

Our analysis of 100- μm -diam $(\text{CH})_n$ pellet heating [Fig. 22(a), (b), (c)] indicated a typical yield of $\sim 2 \times 10^{16}$ ions of H^+ , C^{4+} , C^{5+} , and C^{6+} at kinetic energies of near 1 keV from an initial pellet of some 5×10^{16} atoms. Test results were in good agreement with LASNEX calculations and Puell's theory: the highly stripped carbon atoms²² and significant x-ray signals received through 0.001-in.-thick Al indicated that the electron temperatures in the absorption zone were near 200 eV. However, the fractional measured ion accountability ($\sim 40\%$) and the limited absorption (up to 25% including estimates

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Fig. 22. Typical data showing the results of the laser-pellet heating experiments (voltage measured across 50Ω): (a) Top trace shows the electron multiplier output from ions causing secondary emission. Bottom trace is from visible light incident on a photo-multiplier tube and is used to affix the zero time in the shot. (b) and (c) Output of the time-of-flight detectors.

of ionization and radiation from C^{5+} and C^{6+}) were not consistent with the LASNEX prediction of 41% absorption unless we also accounted for the predicted rocket-reaction loss out of the focal zone at times >25 ns after the start of heating.

Late in the report period, we started two-sided irradiation with the small test laser with half of an NaCl lens acting as a beam splitter on one side and the Cu mirror on the other. We have also begun major two-sided irradiation computations with the LASNEX code in preparation for the July 1975 delivery of a new 300-J CO_2 laser. This laser will be installed on Baseball II-T and will be used for plasma-target experiments with the free-flight NH_3 pellets.

Ammonia-Pellet System

Production of Solid-NH₃ Pellets for Laser-Initiated Target Plasmas

We have advanced to ammonia-pellet production after performing our first experiments with water drops.² The experimental arrangement is shown in Fig. 23. Uniform NH₃ drops* separate from the acoustically driven glass capillary at a rate of about $1.5 \times 10^4 \text{ s}^{-1}$. Selected drops are charged negatively by a $5 \times 10^4 \text{ V}\cdot\text{m}^{-1}$, 50- to 100- μs electric field applied axially just off the tip of the 100- μm -diam capillary. Charging-pulse repetition rates of 30 to 3200 pps have been used.

The charged drops are separated from the main drop stream by either a static or a pulsed electrical field of $1.5 \times 10^5 \text{ V}\cdot\text{m}^{-1}$ normal to the stream. After the charged drop has been lifted several mm from the neutral stream, the neutral stream is deflected by a simple skimmer plate. The speed of the drop is $\sim 10 \text{ m}\cdot\text{s}^{-1}$ as it enters a 2.29-mm-diam orifice that separates the high-pressure, drop-generation region ($6 \times 10^3 \text{ Pa}$) from the vacuum region. The high vacuum is maintained at less than $1.3 \times 10^{-3} \text{ Pa}$ by high-speed, LN₂-cooled condensation pumps.

Because the drop is accelerated as it passes through the orifice, its speed changes from $10 \text{ m}\cdot\text{s}^{-1}$ before the orifice to $\sim 35 \text{ m}\cdot\text{s}^{-1}$ in the high-vacuum

* The pure, anhydrous, liquid NH₃ had insufficient electrical conductivity to be charged by the technique that had proved so successful with H₂O. It was found necessary to add small amounts of ionic impurities, less than 0.04%, to provide charge carriers.

Fig. 23. Ammonia-pellet generator.

region. After about 300 mm of flight in the high-vacuum region, the charged NH_3 drop is frozen into a solid sphere. The NH_3 pellet is then in free flight with only electrostatic correction to its trajectory over the 3750-mm path to the test target. One simple target has been a 5-mm-diam hole in a mask covering a charge collector.

The initial charge-to-mass ratio is determined by the deflection of the charged drop from the neutral stream in the high-pressure region. This charge-to-mass ratio is usually about 10^{-3} C/kg.

The rate of impingement of the solid- NH_3 , 200- μm -diam pellets on the 5-mm-diam target hole is about 1 pellet/s. At this impingement rate, one pellet would be expected to pass through a 0.4-mm-diam focal zone every 156 s. We believe that the position of the pellet within the target area is almost random due to the noise introduced into the pellet velocity at the orifice. At 300 mm from the orifice, the stream of charged drops forms a pattern about 2.5 mm in diameter, suggesting that the stream at 3×10^3 mm would be 25 mm in diameter. The ratio of beam area to the target area is 2500. Therefore, with an input rate of 3200 pellets/s we would expect slightly more than 1 pellet/s (the observed rate) into the 5-mm-diam target.

If a high vacuum could be maintained, we could probably increase the rate into the target area by an order of magnitude with an electrostatic focusing lens incorporating large potential gradients. This would provide 1 pellet/min into a 0.2-mm-diam focal zone.

However, reproducible plasma generation may require even more accurate placement of the pellet within the focal zone. As explained later, the accurate guidance of a pellet to within ± 0.01 mm at the focal zone appears feasible. Because of the present characteristics of the neutral beam source in the Baseball II-T experiment, we must be certain of the following:

- That a pellet will enter the focal zone within a given 800-ms window; and
- That we know at least 2 ms before a pellet will pass into the focal zone so that the neutral beam may be started.

While we have reason to believe that these source characteristics might be made less stringent, our present plan is to guide a previously selected pellet into the focal zone.

Pellet-Guidance System

As pointed out above, the dispersion of the NH_3 pellets after they pass through the orifice into the high-vacuum region is too large for satisfactory operation on the Baseball II-T experiment. Therefore, we have built a guidance system (Fig. 24) that will enable us to focus those pellets that fall within approximately ± 1 mm of the axis into the laser focal zone.

The position monitors operate under a very simple principle. As a charged particle passes through the detector, an image charge is induced in each of the four plates. The image charge is largest on the plate that is closest to the pellet. This charge is measured using standard LLL charge-sensitive amplifiers. The signals on plates 1 and 3 are subtracted to give a voltage that is proportional to the product of the charge and the displacement in the x-direction. Similarly, the signals on plates 2 and 4 are subtracted to obtain the y-displacement. The signals on all plates are added to obtain the total charge on the pellet. This sum is independent of the position of the pellet.

The detectors were calibrated by applying a potential to a wire that passes through the detector. With a sum voltage of 8.6 V, the sensitivity is about 2.5 V/mm displacement. The sum voltage observed with NH_3 pellets varies from 5 to 10 V, depending on how the pellet generator is tuned. The noise level of the amplifiers is equivalent to less than a 3- μm displacement of the pellet. Thus, measurements to 5- μm accuracy are quite easy.

Fig. 24. Pellet-guidance system.

The guidance system functions as follows:

- The initial position of the pellets is measured by detector 0.
- The information on the pellet position and charge is digitized and stored in the memory of an LLL 8080 microprocessor.
- The pellet passes through the timing detector shown in Fig. 24.
- The transit time is measured, and the computer calculates the velocity (V_z^2) before the pellet arrives at detector 1.
- The position is measured at detector 1, and the computer has sufficient information to calculate the required correction field.

At the present time, we do not measure the charge-to-mass ratio (q/M) for each pellet, but assume that this value remains the same for all pellets.

By the end of this reporting period, the pellet-guidance system had been assembled, and we were debugging the hardware and software. The present system has two anticipated limitations:

- We have assumed a constant q/M . If this is not so, we must significantly modify the whole system.
- The microprocessor is only an 8-bit machine. Therefore, the accuracy with which we can sense the position of a pellet is limited to about 15 to 20 μm , and the accuracy with which the pellet can be guided is thus also limited.

The displacement of a charged pellet at the center of the Baseball II-T magnetic well due to the effect of the $\vec{v} \times \vec{B}$ Lorentz force on its trajectory has been calculated using the particle-orbit code TIBRO, with the force of gravity added. The Lorentz-force displacement at the center is small ($<3 \mu\text{m}$) compared to the expected pellet diameter of about 100 μm . By also calculating the pellet trajectories beyond the center (until they leave the baseball-coil region and reach the vacuum-chamber wall), we have obtained information that will help us determine how to cleanly dispose of those pellets not irradiated by the laser.

Optical System for the 300-J Laser Beam

The optical system for the laser that will be installed on Baseball II-T,²³ depicted in Fig. 25, is designed to irradiate $\sim 100\text{-}\mu\text{m}$ -diam pellets with a laser power density on the order of 10^{13} W/cm^2 . At this energy density, a minimum laser energy of 50 J is required to burn the pellet through in $\sim 50 \text{ ns}$.

The power densities at the pellet are limited by the divergence of the laser and by the diffraction of the focused beam. Because the damage threshold

Fig. 25. Optical system used for irradiating pellets with 300-J pulsed beam.

of the optical system is $\sim 2 \text{ J} \cdot \text{cm}^{-2} \cdot \text{ns}^{-1/2}$, the total laser power for a given beam diameter is limited. In the Baseball II-T experiment, these requirements are satisfied using a commercially available CO_2 laser with an output of 300 J in a 50-ns pulse and a 20-cm-diam beam.

To prevent the pellet from rocketing, the beam is split in half so that it irradiates the pellet symmetrically from two sides. Focusing with $f/2.5$ optics results in a power density in excess of $3 \times 10^{13} \text{ W/cm}^2$ on each side of the pellet.

Optical access through the Baseball magnet is severely constrained by the structure of the magnet and by the requirement that all components be outside the magnetic mirrors. Off-axis parabolic mirrors provide the simplest symmetrical access through the magnet; however, the fabrication of these mirrors is a severe test of the state of the art.

All mirrors handling the high-power laser are made of OFHC copper. The flat mirrors were directly machined to optical tolerances with a single-point

diamond tool. The parabolic mirrors were generated on a specially built machine, then polished by hand. All laser windows are commercially available, single-crystal sodium chloride that were anti-reflection coated in the LLL optics shop.

Alignment and timing of the optics (Fig. 25) and laser are critical if the pellet is to be irradiated uniformly and symmetrically. For alignment at the pellet, design tolerances were set at $\pm 10 \mu\text{m}$. The alignment system takes advantage of the symmetry of the laser optics to provide coaxial interferometric analysis of the alignment and focus of the laser system. The 40-m/s velocity of the pellet requires that the timing accuracy of the laser be $\pm 250 \text{ ns}$. A laser beam that is displaced slightly from a coaxial alignment detects the presence of the pellet 5 μs before it reaches the system focal zone. The final alignment can be completed with the Baseball II-T system under vacuum and cooled for magnet operation.

20-KeV Neutral-Beam Injector

As shown in Fig. 18, a beam line has been assembled on the Baseball II-T vacuum chamber. The beam source is an LBL pulsed-beam module rated at 20-keV, 50-A D^0 for 10 ms. We plan to operate with hydrogen to obtain an orbit size and hence a minimum plasma size that will match the expected target dimensions. The ion source has been tested with hydrogen, and the full output (50 A) is reached at an extraction voltage of $\sim 17 \text{ kV}$.

The vacuum tank, which has a volume of $\sim 3 \times 10^6 \text{ cm}^3$, also contains a full LN_2 -cooled liner and Ti sublimators for high-speed pumping of the source gas. The beam is transmitted through the Baseball magnet, with an estimated 2% loss to the defining apertures, and is terminated at a Ti-coated target in the beam-burial chamber. We estimate that the thermal hydrogen density in the magnet chamber (including the beam trapped by the target plasma) will remain below an allowable density of $\sim 10^{11} \text{ cm}^{-3}$ for 5 ms. Charge-exchange losses are therefore not expected to dominate during this period.

Beam Focus and Steering

An instrumented beam target mounted in the vacuum chamber of the source monitors the beam focus and steering by displaying the current sampled by 45 Faraday cups that are distributed on the beam target.

A commercially available, very compact, and complete mini-data-acquisition system was purchased and adapted to this application. The system consists of a 64-channel, solid-state multiplexer scanner switch, a differential amplifier,

a sample-and-hold amplifier, and a 12-bit analog-to-digital converter. The maximum scanning rate is about 10 μ s/channel.

The 64-channel multiplexer scanner switch is electronically triggered and can be made to start before or during the neutral beam pulse. The scan duration can be varied from just one complete 64-channel scan to continuous scanning for up to 20 ms.

Each sweep of the scope trace displays a bar graph of the beam current signals into all the target elements.

Total Beam Energy

A 4- by 13- by 1/4-in. Cu plate can be positioned so that it intercepts the neutral beam pulse. (In fact, it is through small holes in this Cu plate that the 45 density-profile target elements receive their beam current signals.) If the temperature rise of the Cu plate (of known thermal capacity) can be accurately measured after each beam pulse, then the total beam energy can be determined.

Four semiconductor temperature sensors are mounted on the rear of the Cu beam-target plate. These sensors have ~ 200 times the sensitivity of conventional thermocouples. The Cu plate is held near room temperature by a cooling-water circuit that is shut off just before a beam pulse and is held off until the subsequent temperature rise is observed. A suitable amplifier circuit was built to power amplify the output of the temperature sensors for strip-chart recording. It is easily possible to observe the temperature rise to an accuracy of $\pm 0.1^\circ\text{C}$.

Vacuum Pressure Rise

An electrometer amplifier circuit with a fast, logarithmic response was built for use with a conventional, nude, ion gauge tube to monitor the sudden vacuum pressure rise resulting from a beam pulse. As expected, this pressure rise excursion in the source vacuum tank extends over a 3- to 4-decade range in the first few milliseconds of the source pulse.

Cryogenic System

The He liquifier used to cool the Baseball magnet was thoroughly overhauled during the year. The incorporation of improved heat-exchangers in the cold box resulted in significantly reduced consumption of LN_2 during operation. To improve reliability and possibly increase the LHe production rate, we added a second He compressor to the system. However, difficulties with bearing clearances have delayed testing of this unit.

The need for better instrumentation of the complex cryogenics system that is part of the Baseball II-T facility was the motivation for the development of an inexpensive, versatile, temperature sensor for cryogenic surfaces or liquids. The known forward voltage drop vs temperature characteristic of a silicon P-N junction diode was investigated. An LLL stock item, a glass-encapsulated switching diode, was found to have a very constant, linear V_f vs temperature variation from 40 K to room temperature. Its characteristic was similar to that of expensive commercially available diode junctions specifically developed for this application. We built an amplifier and signal-conditioning circuit to take advantage of this fundamental characteristic and to provide a digital panel meter readout directly in kelvin. We plan to use these devices for both monitoring and controlling temperatures in the cryogenic system.

Diagnostics

Diamagnetic Pickup Loop

A 250-turn, diamagnetic pickup loop for the Baseball II-T experiment has been fabricated. To minimize interference with the neutral beam and with other diagnostics, the pickup loop is wound in the shape of a baseball coil. An insulated, toroidal, Cu tube provides electrostatic shielding of the pickup loop. This shielding tube has been broken to prevent induced currents from slowing down the time response of the pickup loop.

To test the diamagnetic loop, a 700-turn cylindrical coil (15 cm in diameter and 26.5 cm long) was built to create a magnetic field that simulates the plasma. The diamagnetic pickup detector was then calibrated by comparing its signal with the signal from a circular coil.

Microwave Interferometer

The existing 17-GHz interferometer is not adequate for measuring the densities anticipated for the laser target plasma of the Baseball II-T experiment. A higher-frequency interferometer is required; therefore, we have selected a 140-GHz interferometer that will provide density measurements in the range from 10^{10} to 10^{14} electrons/cm³. We have completed a bench test of the equipment, and a simple interferometer has been set up in the side laboratory. An improved version is being installed in the Baseball II-T facility.

The existing 17-GHz interferometer will be used to measure the plasma density just outside the magnetic mirrors.

Measurements of Plasma Dimensions by Neutral Beam Attenuation

Plasma density can be measured by observing the attenuation of a neutral beam as it passes through the plasma. If the neutral-beam attenuation is measured at different spatial positions, then the spatial dimensions of the plasma will be obtained. A series of radial and axial secondary electron detectors is being installed in the Baseball II-T beam-burial chamber. With these detectors, we can measure both the axial and radial profiles of the plasma by observing the attenuation of the primary plasma-trapping beam.

Data-Handling System

The digital-computer facility used for processing experimental data has been expanded by the addition of two digital magnetic discs and a storage-oscilloscope display console and keyboard.

One magnetic disc unit will contain the data handling and analysis programs. The second has an easily exchangeable disc cartridge and will be used for data storage. Each disc cartridge holds about 1.5 million 12-bit words. The dual-disc system provides for rapid information transfer to and from the computer.

The storage-oscilloscope display console and keyboard provide a faster and more versatile method for displaying the data and computer results and for making permanent copies, and also provides for prompt feedback from the physicist to the computer. The new console can also display analog signals from other sources.

An analog disc will be used to record some of the fast-transient diagnostic signals from the Baseball II-T experiment. Initially, it will record 8 signals, but later it can be expanded to read 16. The time response of the disc is 2 MHz, and 33 ms of data can be stored for each of the 8 signals. The analog disc will be interfaced to our small computer so that the recorded data can be transferred to digital disc or tape for either long-term storage or computer analysis.

We will continue to use our analog-magnetic-tape system²⁴ for extensive recording of experimental signals. Fourteen channels are available, with a frequency response of 0 to 40 kHz and up to 300 kHz for ac-coupled signals. The recorded signals can be read out on paper during or soon after an experimental shot. By thus displaying many signals together on a permanent display, the experimenter can more easily obtain an overall view of what occurred during the shot, and pertinent time correlations often quickly become apparent.

Buildup and Adiabaticity Calculations

Radially Dependent Fokker-Planck Code

In previous calculations describing the trapping of an energetic neutral beam on a decaying laser-target plasma, we used a multispecies Fokker-Planck code to describe the important kinetic effects (e.g., spectral hardening) that occur during the decay of the laser-produced target plasma. In addition, to study the critical condition of buildup at the plasma surface we used a separate code that employed radially dependent rate equations.²⁵ However, because a separation and solution of the problem using two independent codes does not adequately describe the simultaneous physical processes, we have formulated a radially dependent Fokker-Planck code. We expect that this code will have broad applications in more adequately describing the classical plasma behavior in magnetic mirror fields.

The new code solves the time-dependent Fokker-Planck equation for an arbitrary number of charged species as a function of radius. The coupling between different radial positions occurs as a result of atomic trapping and loss processes. For example, charge exchange of the energetic neutral beam with trapped ions results in radial diffusion of the ions across the magnetic field. The code also solves for the self-consistent radial dependence of various neutral species, taking into account various gas sources such as both diffuse and direct streaming of gas from beam sources, outgassing from the walls of the vacuum chamber, and wall reflux of neutrals following bombardment by various ion and neutral species. The Fokker-Planck equation in the code is now being solved at each radial position by using a one-dimensional, multispecies code.²⁶ As an option, provision is being made for the substitution of a two-dimensional code.

In the limit of low-density, high magnetic field, and no gas, the present code agrees, as expected, with previous Fokker-Planck calculations. Before we use the code to describe the trapping on a decaying laser-target plasma, we shall complete an additional comparison with the results of the buildup code that employs rate equations.

Plasma Parameters for Steady-State Injection

Several constraints define a range of plasma parameters suitable for steady-state neutral beam injection in mirror experiments:

- A minimum average ion energy is set by charge-exchange and ionization cross sections, based on one-for-one wall backscattering of incident neutrals.²⁷

- To minimize losses by enhanced scattering,²⁸ we require the density to meet the requirement $\omega_{pe}^2 / \omega_{ce}^2 \geq 1$.
- There are losses due to nonadiabatic trajectories at high ion energies, particularly as the vacuum field is modified by a finite- β plasma.

Using a Fokker-Planck calculation that includes a β -dependent cutoff on ion energy to account approximately for nonadiabatic effects, we have estimated a steady-state injection "window" for the Baseball II-T experiment. These calculations show that the three constraints limit the injection to the energy range $25 \text{ keV} < E_i \leq 60 \text{ keV}$. Figure 26 illustrates that region of parameter space for which equilibrium solutions exist. Since the upper boundary is also a function of injection energy, it appears somewhat fuzzy in this representation.

Recent Adiabaticity Results from Orbit Calculations

As part of our endeavor to find a straightforward method for predicting the limits of nonadiabatic behavior in high- β magnetic-mirror configurations, we are making extensive use of TIBRO,²⁹ a particle-orbit computer code. The numerical orbit results on nonadiabatic behavior thus obtained can be compared with the predictions of analytic expressions for changes in the magnetic moment. Such comparisons are producing encouraging agreement,³⁰ which in turn is giving

impetus to further numerical and theoretical work.

Fig. 26. Parameter space representing equilibrium conditions for steady-state injection in Baseball II, with $B_0 = 1.2 \text{ T}$.

During this last year, TIBRO has been extensively revised and improved. The orbit integration routine is now more accurate and versatile, and there are more options to facilitate the use of this code. With the recent additions, it is now easy to insert new sets of equations from which the magnetic field at each orbit point can be calculated. A combination field can be obtained by adding the results from analytic equations to those calculated by the former methods, either from a set of current-carrying elements or by interpolating within a grid of previously calculated magnetic-field values.

Many of the recent orbit results have been obtained for fairly simple magnetic fields of the axisymmetric, magnetic-well type. One configuration investigated was that of a long, thin, finite- β -equilibrium plasma in an axisymmetric mirror field (magnetic-field equations derived by W. A. Newcomb³¹). Orbit results have been obtained for $\beta = 0, 0.25, 0.50, 0.75$, and 0.90 . A second axisymmetric magnetic field examined had the magnitude of the field increasing outward from the center along the magnetic axis, and had a radial gradient that could be independently changed. Orbit results for this magnetic field are available for three different positive values of the radial gradient and one negative value (i.e., for a simple mirror).

In an orbit calculation, each charged-particle orbit is followed for many transits through the central region of a magnetic field, and the maximum observed fractional change in the magnetic moment during a single transit, $(\Delta u/\mu)_{\max}$, is plotted. The results show a strong and smooth variation of $(\Delta u/\mu)_{\max}$ with particle velocity, v , for constant initial position and pitch angle, and exhibit the behavior predicted by $(\Delta u/\mu)_{\max} \propto \exp(-F/v)$. The orbit data for the finite- β -equilibrium plasma are fitted well by this relation when $F = 1 - \beta$.

We have also obtained further orbit results for the three baseball-seam coils used in experiments here at LLL. The measurements of the nonadiabatic limit in the Baseball I experiment can be combined with these orbit results to predict the conditions for nonadiabatic behavior in the Baseball II-T experiment and possibly in a restricted class of other magnetic-well configurations.

The procedures and results of our recent orbit analysis are summarized in Ref. 32. This work is continuing.

Further Analysis of Baseball II Vacuum-Buildup Experimental Data

We have obtained an encouraging comparison between some of the Baseball II vacuum-buildup, instability-threshold data and the predictions of the electron-bounce-mode theory being developed by Berk and Neilsen.³³ The data give an unexpectedly steep variation of $\epsilon = (\omega_{pi}/\omega_{ci})^2$ at threshold with $e\phi/W_1$.³⁴ No good explanation for this strong variation had been previously available. The predictions of the electron-bounce-mode theory are being compared with our data, especially with the series of threshold measurements in which an axial plasma limiter was gradually moved in toward the plasma center. These measurements are particularly pertinent because the plasma length is a parameter in the theory. The electron-bounce-mode theory gives a steep variation with

$e\phi/W_1$ of ϵ at threshold for the parameters of the axial-limiter data, similar to the variation found experimentally.³⁵ The magnitudes of the predicted ϵ values are also about the same as the experimental values. It is difficult to compare the rest of the threshold data with the theory because the experimental parameters that were varied do not directly enter into the theory. However, the approximate agreement obtained for the limited comparisons possible is promising.

SECTION 2. SUPPORTING RESEARCH

INTRODUCTION AND SUMMARY

During the report period, development and technology efforts at LLL remained largely in support of mirror program requirements. However, much of the work was also of direct interest to other CTR confinement system needs. Some highlights of this aspect of the year's work follow.

- Superconductors - The "bronze" method for producing multifilamentary Nb_3Sn in sizes up to 10 KA appears successful; no serious manufacturing problems have appeared with two approaches; the third approach has encountered serious difficulties.

- Direct energy conversion - Predicted high-efficiency direct recovery has been demonstrated using variable energy sources and two types of scaled-down (in energy) expander-collector systems. The principles were also established for direct conversion of residual charged particles in neutral beam lines.

- Reactor studies - Detailed physics and engineering parameter studies were made on both fusion-fission and pure-fusion reactors, and preliminary conceptual system designs were started. Beam-plasma interaction, high-efficiency neutral injectors, blankets, and several coil-support methods were studied.

- Neutral beams - A 50-A, 40-kV pulsed source was developed, work was started in D^- beams, a high-voltage test facility was designed, designs for the tokamak fusion test reactor (TFTR) beam were initiated, and considerable progress was made in the fundamental understanding of high-current sources.

- Neutron sources - The ICT-RTNS-I source strength of 6×10^{12} n/s was achieved. We completed the preliminary design of the RTNS-II facility, and source and target development was started.

- 14-MeV neutron irradiation studies - Radiation-strengthening studies were started on Cu and Nb, and implantation experiments using tritium decay were started. Many cooperative experiments with other laboratories were carried out using LLL's RTNS-I neutron source.

- Tritium - Work was initiated on deriving basic data for the extraction of tritium from the atmospheres of reactor enclosures. Also, experimental work was started on improving tritide targets for the RTNS-II neutron source.

All of the described programs are long-range and will continue into the next several years.

SUPERCONDUCTING MAGNET DEVELOPMENT

The overall plan for developing very large, high-field, superconducting magnets for fusion research is centered around the development of suitable, multifilamentary, high-field superconductors.³⁶

During FY 1974, we initiated three routes toward the fabrication of a Nb₃Sn conductor.² Progress in each during FY 1975 was as follows:

- The Intermagnetics General Corporation approach³⁷ in which an electroplated layer of Sn diffuses through a Cu matrix to react with embedded Nb rods, has encountered serious problems. Voids appear in the Cu as the outer rim swells and separates from the main body of the conductor during the early diffusion phase. As a result, further work in this approach has been suspended.
- The internal bronze route being pursued by Supercon continues to look promising. However, progress has been slowed by the long delivery time of the Nb tubes into which bronze rods are inserted. Bend tests on small conductors are of particular interest.³⁸ These results show that the critical current increases, in some cases by as much as 20%, with strains up to 0.4% and that it does not fall below the initial value until the strain exceeds 1%.
- The most rapid progress has been made on the more usual bronze approach in which Nb rods are inserted in a bronze matrix that is then extruded, drawn, and finally reacted. This work has been carried out by AIRCO, and its rapid rate of development is partially due to the similarity between this production route and that for multifilamentary Nb-Ti superconductors.

AIRCO has made sample conductors rated at 1, 3.5, and 10 kA (at 12 T) that meet the critical current specification.³⁹ Initial problems with fracture of the Ta barrier (which is inserted to prevent the conductivity of the stabilizing Cu from being degraded by Sn diffusion) have been overcome.

Figure 27 is an electron microscope scanning photograph of part of the section of a conductor after the surface has been etched. The Ta tube surrounds the bronze matrix in which were embedded 3,553 Nb rods. The Sn in the bronze has reacted with the Nb to form a surface layer 1 to 2 μ m thick on each

Fig. 27. Section through multifilamentary conductor.

rod. The high-purity Cu can also be seen between adjacent Ta tubes. The 10-kA conductor consists of 187 Ta tubes, giving a total of 664,411 filaments in an overall size of 13.75 × 6.0 mm.

Two 27-cm-bore solenoids using 100 m and 300 m lengths of the 1-kA conductor have also been tested in a 5-T background field. Both operated up to short-sample critical current; tests on the larger coil are reported in Ref. 40.

Characterization and optimization of this type of conductor are continuing, one of the most important parameters being the effect of strain on the performance of the brittle Nb₃Sn filaments.

We have completed the preliminary design of a new, large, 8-T, 1-m-bore test facility in which to test a 3.5-kA Nb₃Sn solenoid up to 12 T, and we plan to begin fabrication in FY 1976.

DIRECT ENERGY CONVERSION

During the report period, we used the direct conversion test facility to study space-charge effects, both in the periodic-focusing direct converter and in the magnetic expander. We developed a modified FIG-type plasma source to produce the required energy and current of hydrogen ions.

Space-charge effects on the efficiency η of the periodic-focusing direct converter are given by the relation

$$\eta = \eta_0 - k(\omega_p \tau)^2 (d/L)^2, \quad (2)$$

where ω_p is the ion plasma frequency, τ is the mean transit time for ions through a spatial period L of the periodic focusing, and d is the thickness of the beam. The values of η_0 were found by extrapolating measured and calculated values of η to $\omega_p \tau = 0$; η_0 and k depend on the shape of the energy distribution of the ions. Using the DART⁴¹ code, we calculated $\eta_0 = 0.90$ and $k = 2.65$ for a flat-topped current distribution with a 3 to 1 spread⁴² in energy; and $\eta_0 = 0.95$, $k = 17.3$ for one with a 1.2 to 1 spread. These calculations show that η is more sensitive to space charge when the energy spread is small.

In the direct conversion test facility, the hydrogen ions have a mean energy of 320 eV and an energy spread of about 1.2 to 1. Values of the other parameters are: $d = 7.5$ cm, $L = 22.5$ cm, and the beam width $l = 20$ cm. Equation (2), when expressed in terms of these parameters and the beam current $I(\mu A)$, becomes:

$$\eta = 0.95 - (0.0066)I.$$

Fig. 28. Schematic of the FIG ion source.

Thus, we require several tens of μA to study space-charge effects [$10 \mu A$ gives $(\omega_p \tau)^2 = 0.034$].

The source, shown schematically in Fig. 28, is a cold-cathode FIG in a uniform, 0.8-T magnetic field with a hydrogen-gas feed. The second anode provides some control of the mean ion energy. Figure 29 shows the energy distribution of the ions when the

second anode is set at 200 V. Time-of-flight measurements indicate that the beam consists of about $2/3 \text{ H}^+$ and $1/3 \text{ H}_2^+$ ions.

By varying the bias voltage of the first cathode, we can vary the electron component in the beam from zero up to a current equal to the ion current. The electron energy is rather high — up to 100 eV (thus suggesting the presence of high-frequency oscillations in the source). The

Debye length is roughly equal to the diameter of the beam (and remains so all along the length of the magnetic expander), and the neutralization of space charge is incomplete. At our highest currents, the potential at the center of the beam can be 10-V positive with respect to the grounded expander tank. The resulting radial electric field causes some loss of ions to the walls near the exit end of the expander where the magnetic field is only 0.0067 T.

Also, the increased space charge with increased current results in a larger and more divergent beam of ions at the entrance to the direct converter. This variation in input conditions with beam current makes it difficult to measure the effect of space charge in the direct converter. To make the size and divergence of the input beam nearly independent of space charge, we installed two rectangular apertures the size and shape of a low-density beam: one 7.5-cm by 20-cm aperture at the exit from the expander and one 7.5-cm-wide horizontal slot just after the negative stage in the direct converter.

To vary the current density without also changing the ion energy distribution, we inserted grids of known transmittances into the beam near the source. We obtained the total beam power into the direct converter by measuring the area under the curve on a plot of current vs retarding potential. The efficiency of the direct converter is given by the ratio of the sum of the power recovered on all the electrodes to the total power into the direct converter.

Figure 30 shows the measured efficiency η plotted against input ion current. The solid line shows η as calculated by our DART code using the measured spread in ion energy and the beam size and divergence that should result from the magnetic field and the apertures. The scatter in the measured points results mostly from variations in the energy distribution. The satisfactory

Fig. 29. Energy distribution from the PIG source.

Fig. 30. Effect of space charge on calculated and measured efficiency of direct recovery.

agreement between calculated and measured dependence of efficiency on space charge verifies the correctness of our calculational techniques.

We also used the FIG source to measure the efficiency of the two-stage, venetian-blind⁴³ direct converter in a steady-state beam that had a significant spread in energy. The results were in good agreement with our previous measurements, which used a monoenergetic ion beam that was varied in energy.

We used the DART code to study the in-line beam direct converter and the four-stage plasma direct converter.

Both of these use the space charge of the decelerating beam to deflect the ions into the electrodes.⁴⁴

A schematic drawing of the beam direct converter is shown in Fig. 31, and the four-stage plasma direct converter is shown in Fig. 32. A fan-shaped expander would provide the slab beam for the four-stage device. The fan-shaped expander would also provide magnetic deflection of electrons and therefore would avoid the possible problem of the electrons penetrating the negative potential barrier.

Fig. 31. Space-charge-dominated beam direct converter.

Fig. 32. Space-charge dominated plasma direct converter.

An analysis of these two space-charge-dominated direct converters shows that the efficiency varies with density according to

$$\eta = \eta_0 - k(\omega \tau)^2 (d/L),$$

where now L is the distance that a mean-energy ion can penetrate the retarding electric field, and τ is the time required for a mean-energy ion to travel a distance L . In the numerical calculations for the four-stage design, we approximated the energy distribution of the ions that enter the loss cone from a mirror-type reactor by a triangular shape with a four-to-one spread in energy. The resulting values were $\eta_0 = 0.80$, and $k = 0.10$. For the beam direct converter, $\eta_0 = 1.0$ and $k = 0.11$. An actual beam will probably consist of ions of several different energies because they will result from the dissociation of molecular ions. In that case, η_0 will be reduced as the direct converter becomes more like the four-stage unit.

A scaled version of the beam direct converter is nearly completed and will be tested using a MATS III source. We plan to inject and recover about 3 kW of beam power.

FUSION REACTOR STUDIES

In FY 1975, our reactor studies included investigations of first-wall cooling, neutral beam-plasma interactions, blanket- and coil-structure designs, and mirror machine vacuum systems. On the basis of earlier conceptual reactor designs, these rather diverse subjects had been identified as major technological problem areas. The knowledge gained from the investigation of these problems has prepared us to produce improved mirror machine designs for power reactors as well as nearer-term machines.

First-Wall Cooling

The first-wall cooling investigation was a continuation of work done in FY 1974 for the conceptual design of FERF.⁴⁵ The first walls of such compact machines must withstand very high local-energy fluxes that originate from the neutral-beam injectors. We had proposed a water-cooled array of thin-walled tubes for the first wall for FERF. Our FY 1975 analysis and computer-aided calculations indicate that first-wall heat fluxes over 3 kW/cm^2 can be handled with an adequate structural safety factor and modest coolant pumping power.⁴⁶

Neutral-Beam/Plasma Interaction

The neutral-beam/plasma-interaction work done in FY 1975 was also a continuation of work begun for FERF in FY 1974. The new work extended the previous analysis to include the 1/2- and 1/3-energy neutrals that exist in present-day neutral-beam sources. We found that these low-energy neutrals are detrimental to the plasma because of excessive charge exchange.⁴⁷

Design of Blanket and Coil Structures

In our investigations of designs for blanket and coil structures, we emphasized obtaining simultaneous solutions to the problems of supporting the large magnetic forces of a Yin-Yang coil and providing access for blanket maintenance. Coil structures considered in some detail during FY 1975 included solid C-clamps, truss C-clamps, and an internal coil structure.⁴⁸⁻⁵⁰ The internal coil structure has the most promise for reducing structural cost (especially when used in conjunction with specially designed coils having mirror points shifted toward one edge), but it does preclude blanket access through the coil.

Vacuum Pumping Analysis

Our investigation of the operation of a vacuum system for a mirror machine was begun in FY 1975 as an element in LLL's preliminary design of a near-term experiment (MX). However, the analysis was carried out in a general manner, so as to be applicable to the vacuum analysis of many fusion machines and components. The resulting computer model treats steady-state, free molecular gas flow in a system consisting of a central chamber (the plasma chamber) connected by orifices or ducts to an arbitrary number of one- or two-chamber peripheral tanks.⁵¹

FUSION-FISSION REACTOR STUDIES

The major emphasis of our work on the fusion-fission concept was the development of a hybrid reactor design that employs mirror confinement and a fast-fission blanket that produces both power and fissile plutonium.⁵² To allow evaluation of system performance and costs, all main reactor subsystems were considered.

The fusion component of the hybrid reactor is a D-T plasma confined by a magnetic field produced by Yin-Yang coils and sustained by the injection of hot neutral beams. The 14-MeV, D-T fusion neutrons directly fission uranium (principally ²³⁸U) in a He-cooled blanket composed of natural uranium carbide plus lithium aluminate. A vertical cross section through the reactor is shown in Fig. 33. A somewhat conservative design was developed by requiring the use of present or near-term technology such as Nb-Ti superconductors, positive-ion injectors, and stainless-steel structure in the He-cooled blanket.

This conceptual hybrid reactor produces ~600 MW_e plus ~700 kg/y of ²³⁹Pu (averaged over 30 years). At the estimated capital cost of ~\$1200 million, the production cost of power and Pu is 40 mills/kWh_e and \$20/g.

We believe that the results of this study support the contention that the fusion-fission hybrid is a conceptually feasible approach to producing fissile fuel and/or electrical power. Because the design resulting from this study is far from being optimized, we expect that further design iterations will provide substantial reductions in costs.

Fig. 33. Vertical cross section through mirror hybrid (fusion-fission) reactor.

100-keV D^0 NEUTRAL-BEAM INJECTOR DESIGN

As part of a study for a mirror fusion-fission hybrid reactor,⁵² we prepared a preliminary design for a 225-MW neutral-beam injector of fast deuterium atoms at 100 kV and fast tritium atoms at 150 kV.⁵³ The injector layout consists of four assemblies, each comprising 70 ion-source modules mounted in a converging array (Fig. 34). We propose an efficient, long-lifetime cathode for the plasma sources. The requirements for ion extraction and acceleration are satisfied by a two-stage accel-decel-accel-decel grid system designed to operate within the limitations imposed by beam space charge, beam optics, voltage breakdown, and grid bombardment by secondary ions and electrons. A low-temperature neutralizing cell followed by a system for recovery of the energy of the unneutralized fraction of the beam has been designed to provide an overall injector power efficiency greater than 70%. To maintain required pressures within the acceleration assemblies, the neutralizers, the beam energy

Fig. 34. Injector layout.

recovery systems, and the beam line itself, pumping systems capable of handling a total gas flow of $2400 \text{ Torr} \cdot \text{l} \cdot \text{s}^{-1}$ are required. We have evaluated the problems associated with magnetic shielding of the ion source assemblies from the reactor fringing field as well as the mounting of the accel-decel grids at high voltage and high temperature.

NEUTRAL-BEAM DEVELOPMENT AND TECHNOLOGY

Introduction

The main elements of the neutral-beam development program for FY 1975 were:

- Experimental work on "pulsed beams," "efficient beams," and advanced development;
- Test-facility construction; and
- A start at a conceptual beam-line design for the TFTR.

The primary goal of the pulsed-beam program was to develop and operate a 50-A (equivalen.) pulsed source at 40 kV: this has been achieved. In the efficient-beam program, a Cs-jet charge-exchange cell and a multi-ampere, 1-keV, pulsed source of positive ions have been developed and operated to study

the double-charge-exchange approach for producing D^- . These experimental activities have been accompanied by the construction of test facilities (power supplies and vacuum chambers) necessary for the development of the next generation of higher-voltage, longer-pulse-length, neutral-beam systems. Although general information meetings about TFTR had been held through the fiscal year with the Princeton Plasma Physics Laboratory (PPPL), Westinghouse, the ERDA Division of Controlled Thermonuclear Research (DCTR), and Oak Ridge National Laboratory (ORNL), a request by PPPL late in the fiscal year for an independent conceptual design for the TFTR neutral-beam-injection system resulted in an intensive design activity which will culminate in a design plan early in FY 1976.

Pulsed Beam

A detailed description of the status of the pulsed beam program as of late Autumn, 1974, can be found in Refs. 54 through 56. Since then, the 50-A (equivalent) source has been upgraded to 40-kV operation by installing a thicker insulator (3.8-cm long) and increasing the accelerator gap from 2.25 mm to 5.25 mm. The operating parameters and beam characteristics for the 50-A, 40-kV system, operating with deuterium, are summarized in Table 1.

Our present designs for obtaining the 120-keV, 500-ms beams required by the TFTR call for a four-grid structure (two accelerator gaps, one electron suppressor gap), each grid being made up of shaped rods or bars of approximately twice the size (of the order of 3-mm diam) of the present grid structures. This more rugged design simplifies the manufacturing process and provides more heat

Table 1. Operating parameters and beam characteristics for the 40-kV, 50-A source.

40-kV, 10-ms pulses:

~64 A of deuterium ions extracted (~2.8 MW)

54 A (equivalent, ions and neutrals) to 20×40 cm @ 2.9 m (2.2 MW)

40 A (equivalent, ions and neutrals) to 10×20 cm @ 2.9 m (1.6 MW)

~80% neutrals

Arc power: $3000 \text{ A} \times 50 \text{ V} = 150 \text{ kW}$

Filament power: $2000 \text{ A} \times 11.5 \text{ V} = 23 \text{ kW}$

Suppressor grid power: $7 \text{ A} \times 2200 \text{ V} = 15 \text{ kW}$

Gas flow: ~22 Torr·l/s

capacity and the better thermal characteristics needed for long pulses. Both of these design features have been tested separately up to 40 kV, 10 ms (the limit of our present power supplies), in 10-A extractors. The larger-scale grids, incorporated in a three-grid extractor, performed as expected from the $V^{3/2}/d^2$ Langmuir-Child scaling; this extractor will be used to test the design for long pulses (0.5 s) when the 20-kV, 20-A, 0.5-s power supply is completed early next fiscal year.

The four-grid concept was tested with standard-size grids used on 20-kV sources,⁵⁴ with gap spacings between electrodes of 2.25, 2.25, and 1.25 mm. The beam width ($\pm 1/e$ points of a Gaussian distribution) vs the potential drop across the first gap, V_{12} , is shown in Fig. 35 for 40-keV deuterium beams. Note that for the potential range covered, the narrowest beam ($\pm 1.25^\circ$) is obtained with 10 kV across the first accelerator gap and 30 kV across the second gap; the extracted current, however, decreases with decreasing V_{12} (13 A at 20 kV, but 6 A at 10 kV). The beam width calculated with the WOLF code⁵⁷ is shown by open circles in Fig. 35. The excellent agreement with the measurements reinforces our confidence in the calculated WOLF designs for 120 kV.

In addition to the work on 40-kV sources, three 50-A, 20-kV sources⁵⁴⁻⁵⁶ were built and tested during FY 1975 — two for the ATC experiment at PPPL and one for the Baseball II-T experiment at LLL. A four-grid, 40-kV, 10-A source was also built for PPPL.

Fig. 35. Variation in the divergence of a 40-keV beam with changes in the potential difference across the first (extraction) gap of a four-electrode, 10-A (equivalent) extractor.

Efficient Beams

During the past year, a negative-ion program was started with the purpose of obtaining intense negative deuterium beams, accelerating them to 100 to 200 keV, and stripping the attached electron to yield a neutral beam produced at high power efficiency. Experiments with pulsed sources have begun, and a negative-ion beam has been obtained at 1 keV. In addition, we are constructing a high-voltage test stand (HVTs) for testing dc negative and positive beams.

In addition to these experiments and construction work, described in more detail below, pertinent work discussed elsewhere in this annual report includes:

- Computer calculations of transport of beams through background gas.
- Analytical calculations of the transport of weakly diverging ion beams in periodic magnetic fields.
- Modeling of the use of negative ions in mirror reactors.

An approach to the production of intense negative-ion beams is shown schematically in Fig. 36. Results to date include production of low-energy ions and their conversion into negative ions. Analysis of the negative-ion beam and its acceleration are goals for the next year.

Low-Energy, Positive-Ion Source

A specially designed, three-grid extractor (Fig. 37) was installed in a standard LBL 10-A source. To provide focusing in the vertical plane, each vertical grid rail has a 2-m radius of curvature. The 7- by 7-cm extraction surface has a 62% transmission. The second, or intermediate, grid is held at

Fig. 36. Conceptual design of a high-energy, negative-ion beam.

a high negative potential, thus furnishing the strong accelerating potential required to give high current densities. The third grid, held at ground potential, creates a decelerating field and furnishes the ground plane from which the beam emerges. Using the WOLF computational code, the potential of the intermediate electrode was chosen to give optimum beam optics.

Using these grids, we have produced intense, low-energy, deuterium beams. Calorimeter profiles of a 1-keV beam arriving at the 2-m focal

Fig. 37. Calculated (WOLF code) trajectories and equipotentials in the 1-keV extractor.

point are shown in Fig. 38; total current is ~ 5 A (charged + neutral), with peak current density ~ 40 mA/cm². With the present pumping arrangement, the beam is observed to be $\sim 90\%$ neutral atoms, a value in agreement with the equilibrium fraction cited in the literature.

Cesium Charge-Exchange Cell

The charge-exchange cell used in our experiments is illustrated in Fig. 39. Cesium vapor from a heated oven passes through a jet and is collected in a cooled hopper. The hopper is periodically warmed to return the cesium to the (cooler) oven. Cesium axial-density profiles have been measured using a hot-wire probe, with the results shown in Fig. 40. In the present arrangement, the distance from the Cs cell to the ion source is >1 m, and no problems of source contamination by Cs have been observed.

Negative-Ion Production

To identify the energy-to-charge ratio of the ions that comprise the low-energy beam, we have constructed a simple, electrostatic, energy-analyzer

Fig. 38. Beam profiles of the 1-keV beam. (Total deuterium current = 4.6 A.)

Fig. 39. The Cs charge-exchange cell.

Fig. 40. Cesium density profile along the axis of the charge-exchange cell. The line is $n = \frac{\cos \theta}{r^2} = \frac{h}{r^3}$, with $r = 0$ 2 cm below jet.

system. The symmetric electrostatic structure, schematically illustrated in Fig. 41, simultaneously records positive- and negative-ion fluxes and energies. Each deflection plate is swept with a linearly rising voltage, V_d , of equal but opposite polarity. Because the sweep time (1 ms) is short compared to the total pulse time, time variations can be studied throughout the total pulse. The detectors could be either Faraday cups or calorimeters; the former have been used because of their better time response. The acceptance solid angle of the detectors selects only those ion trajectories that have a given ratio of V_d to particle energy. We set the maximum value of V_d to be slightly greater than that voltage necessary to steer the full-energy particles to the detector.

Examination of a 2-keV ion beam that exits the Cs cell (see Fig. 41) in the absence of Cs vapor showed that little positive-ion molecular dissociation had occurred and that most ions were of full energy. Time-of-flight analysis indicated that the full-energy beam contained D^+ , D_2^+ , and D_3^+ . The small negative-ion signal is due to residual Cs on the surfaces of the Cs cells. With the pulsing of the Cs vapor valve, the positive-ion content is reduced, and negative ions are recorded at full, 1/2, and 1/3 energy.

Fig. 41. Ion beam analyzer. The inserts show beams with and without cesium.

Beam Transport in Gas and Plasma

Low-energy beams, especially negative-ion beams, are sensitive to collisions with gas and plasma and to space-charge effects. We have therefore examined the plasma created by collisions between a neutral beam and background gas. Measurements were made in deuterium gas at pressures of 1 to 10 mTorr, beam energies 1 to 7 keV, and current densities <10 mA. In this regime, the plasma electrons had a low temperature (0.4 to 1 eV). The plasma density was proportional to the ionization cross section of the beam gas (a function of beam energy), as one would expect from simple, particle-balance arguments.

Beam Transport by Periodic Magnetic Fields

The transport of beams is limited by divergence due to transverse ion energy. This limitation is particularly serious in low-energy beams. As shown in the example in Fig. 42, a magnetic "pipe" consisting of a periodic magnetic structure can transport an ion beam without serious perturbation of the phase-space ion density.⁵⁸ Analysis and computer calculations show that for sufficiently small $m v_x / m_p I$, the particles are specularly reflected (where m is the particle mass, m_p is the proton mass, v_x is the transverse speed, and I is the

Fig. 42. Ion-beam transporter.

current in each wire). In Fig. 43, results are shown plotted against v_x/v_z , with v_z the directed velocity. The theory,⁵⁹ is discussed elsewhere in this report. Construction of a transporter is underway.

Advanced Development

Although most of the neutral-beam development resources are allocated to meet near-term goals and milestones, there has been an occasional opportunity to pursue advanced development topics. Spectroscopic studies of Balmer-line emission from the atoms in the source have shown that the atom temperature in the source (from Doppler broadening) is ~ 0.4 eV. The ion "temperature" (~ 1.4 eV) has been measured with a Langmuir probe. These parameters have been used in a first attempt at a self-consistent model of the plasma source.⁶⁰ This work is continuing, since a better understanding of the plasma source will be necessary in order to improve gas efficiency, reduce ion temperature (and so reduce the beam divergence), control molecular-ion composition of the beams, and provide better input data for the WOLF code.

As the energy and pulse length of neutral-beam sources are increased, the heat-load on the grids from secondary ions and electrons formed by ionization and charge exchange in the accelerator structure becomes more important. The WOLF code will be modified to include the trajectories of these secondary

Fig. 43. Computed and theoretical calculations of the beam velocities confined in the transporter.

particles in the optimization procedure. Once the problem areas are identified, it should be possible to minimize the heat loads by appropriate alterations in the shape of the grid bars.

Another problem arising with high-power beams of the type required for the TFTR is that of diagnosing the neutral beams. The power densities will be so high in the focal plane (peak power densities of the order of 100 kW/cm^2) that standard calorimetric techniques cannot be used, since even W, at normal incidence, would melt in a few milliseconds. It should be possible to diagnose the beam quality by measuring the Doppler shift of Balmer-line radiation from the beam. Preliminary spectroscopic measurements show that the fractional-energy D atoms resulting from molecular ions in the beam can also be detected by Doppler-shift spectroscopy.

An alternative to the negative-ion approach for achieving high-energy neutral beams with high electrical efficiency is a scheme in which the neutralizer is at high negative potential, so that the unneutralized ions are decelerated as they leave the neutralizer.⁶¹ We have prepared a conceptual design for such a scheme, with an LN_2 -cooled, vane-shaped, close-coupled neutralizer.⁶² No experimental work on this design has been done.

An analysis of the surface-plasma, negative-hydrogen-ion source developed by Belchenko *et al.*⁶³ has led to a hypothesis⁶⁴ for negative-ion formation by atom collisions with the cesiated cathode. In this model, a near monolayer of Cs is formed on the W cathode. The collision of an energetic (few-eV) neutral atom with the surface forms an intermediate CsH^- molecular configuration, from which an H^- ion rebounds. In its qualitative formulation, the model indicates negative-ion formation will occur in any tungsten-alkali-hydrogen system. A quantitative analysis of this system requires an accurate knowledge of the system energetics. In collaboration with the LLL Chemistry Division, we are working on a Hartree-Fock calculation of the energetics of alkali-hydride diatomic systems. Subsequently, we shall extend these calculations to compute the energetics of hydrogen-alkali surface interactions.

Test Facilities

The various test facilities, completed and under construction, are shown in Table 2. During FY 1975, the 20-kV, 80-A, 10-ms power supply was upgraded to 40 kV, 80 A, 10 ms (Item 3, Table 2) for the development of the 40-kV, 50-A source. A second beam line was added to the 2600-l, 7000-l/s vacuum system so that the 20-kV, 20-A, several-second power supply (Item 4) can be used to test

Table 2. Neutral-beam test facilities.

Electronics	Approximate completion date	Vacuum systems (volume; pumping speed)
<u>Pulsed:</u>		
1. 20 kV, 20 A, 10 ms		6,000 l; 7,000 l/s (air)
2. 40 kV, 20 A, 10 ms		700 l; 1,000 l/s (air)
3. 40 kV, 80 A, 10 ms		2,600 l; 7,000 l/s (air)
4. 11 kV, 7 A dc; or 20 kV, 20 A, few seconds	Summer 1975	
5. 100 kV, 20 A, 300 ms; or 50 kV, 40 A, 300 ms	Fall 1975	170,000 l; 30,000 l/s (air)
6. 80 kV, 80 A, 45 ms; or 125 kV, 80 A, 35 ms	Fall 1976	
<u>dc (HVTs):</u>		
7. 200 kV, 25 A dc; or 100 kV, 100 A, s; or 150 kV, 50 A, s	Spring 1977	20,000 l; 700,000 l/s (D ₂)

long-pulse sources on the same vacuum system. This power supply, which had been built (but never debugged) for the low-voltage Baseball II source,⁶⁵ is in the trouble-shooting stage and should be operational early in FY 1976.

A very-large-volume (170,000-l), moderate-pump-speed (30,000-l/s) vacuum system was almost completed during FY 1975 and should be operational by October 1976. This system, which relies on "inertial pumping" (expansion into a large, evacuated volume), will be capable of handling a 0.5-s pulse from a 50-A source. The pressure will rise to $\sim 5 \times 10^{-5}$ Torr at the end of the pulse, and the pumps will return the system to its base pressure (expected to be 10^{-6} Torr) within 1 min.

We extended the expected completion date of Item 5 to February 1976 so that the power supply could be upgraded to a 150-kV, 20-A, 500-ms capability for TFTR development. This power supply, the first high-current supply with long pulse-time capability at voltages above 100 kV for neutral-beam development, will have a saturable-reactor control in the primary winding of the high-voltage transformer that will allow a shunt regulator (as opposed to a series regulator) on the output. The regulator scheme will be described in the TFTR conceptual design⁶⁶; we estimate that the regulator could result in a 25% reduction in the cost of the TFTR power supplies.

The capacitor banks for Item 6, Table 2 (125-kV, 80-A, 35-ms) were fabricated in FY 1976; the complete power supply is not scheduled for completion until Autumn, 1976.

The power supply for the HVTS⁶⁷ (Item 7) will be capable of either dc operation at 200 kV, 25 A, or several-second, pulsed operation at either 100 kV, 10 A or 150 kV, 50 A. The site for the HVTS becomes available on January 1, 1976. The principal effort during FY 1975 has been in planning, in detailed designing, and in accumulation of long-lead-time items such as transformers and switch gear. All of the major components for the high-voltage power supply are on site.

The HVTS will be pumped by cryopanel. The parts for the first cryopumping module, Fig. 44, have been fabricated and will be assembled and tested early in FY 1976. For the initial testing, the module will be set up with LHe supplied by gravity feed from an overhead Dewar. The module has been instrumented for measurement of pressure, gas throughout the module, temperature distribution on cryogenic surfaces, and residual gas species. Measurements of the module's pumping speed will be used for final design of the main cryopump, which will have a design pump speed of $450,000 \text{ l}\cdot\text{s}^{-1}$. Specifications are now

being written for the He liquifier.

We are looking at potential schemes for the transfer of liquid and gaseous He and LN_2 across a 200-kV potential drop. At the same time, we have changed the site-modification plans to allow enough flexibility for individual Dewars on the pumps, should high-voltage transfer of cryogenic fluid prove to be unfeasible.

Fig. 44. Modular cryopump for high-voltage test stand. (Baffled-pump area = 1.6 m^2 ; minimum pumping speed for H_2 or D_2 = $80 \text{ m}^3\cdot\text{s}^{-1}$; pressure range = 1.3 to 13 mPa; gas throughput = 43 to 430 $\mu\text{mol}\cdot\text{s}^{-1}$.)

Conceptual Design of Injectors for a Tokamak Fusion Test Reactor

Late in FY 1975, we began an intensive effort on a conceptual design for neutral-beam injectors for the TFTR. This effort is continuing and will culminate in a report⁶⁶ that

will contain conceptual designs (and cost estimates) for the beam line, power supplies, and computer-control system.

INTENSE 14-MeV-NEUTRON SOURCES

Significant progress was made in FY 1975 in several aspects of 14-MeV-neutron source technology at LLL. Important achievements in operation of the present facility, in design of the new source facility, and in development of source technology are detailed below.

Present Facility

Improvements in the ion source and transport system of the present RTNS-I source have raised target current to 22 mA D^+ . A peak source strength of 6×10^{12} n/s has been produced; for a recent 100-hour run, the average source strength was 5×10^{12} n/s. Availability of the source has been increased by going to two-shift operation. Reference 68 contains a detailed description of the facility and the associated experimental program.

New Facility

We have completed the conceptual design of the RTNS-II neutron sources and the buildings to house them.⁶⁹ An artist's conception of the complete facility is shown in Fig. 45. The new facility will provide two neutron sources, each producing 4×10^{13} n/s. The option of upgrading all sources to 1×10^{14} n/s operation is preserved in the facility design. In addition to the neutron sources themselves, the facility will contain an electrostatic accelerator, ion sources, and x-ray generators. Thus, we shall be able to simulate a first-wall environment in fusion reactors by the simultaneous bombardment of samples with neutrons, photons, and charged particles.

Construction of the RTNS-II facility is expected to require 2 years. If funding is authorized in early FY 1976, initial operation should be possible in early FY 1978. Routine operation at 4×10^{13} n/s levels is expected within 6 months thereafter. LLL will operate these sources as a national facility for the CTR program; experiments will be scheduled by a user's group established by DCTR. Access to the facility by non-U.S. researchers will be possible by arrangement with DCTR.

Fig. 45. Artist's conception of RTNS-II facility.

To determine significant cost-benefit trade-offs, an architectural engineering firm will examine the conceptual design of the facility. Alternate approaches to the building and building subsystems may result from this study.

Source Technology

To support the upgrading of the present facility and the design of the new facility, in FY 1975 we carried out an expanded research and development program in the areas of accelerator and target technology. Measurements of emittance, beam quantity, and component lifetime have begun on the LLL MATS-III ion source and on a single-aperture duoplasmatron source modified for dc, high-power operation. Initial results suggest that the MATS-III source may be an excellent choice for the new neutron sources.

To sustain the higher power density of the deuteron beam from the new accelerators, we have developed a new target that rotates at 5000 rpm and that has internal coolant flow. This target will be in routine operation on RTNS-I in mid-FY 1976. Target lifetime on the present source should be greatly improved.

Finally, we have developed diagnostic techniques for the study of hydrogen-isotope inventory and transport under conditions of radiation-enhanced diffusion. These methods plus macroscopic analysis of target materials and computer studies of the tritium diffusion process allow systematic evaluation of new target materials and concepts.

14-MeV-NEUTRON IRRADIATION STUDIES

All potential fusion reactors generate high fluxes of high-energy neutrons. We know that fission and fast-fission neutrons have deleterious effects on reactor materials. For several reasons, we expect that equivalent fluences of 14-MeV neutrons will have even more severe effects: high-energy neutrons create a larger number of displaced atoms per primary knock-on; more helium is formed in materials because cross sections for (n, α) reactions are higher for fusion neutrons; and surface-damage phenomena such as sputtering and spalling are enhanced.

The 14-MeV-neutron irradiation study continues to have three principal objectives:

- To study and characterize the damage produced by 14-MeV neutrons, including the type, density, and morphology of radiation-induced defects, helium generation rates, bubble nucleation and growth, and initial damage rates.
- To determine the effect of 14-MeV neutron damage on the physical and mechanical properties of potential fusion reactor materials. These results will be correlated with changes in microstructure produced by irradiation.
- To use computer programs to model both high-energy neutron collision events in solids and deformation processes in materials undergoing neutron irradiation.

Rotating Target Neutron Source Irradiations and Dosimetry

During FY 1975, 27 irradiations were carried out in the rotating target neutron source (RTNS), two of them being high-temperature irradiations. Thirty-five experimenters representing 10 outside laboratories provided more than 450 samples for irradiation.⁷⁰⁻⁸⁶ The maximum average flux obtained was 1.26×10^{12} n/cm²·s from a 45-h run. Niobium foils were used for dosimetry.⁸⁷

Radiation Strengthening of Cu and Nb by Irradiation with 14-MeV Neutrons

We are conducting a comparative study of the radiation strengthening and bulk damage structures produced in Cu and Nb during irradiation with 14-MeV DT-fusion neutrons and with fission reactor neutrons. Our intent is to assess the nature and magnitude of the radiation damage caused by fusion neutrons in candidate structural materials for controlled thermonuclear reactors.

Figures 46(a) and (b) show the increase in yield stress vs neutron fluence for tensile samples of Cu and Nb irradiated either with DT-fusion neutrons in the RTNS or with fission-spectrum neutrons in the Livermore pool-type

Fig. 46. Increase in tensile yield stress vs neutron fluence (a) in Cu, and (b) in Nb.

reactor (LPTR).⁸⁸ Note that the fusion neutrons are considerably more effective in strengthening both Cu and Nb than are the fission-reactor neutrons. At the higher neutron fluences, the increase in yield stress produced by a given fluence of fusion neutrons requires approximately 20 times as great a fluence of fission-reactor neutrons ($E > 0.5$ eV). If the fission-reactor neutron fluence is measured in terms of $E > 0.1$ MeV, the fission-to-fusion neutron ratio for equal strengthening is about 10.

Figures 47(a) and (b) show the increase in yield stress for the same Cu and Nb samples vs neutron damage energy. (The damage energy is that energy delivered to the materials that goes into displacing atoms from their lattice sites.) Note that at the higher damage states, about a factor of 2 less damage energy is required from fusion neutrons to produce the same strengthening as that produced by fission-reactor neutrons.

Figures 48(a) and (b) are dark-field-stereo transmission electron micrographs of the damage structures in two Cu samples irradiated by fusion neutrons and fission-reactor neutrons, respectively. These samples, marked "S" in Fig. 46(a), underwent about the same amount of radiation strengthening. However, Figs. 48(a) and (b) show significant differences in the quantities and distributions of the structural damage in the form of vacancy and interstitial point-defect clusters and small dislocation loops (small white spots).⁸⁹ Our analysis of the damage defects showed that the same types of clusters are produced in Cu during irradiation by fusion neutron and fission-reactor neutrons.

Figure 49 shows estimates of the size-number density distributions of the clusters in Figs. 48(a) and (b). Note that the highest cluster-density distribution in the Cu irradiated by fission-reactor neutrons is comparable to that in the sample irradiated by fusion neutrons. Since the Cu sample irradiated by fusion neutrons received a fluence 10 times less than the fluence in the sample irradiated by fission-reactor neutrons ($E > 0.1$ MeV), it appears reasonable to conclude that the rate of accumulation of structural damage in the form of point-defect clusters is substantially greater during irradiation with fusion neutrons than during irradiation with fission-reactor neutrons.⁹⁰

Since there appear to be no differences in the nature of the primary damage defects produced in Cu during irradiation with fusion and fission-reactor neutrons, the differences in the radiation strengthening appear to result from the differences in the quantities and distributions of the resultant damage. These differences in structural damage appear to be associated

Fig. 47. Increase in tensile yield stress vs damage energy (a) in neutron-irradiated Cu, and (b) in neutron-irradiated Nb.

(a)

(b)

Fig. 48. Dark-field, three-dimensional stereo micrographs of neutron damage in Cu (a) fission-neutron damage, $\theta_t = 1.27 \times 10^{17} \text{ n/cm}^2$, 25°C , $Z = [001]$, $g = [400]$; and (b) fusion-neutron damage, $\theta_t = 3.3 \times 10^{18} \text{ n/cm}^2$, $E > 0.5 \text{ eV}$, 65°C , $Z = [001]$, $g = [400]$.

Fig. 49. Size/number-density distributions of clusters in Cu irradiated by fusion neutrons or by 65°C fission neutrons.

with the presence of high-energy recoil events. Such events, which occur during irradiation by the fusion neutrons, produce vacancy clusters spontaneously at high-energy displacement cascades.

Helium in Metals

Helium is produced in materials subjected to 14-MeV neutrons as a result of (n,α) , $(n,n'\alpha)$, and similar nuclear reactions; we must know the amount of He generated. Unfortunately, in many important cases cross sections for the reactions are not well known. The overall objectives of this project are thus

- To accurately measure the amount of He introduced in metals by (n,α) reactions of 14-MeV neutrons,
- To determine the rate of diffusion of He in metals,

- To study the nucleation of voids in irradiated and nonirradiated specimens, and
- To evaluate the effect of He concentration and distribution on mechanical properties.

We have constructed equipment for heating and melting a sample in vacuum and then analyzing the He liberated by use of a mass spectrometer. Because the equipment can measure $<10^{10}$ atoms of He, concentrations of parts per billion in 10-mg specimens can typically be determined. This equipment has an important and unique feature: specimens can be heated in a controlled way and the temperature monitored so that the rate of release of the He can be observed and mechanisms of migration in the solid deduced. Such measurements coupled with electron-microscope examination of specimens will show whether the He condenses into bubbles within the solid or escapes by atomic migration to surfaces.

Because Cu is a convenient material for study and is well characterized,⁹¹ we used irradiated Cu during the preliminary development of this experimental technique. The derived cross section for the (n,α) reaction is 54 millibarns compared with the value of 30 millibarns deduced from the resultant ^{60}Co production. This disagreement has not been resolved; however, the measured value may be more correct than the deduced and generally accepted value.

Aluminum, Fe, Ni, and 304 and 316 stainless steel have been doped with He by allowing dissolved tritium to undergo radioactive decay.⁹² Helium concentrations below 1 atomic ppb were produced. Using high-sensitivity, mass-spectrometer techniques, we observed He release during isochronal and isothermal anneals.⁹³ In the case of 304 stainless steel, with isochronal annealing, He is released in two temperature ranges, one near 300°C and the other between 800°C and the melting point.⁹⁴ The latter release is interpreted as attributable to bubbles of He gas. The release near 300°C has been studied isothermally between 150 and 300°C and has been analyzed in terms of two stages of exponential decay. The fast- and slow-release stages have relaxation times near 10^2 and 10^3 s, respectively, and the fast release accounts for roughly 85% of the total release at low temperature.

High-energy neutrons not only cause displacement damage, but also produce He in the matrix by (n,α) reactions. Bubbles of He gas trapped in the microstructure can alter the mechanical properties and often lead to embrittlement as He is accumulated. Therefore, to separate and study He effects on mechanical properties, we are using the "tritium trick"⁹² to dope Nb tensile and creep specimens with various concentrations of ^3He . In this method, tritium

is dissolved in Nb at $T \geq 300^\circ\text{C}$ and allowed to decay to ^3He . When a predetermined concentration of He has been incorporated into the microstructure, the more mobile tritium is reduced to a low concentration by high-vacuum pumping ($T \geq 300^\circ\text{C}$).

The distribution of the ^3He in Nb specimens is being characterized by locating the residual tritium with high-resolution autoradiographic techniques. Results indicate that the residual tritium is uniformly distributed in the microstructure with no preference for the grain boundaries. By inference, the ^3He should also be uniformly distributed in the material.

Several pure, polycrystalline Nb tensile and creep specimens have been doped to obtain ^3He levels from 25 to 500 atomic ppm. We plan to run tests at elevated temperature to determine the effects of the ^3He concentration on the mechanical properties at various strain, strain rate, and stress levels.

14-MeV-Neutron Sputtering and Particle Release

Surface studies have been primarily concerned with assessing the sputter damage resulting from a 14-MeV-neutron flux. In the past few years, various investigators have obtained markedly different sputter yields (from 10^0 to 10^{-5}) and have observed both atomic and "chunk" sputtering. In February 1975, the participants at a Neutron Sputtering Workshop held at Pacific Northwest Laboratory, Richland, Washington decided that a "round robin" of neutron sputtering experiments should be carried out to attempt to resolve these differences. We are participating in this "round robin." Considerable effort has gone into the very careful design of the experimental procedures and of the pertinent apparatus for our sputtering experiments for this "round robin."

In a preliminary experiment with Manfred Kaminsky of Argonne National Laboratory (ANL), a Nb target was exposed to a 14-MeV neutron fluence of $\sim 10^{17}$ n/cm². A 1-in.-diam Si catcher disc was placed in the forward scatter direction. This catcher disc was divided into two semicircular sections. We analyzed one; the other was taken to ANL. We surveyed the entire area in an ion microprobe and found a general atomically scattered Nb background, two areas of more intense scatter (scanning electron microscope examination disclosed no visible particles >100 Å), and one Nb particle ~ 2 μm in diameter. Although yield calculations await further equipment calibration, the sputter yield will probably be closer to the lower end of the value scale stated previously.

Initial Damage Rate Production

The RTNS has been successfully used for β -radiations of Nb, V, and Mo at 4.2 K. Residual resistivity measurements with a sensitivity of 1 part in 10^5 have been made with the neutron source operating. We have also completed the determination of total defect production rates as a function of fluence for 14-MeV and fission neutrons.

Radiation-Enhanced Diffusion

In two studies involving mass transport at room temperature during irradiation with 14-MeV and fission neutrons, we have obtained a relative measure of the number of free vacancies produced during irradiation:

- The development of short-range order in α -brass as determined by resistivity changes,⁹⁵ and
- The clustering of Fe in dilute Au-Fe alloys using the Mössbauer effect.⁹⁶

Both studies indicated that 14-MeV neutrons produce about twice as many free vacancies as one would predict from fission-neutron irradiations on the basis of total damage energy.

Computer Modeling of Crystal Defects

Theoretical modeling of crystal defects has primarily centered on point-defect calculations using BURST, the many-body, dynamic, crystal code. The calculations serve the twofold purpose of gaining experience with the code and providing the ground work for more extensive calculations involving the modeling of 14-MeV-neutron displacement cascades.

Using BURST, we have completed an extensive study of interstitial diffusion in W in which we compared the results of static calculations with diffusion coefficients determined dynamically by actually following the motion of the interstitial.⁹⁷ We have also completed calculations on the temperature dependence of the displacement threshold, interstitial-vacancy recombination volume, and He detrapping during irradiation.^{98,99}

TRITIUM TECHNOLOGY

The successful development of fusion-generated power is dependent upon major advances in tritium technology. The recovery and containment of tritium are expected to be particularly difficult problems. Current projects, which

reflect the diversity of tasks, pertain to tritium containment, stripping of tritium from inert cover gases, properties of cryogenic hydrogen isotopes, and tritide-target development for the LLL RINS.

Tritium Containment

Because the processing and handling of tritium inevitably results in tritium-contaminated waste gases, we are studying uranium as a getter material for scavenging tritium from inert gases. The tritium can then be recovered for reuse and the waste gases safely exhausted to the atmosphere. We expect to use uranium traps as part of a new tritium clean-up system in the LLL tritium facility.

In a uranium trap, activated uranium is dispersed in three layers, with each layer segmented for uniform distribution. For our studies, we used mixtures of 0.5 to 4 vol% D_2 in Ar and flow rates of 11 to 67 cm^3 STP/s.

The efficiency of the uranium trap is expressed as the purification factor (PF), i.e., as the ratio of the D_2 concentration at the trap inlet to that at the trap outlet. Results show that the purification factor is inversely proportional to the flow rate through the trap and to the amount of deuterium already reacted with the uranium. At least over the range studied, the purification factor is not affected by the deuterium concentration entering the trap.

To reduce the data, we used a model for a gas-phase, mass-transfer-limited process in a packed bed. Briefly, the model shows that $\log (PF) \propto (p/G)^{1/2}$, where p is the pressure and G is the mass flow rate. When the quantity $(G/p)^{1/2} \log (PF)$ is plotted against the atomic D/U ratio of the trap, the results are shown in Fig. 50 and can be expressed by the equation¹⁰⁰

$$\left[\frac{(G/p)^{1/2}}{p} \log (PF) \right] = -0.048 \left(\frac{D}{U} \right) + 0.144.$$

Similar results were noted when earlier data were analyzed in the same manner.¹⁰¹

Fig. 50. Performance of a uranium trap (normalized for mass flow rate and pressure effects) as a function of the atomic D/U ratio.

Properties of Cryogenic DT

The properties of cryogenic DT must be known for cryopumping CTR reactors and for isotopic recovery of tritium. For cryopumping, we should know the vapor pressure and the permeation rate of He^3 in solid DT. For tritium recovery, we are interested in the chemical equilibria and kinetics of the D_2 -DT- T_2 reaction.

To study the properties of cryogenic heavy hydrogen, in FY 1975 we established a program with the following goals:

- To measure those properties most affected by the tritium radioactivity, and
- To correlate and summarize vital cryogenic properties.

During the report period, we constructed a containment box that included tritium-monitoring equipment and cleanup getters.¹⁰² In addition, we critically reviewed values for a number of physical properties of the hydrogens and extrapolated to estimated values for DT and T_2 .¹⁰³⁻¹⁰⁶

Tritide Target Development for the RTNS

We are continuing a program to improve the neutron flux of the LLL RTNS and the useful life of its targets. We are working closely with personnel who operate the RTNS and who have the responsibility for upgrading the deuteron accelerator and the physical design of the target. Efforts are currently in the following two areas:

- Analysis of the current titanium tritide targets; and
- Development of alternate target materials.

Target Characteristics

During the past year, several used RTNS targets were examined to determine their characteristics. The analyses indicate that the targets were sputtered by the deuterium beam and that a significant amount of tritium was released through thermal heating of the target by the beam. Prior to these preliminary studies, such substantial losses were not believed to occur.

These early data from used targets have been invaluable in providing a background for the detailed investigations that are now beginning. In the coming year, a substantial number of the targets produced will include coupons for destructive analysis. Also, production data will be available to us. Using metallography, scanning electron microscopy, mass spectrometry, and atomic absorption spectroscopy, we will obtain data on tritide thickness, adherence, sputtering, surface condition, and hydrogen-isotope-co-metal ratios

from both the coupons and the targets after use. Auger spectroscopy and electron spectroscopy for chemical analysis (ESCA) capability may also be employed if it proves necessary to study outer-surface effects.

The operational data now being logged for each target include beam current, target position and speed, tritium release (with a residual-gas analyzer), neutron intensity, and possibly target temperature. These combined data then will be analyzed through numerical modeling techniques to determine the degradation mechanism of the current titanium tritide targets.

Alternate Target Materials

Small targets are being made from several other stable binary metal tritides. These will be placed on the insulated-core transformer (ICT) accelerator and run in a pulsed mode (simulating RTNS operation) to determine their suitability as replacements for titanium tritide.

The program outlined above should allow important progress during the coming year towards improving the performance of the RTNS targets.

SECTION 3. RESEARCH

THEORY AND COMPUTATIONS

Introduction and Summary

During the past year, we have made considerable progress in the development of a number of computer codes that are applicable to magnetic mirror problems. We have started a major magnetohydrodynamic (MHD) computational program, with the initial emphasis being the magnetic trapping of laser-generated target plasmas. For this purpose, we have developed two two-dimensional MHD codes, a flux line coordinate version and an Eulerian version.

We are also developing a new three-dimensional equilibrium code for computation of finite- β guiding-center equilibria in minimum-B geometry. This code removes an overly restrictive assumption on the form of the plasma pressure tensor that was used in previous codes. To date, the new code has been used to calculate the effect of nonzero plasma pressure in 2XII. The sharper magnetic gradients introduced by finite- β have reopened investigation of single-particle adiabaticity.

With a modified form of the two-dimensional SUPERLAYER code, we are studying the possibility of using the current of injected neutral-ion beams for field reversal. The code predicts that reversal is possible in the 2XII-B experiment if the beams are focused off-axis.

A major computational effort has resulted in a series of Fokker-Planck codes that describe classical loss processes. In each generation, the model has been improved; the current major step is the introduction of a proper bounce-averaged description in a nonuniform magnetic field. Existing codes, employing magnetic square wells, have been used for Q calculations, calculations of distribution functions in the presence of neutral injection, calculation of experimental lifetimes both with self-consistent and artificially lower electron temperature, and calculation of the mirror-mode β -limit with changing pitch-angle profile. The axial pressure profile in 2XII has been shown to be consistent with a collisional pitch-angle profile.

We have performed a number of analytical and computational investigations of aspects of a two-component, open-ended reactor. These investigations have entailed analysis of the stability of two-component distribution functions, development of a code to model electron heat conditions and sheath formation along the axis of such a reactor, and Fokker-Planck calculations of Q values.

The idea of toroidally linking mirror machines has been receiving increasing attention. The motivations vary, but for MHD stability all such schemes require that the toroidal plasma be of considerably lower β than the mirror-trapped component. A low-density toroidal link would provide the cold plasma thought necessary for the stability of the hot mirror-trapped plasma and possibly would increase the energy containment time of the electrons. A high-density toroidal link would, in addition, offer the possibility of a two-component mode of operation with the hot reacting component limited to one or more mirror cells.

A principal emphasis of the CTR theory program has been on understanding the elusive drift-cyclotron loss-cone (DCLC) mode. This mode now appears to be understood, and a recently developed quasilinear model agrees very well with 2XIIB data. Thus, with renewed confidence in linear and quasilinear theory, we are determining equilibrium and loss characteristics of existing experiments (2XIIB and Baseball II-T) and the proposed MX experiment. Our studies involve linear stability analyses with extensive geometric complications. This information is used as input to quasilinear codes that are then coupled to the two-dimensional Fokker-Planck codes. Specific areas investigated during the past year included:

- Detailed stability boundary to the DCLC mode with the quasilinear filling of the distribution (determines radial dimension).
- Axial scale length restrictions (magnetic and density) provided by the negative energy wave.
- Overall length restrictions given by the Rosenbluth-Post convective loss-cone mode.

We continued to investigate adiabaticity and superadiabaticity. Because we are interested in the confinement of higher-energy particles (with larger gyroradius) in finite- β fields, the theory of nonadiabatic jumps is of renewed interest.

Computations and Code Development

Equilibrium, Adiabaticity, and Confinement Studies

Determination of confinement times and studies of nonadiabatic effects have been undertaken by Foote¹⁰⁷ and others¹⁰⁸ for vacuum fields and for analytical representations of combined vacuum and plasma fields. The study of these effects for self-consistent, high- β equilibria have to date be fraught with difficulties associated primarily with the numerical production of $\nabla \cdot \mathbf{B} \neq 0$.

We have developed a set of codes in Cartesian coordinates that allow for the determination of a wide class of equilibria and also eliminate the $\nabla \cdot \mathbf{B}$ problem.

First in this series of codes is ABCXYZ,¹⁰⁹ which replaces the familiar MAFCO¹¹⁰ code. ABCXYZ computes both the vector potential and the magnetic induction for a general set of current-carrying conductors. With it, any reasonable magnetic coil design may be represented. The resulting fields serve as input for either the equilibrium code or the orbit codes.

The second code in the series, VEPEC¹¹¹ (vec: potential equilibrium code), solves for the anisotropic pressure equilibrium of the form $\underline{P} = \underline{i}(B, \psi)$ by solving equations equivalent to the equilibrium model of Hall and McNamara.¹¹² The distinction is that here vector potential equilibrium fields are produced.

Last in this series is the orbit code ORBXYZ, which follows the trajectory of a charged ion in the vector potential field obtained from one of the above codes. Development of a fast, accurate, three-dimensional, tricubic, spline algorithm for interpolation¹¹³ was essential to building ORBXYZ. By obtaining $\underline{B}$ analytically from the spline formula for $\underline{A}(\underline{B} = \nabla \times \underline{A})$, we find $\nabla \cdot \underline{B} = 0$ to roundoff. ORBXYZ is approximately twice as fast as its predecessor TIBRO and roughly 20 times more accurate in the representation of the magnetic moment. Figure 51 compares theory with TIBRO and TIBRTZ (a cylindrical version of ORBXYZ) for a set of particles run in the Baseball II vacuum field.

All of these codes are referenced to the same Cartesian grid, and the results of one form the input for the next code in the sequence. Both ABCXYZ and one version of ORBXYZ are running codes. VEPEC is in the final stages of debugging.

Fokker-Planck Studies of Magnetically Confined Plasmas

Because the development and use of realistic numerical models

Fig. 51. Comparison between values of $\Delta\mu/\mu$ for single-particle orbits as calculated by three versions of the orbit code. Central processing unit time for nine orbits is given in parentheses.

representing the magnetically confined plasmas in actual experimental devices is not now practical, over the past several years we have developed a series of simpler models.¹¹⁴⁻¹¹⁶

A commonly used model assumes that the plasma is uniform over some finite region of space, and the velocity distribution of the particles is then obtained by solving the Fokker-Planck kinetic equations in a two-dimensional velocity space. A computer code that handles an arbitrary number of ion species within the context of this model was developed last year.¹¹⁷ Since then, the code has been used to investigate several problems in magnetic plasma confinement:

- The transient and predicted steady-state behavior of plasma in the 2XII-B experiment,¹¹⁸ including the effects of charge exchange, neutral-beam injection, and magnetic compression;
- The design of a fusion-fission hybrid reactor⁵²;
- A study of the toroidal fusion test reactor (TFTR), including major-radius compression and transport losses¹¹⁹; and
- Theoretical investigations on more general aspects of plasma confinement.¹²⁰

An important refinement of the basic plasma model is the incorporation of effects due to spatial variation of the plasma in a magnetic-mirror field. We are now developing a reasonably fast, accurate computer code for this model and testing results against previous work¹²¹ and analytic theory.

One-Dimensional Radial-Transport Calculations

The one-dimensional radial transport and buildup code described last year² has also been used to calculate the buildup of a hot ($kT_1 \approx 20$ keV), mirror-confined plasma resulting from a cold ($kT \approx 2$ keV) target plasma and a high-energy ($E \approx 20$ keV) neutral beam. We have included the effects of a cold neutral gas and have found that we need to expand the model to include the effects of a finite Larmor radius. This modification is being made, and the code is being optimized (the revised model greatly increases the calculation time). Figure 52

Fig. 52. Ion density vs plasma radius for $I_{\text{beam}} = 600$ A, 20 keV; $I_{\text{gas}} = 5$ A, 0.025 eV; $a_L = 0$.

represents a zero Larmor radius deuterium plasma (held at a constant temperature) bombarded by a 600-A (equivalent), 20-keV, neutral deuterium beam and a 5-A (equivalent), 0.025-eV, neutral deuterium beam. We expect that the "mixing length" of the finite Larmor orbit¹²² should prevent the plasma surface from being eroded.

Two-Dimensional, Guiding-Center Fluid Equilibrium

We are developing a code to solve the magnetic differential equations of Hall and McNamara¹¹² in two dimensions and from this to generate the equilibrium magnetic field configurations (including finite- β) for systems with one ignorable coordinate. The first application will be to study the equilibrium properties of various axially symmetric tori configurations such as the proposed MIRICLE configuration,¹²³ the Levitron geometry,¹²⁴ and TORMAK.¹²⁵

The problem has progressed to the point where the numerical implicit-difference scheme used to solve the differential equations has been coded and satisfactorily tested for accuracy with several check cases.

Three-Dimensional Plasma Equilibria

The algorithm for computing the three-dimensional equilibrium of a magnetized guiding-center plasma in the formulation of Hall and McNamara¹¹² has been implemented in the MCGUS code. MCGUS assumes the symmetries of a Baseball or Yin-Yang field and solves all equations in one octant of the computational volume. The principal output of the code is the total magnetic induction¹¹²

$$\vec{B} = \vec{B}_{\text{vac}} - \nabla\Gamma - 4\pi\chi\nabla(T/\Gamma) - \eta\vec{B}.$$

The scalar functions that comprise $\vec{B}$ are also functions of $\vec{B}$. Thus, equations determining χ , Γ , η are nonlinear, and a self-consistent solution results by an iterative process. To maintain overall accuracy in this process, algorithms used to compute χ , Γ , η have been upgraded to second order where appropriate.

Calculation of χ , Γ , η necessitates the solution of the magnetic differential equation,¹¹²

$$\nabla \cdot (\Gamma \vec{B}) = \hat{p}_{||}.$$

The divergence operator may be applied in the conservative fashion indicated, or, since $\nabla \cdot \vec{B} = 0$, the equation may be rewritten as a directional derivative, $\vec{B} \cdot \nabla \Gamma = \hat{p}$. For numerical accuracy, it is essential to use the conservative

form in the interior of the computational volume. Near the symmetry planes, however, the magnetic field is essentially two-dimensional, and one must use the directional form. The outcome has been implementation of an ADI difference scheme that is conservative in the interior volume and that is in directional form at the symmetry planes and at connecting points one grid spacing from the symmetry planes.

The scalar function Ω_p is determined by the condition that the total magnetic induction be divergence free. Thus, Ω_p must satisfy Poisson's equation with the source term,

$$\rho = \nabla \cdot [\chi \nabla (\vec{r}/\vec{r}) + (\eta/4\pi) \vec{B}].$$

Previously, the solution of Poisson's equation was either obtained in Cartesian coordinates using a fast Fourier transform algorithm, or, as an independent check, selected points were computed using a trapezoidal approximation to the integral solution. However, as a result of the magnetic-field structure and symmetries, Ω_p and ρ are most appropriately described in cylindrical coordinates. To take advantage of this fact, a cylindrical Poisson solver has been added to MCGUS that uses fast Fourier transforms in θ and z and Gaussian elimination in r . Because the magnetic differential equations are solved in Cartesian coordinates, interpolation between the rectangular and cylindrical grids is necessary. This operation has been programmed in two dimensions (i.e., at each z -plane) using an extensively modified version of a three-dimensional spline package.¹¹³

We have coded the solution of Poisson's equation that is calculated by the cylindrical fast Fourier transform algorithm to take advantage of the symmetries of Ω_p and ρ . Only $\cos(2n\theta)$ modes are calculated in the θ -direction, and only sine modes are calculated in the z -direction.

The code is run by a controller that stores equilibria on magnetic tape, making it easily restartable. Several diagnostic codes have been written to make graphs, movies, and three-dimensional projections of the results. We expect to complete the suite of codes by December 1975, with the codes then going into production on the CTR Computer Center CDC 7600.

Some Magnetic Effects in the Fokker-Planck Equation for a Plasma

The kinetic equation for a plasma situated in a magnetic field, of a strength such that the ion Larmor radius is larger than the electron Debye length, has the form of a Fokker-Planck equation in which the diffusion and

friction coefficients can be derived from "Rosenbluth potentials" in the usual manner. However, these "magnetic Rosenbluth potentials" are anisotropic, even if the plasma distribution function is isotropic, because the magnetic field has two effects:

- It alters the dynamics of ion-electron collisions; and
- It significantly enhances the duration of the interaction between the ions and electrons that have no relative motion parallel to the magnetic field.

The potentials are evaluated explicitly in the case of Maxwellian electrons; for large values of $\eta \equiv \Omega_e / \omega_{pe}$, the dominant effect is that $v^2 \ln \Lambda$ is replaced by $v^2 \ln \left(\frac{\Lambda}{\eta} \right) + \frac{3}{2} v_{\perp}^2 \ln \frac{v_e}{v_{\perp}} \ln \eta$.

Linear Programming

Optimization of linear systems is a discipline whose application to plasma physics is apparently new. Specifically, such problems have arisen from attempts to find the optimal distribution of injectors for neutral injection into a mirror confinement system so as to maximize a figure of merit characterizing the plasma (β , Q , etc.) while maintaining overall stability of the system.¹²⁶

Such problems belong to the theory of games and, when suitably formulated on a finite grid, may be solved on the computer by the methods of linear programming. SIMPLEX, a code that solves linear programming problems by the simplex algorithm, has been written in LRLTRAN for the CDC 7600.¹²⁷ The code maximizes the linear functional $W = \sum_{j=1}^n c_j X_j$, for $X_j \geq 0$, subject to m inequality constraints of the form $\sum_{j=1}^n a_{ij} X_j \leq b_i$ and l equality constraints of the form $\sum_{j=1}^n a_{ij} X_j = b_i$. After completing an initialization procedure that deals with the equality constraints, the code performs the simplex algorithm in a format similar to that of Owen.¹²⁸

SIMPLEX is designed as a subroutine that may be called by a larger program that could, for example, include such complicated systems as the Fokker-Planck codes for the determination of particle distribution functions from the velocity-space diffusion of particles in a mirror trap. SIMPLEX itself contains 14 subroutines and 357 source lines of code.

Numerical Experiments with the Tracer Particle Fluid Code

Workers using particle codes to simulate plasma have long sought and devised methods to reduce the nonphysical, stochastic, large-amplitude electric

fields associated with using small numbers of simulation particles. For the study of collisionless plasma phenomena, it is desirable to eliminate this stochastic part of the interaction. We have developed a collisionless fluid model for the plasma that includes self-consistent, velocity-space effects.¹²⁹

The electric field is produced by the fluid charge density generated by the fluid code that represents the collisionless plasma. Tracer particles are used to follow the velocity-space evolution of the collisionless fluid and to generate the heat-flow tensor, which in turn truncates the fluid equations in a collisionless manner. The tracer particles do not see one another because they are pushed by the fields generated by the fluids.

We are now using a two-fluid (electron-ion), electrostatic, one-dimensional Cartesian code to study the tracer-particle fluid method. To enable careful comparisons, we have also run a pure particle-simulation code (obtained by changing a parameter in the tracer code). We have studied several cases, and velocity space effects such as Landau damping have been demonstrated. Figures 53(a) and (b) show mode-amplitude histories for the two-stream electron instability as calculated by the pure-particle code and the tracer-particle fluid code, respectively. As seen in the figures, the behavior of the short wavelengths is much less noisy in the tracer-particle fluid model. We are now determining the regimes in which the tracer-particle fluid model is preferable to particle-simulation methods.

Fig. 53. Mode-amplitude histories for the two-stream electron instability as calculated (a) by the pure-particle code and (b) by the tracer-particle fluid code.

Future directions include electromagnetic and multidimensional models. Our goal is a three-dimensional fluid model for the dynamic evolution of mirror fusion plasmas. We also plan to study phenomena on longer time scales.

Expansion of the Laser Pellet Plasma in Baseball II-T

Axisymmetric multifluid simulation of the expansion of high- β pellet plasma in Baseball II-T is accomplished by algorithms that calculate the transport with respect to a moving flux-coordinate grid.¹³⁰ Anisotropies in the transport (particularly heat flow)

are accurately represented by this method because the heat-conduction tensor is always diagonal. This allows for a neat numerical separation of parallel and perpendicular heat transport.

We assume that the pellet is completely ionized and that the fluids are as follows:

- The pellet is represented by a one-ion fluid;
- A second, background-ion fluid is used to keep the fast magneto-acoustic speed tolerable to the numerics; and
- The third fluid is composed of electrons that are assumed to neutralize the plasma.

Except for the assumption of axisymmetry, the model includes the three vector components of $\underline{B}$, $\underline{E}$, and $\underline{V}$ for each fluid as well as n and T for each fluid. A general Ohm's law is also included.

Important phenomena occurring in the plasma expansion and representable by the model include: magnetic flux compression, thermo-electric spontaneous generation of magnetic field, resistive diffusion of the magnetic field, Joule heating, anisotropic heat conduction, and adiabatic heating and cooling.

Further features of the method include the ability to rezone in the flux-coordinate space itself so that at subsequent time steps the grid lines represent different flux tubes. This allows the observer or user of the code to construct an expanding window (domain) on the pellet expansion that always encloses the relevant and interesting physics. Figure 54 displays a typical flux-coordinate grid, and Fig. 55 shows the pellet plasma-density contours.

To allow studies of the early-time phenomena when the pellet is only partially ionized, we are incorporating a model for the deposition of laser radiation. Our goal is to build a code similar in capabilities to the LASNEX¹³¹ code, but with different applications.

Fig. 54. Orthogonal flux-coordinate grid midway through a typical simulation of the expansion of high- β pellet plasma in Baseball II-T. The horizontal lines are flux surfaces, and the vertical grid lines have been constructed orthogonally.

Fig. 55. Pellet plasma-density contours corresponding to the magnetic configuration shown in Fig. 54.

Simulation of Self-Consistent Magnetic Fields and Approach to Field Reversal in 2X

We are using a modified form of the two-dimensional (r,z) SUPERLAYER code to study the self-consistent magnetic fields arising from the currents of neutral injected beams and the conditions necessary for high- β and field reversal in 2X.

The SUPERLAYER code is limited in scope in that it does not allow electron current or space-charge effects. Within these limitations, the code should be able to examine the r,z equilibrium, including all effects of the mirror-tearing mode and the full generality of five phase-space dimensions. One rather severe approximation is made: the relevant time scales, τ (e.g., the drag time or filling time), are shortened considerably, typically by factors of order 100. The product $I\tau$ is kept consistent with the experiment, and an attempt is made to keep τ long compared to an axial-bounce period.

The initial work, reported in last year's Annual Report,² indicated that field reversal was easily obtainable and that, if the beams were arranged to form a coherent ring current, it persisted in a steady state after initial transients. This injection prescription is actually unrealistic, and this year we have concentrated on simulating 2X with realistic injection. The code predicts that reversal is possible in the 2XIIB experiment provided the beams are focused off-axis: high- β $\left(\beta = \frac{p_{8\pi}}{2 B_{vac}} > 1 \right)$ is obtainable regardless of the

focusing. This condition, however, is accompanied by a slow but steady axial loss of particles (this did not occur with ring-like injection). We do not yet know whether this axial loss saturates or if it is a real, long-time persistent effect (due to minor or tearing mode?). If the former, it should be viewed only as a longer-lived transient caused either by the physics or perhaps by numerical effects. If the latter, this axial loss possibly even prevents buildup in a system with realistic time constants.

Numerical Simulation of a Proposed Cold-Gas Feed in 2XIIB

We are investigating the conditions for maintaining a cold plasma by a surrounding external cold-gas source, as proposed by Logan.¹³² The essential features of this proposed cold-gas feed are a cold ($kT_i \approx 5$ eV) plasma bombarded by a cold D_2 molecular gas ($kT \approx 0.025$ eV) that interacts with the plasma electrons ($kt_e = 100$ eV) to create Frank-Condon D atoms. The D_2 is excluded from the plasma interior; however, the D atoms can penetrate because of their higher energy (2.5 eV, 5 eV, 9 eV) and thus, through ionization

processes, can act as sources for the plasma. The plasma loss time (due to flow) is v_s/L (where v_s = sound speed, and L = characteristic length of the system).

The vital questions are:

- How much D_2 current is needed to maintain a steady-state plasma?
- What is the spatial profile of the steady-state density and temperature?

The calculations use a modified version of a one-dimensional radial-transport code.² The code was modified because this situation requires a more exact treatment of the dynamic fluid equations for the neutral gases and results in a completely different numerical scheme for their solution.

Particle- and Energy-Balance Code for a Toroidally Linked Mirror FERF

We have developed a time-dependent computer code that solves rate equations for both particle and energy balance in a FERF mirror system with a toroidal link. We thus find the densities and temperatures of the following groups of particles in the mirror and in the torus: trapped ions (mirror only), hot ions, cold ions, and electrons. The mirror is assumed to behave classically with particle loss due to Coulomb scattering. The particles lost from the mirror go to the torus. The loss of particles and energy from the system occurs in the torus by diffusion to the wall and by charge exchange with neutrals.

The code enables one to perform an efficient survey of how the equilibrium states of such a system depend on various parameters. For example, the diffusion time to the wall in the torus is an uncertain parameter, and the effect of its having a range of values can be determined quickly. The code also calculates the flux of neutrons incident upon the walls of the mirror and the torus. It is this flux that one wishes to maximize with a FERF.

Axial Flow of the Cold Plasma in a Two-Component System

In a two-component mirror machine, there are both hot ions and cold ions. The hot ions are confined by the magnetic well; however, the cold ions are not confined and thus flow out the ends of the machine. For two reasons, it is important to have a quantitative model for this flow: it represents an energy loss out the ends of the machine; and the density profile of the cold ions may affect the containment of the hot ions.

Such a model has been developed at LLL over the last 2 years. This model assumes that the cold ions can be described by the fluid equations owing to their low temperature and consequent collision-dominated motion. The appropriate general solutions to fluid equations have been given¹³³ for the case of

no hot component present. The computer code MARTENI utilizes these solutions for specific cases.

This year, we have generalized the model by including the effect of a hot-ion density profile and the effect of heating the cold ions by collisions with hot ions and electrons. The hot-ion density profile sets up an ambipolar potential in the center of the mirror machine. If the cold-ion density is low, this potential will prevent most of the cold ions from penetrating into the center. However, if the cold-ion density is much larger than the hot-ion density, the hot-ion density profile has little effect. The temperature of the cold ions due to collisional heating is usually small, justifying the collisional description. However, this heating does allow a small percentage of the cold ions to penetrate the ambipolar potential barrier set up by the hot ions in the case of low cold-ion density. Finally, we note that with the modifications described above, this code can now model the axial flow characteristics for the two-component experiment proposed for the 2XIIB mirror machine.¹³²

Parameters for a Linear Two-Component FERF

With the intent of locating the minimum power system, we have explored the parameter space for a linear, two-component FERF. By specifying a neutron flux of 10^{14} neutrons $\text{cm}^{-2} \text{s}^{-1}$ at a wall radius that is equal to the plasma radius (1 cm) plus the orbit diameter of an α particle and by restricting the peak field to 20 T at the mirrors, the minimum beam power is ~ 46 MW for a 1-m-long system and ~ 37 MW for a 65-cm-long system. The beam power exhibits a rather broad minimum as a function of injection energy, the minimum occurring between 130 and 170 keV. The electron temperature of the cold component is low (~ 300 eV), and the mirror ratio is also low (~ 2.5).

Simulation of Instabilities in Two-Component Plasma

A two-component plasma consisting of a thermal core target and a beam injected normal to the core (and B_0) is known to be unstable,¹³⁴ especially when the beams are weak but relatively fast. Our model has a dense Maxwellian core with velocity v_t and a tenuous cold (sometimes warm) beam of velocity v_0 (a ring distribution in $v_{\perp}$ space), with $v_{\perp}$, $k_{\perp}$ only ($k_{\parallel} = 0 = v_{\parallel}$). Because the simulation is for a uniform plasma, it need be run only in one spatial dimension x , keeping v_x and v_y with a static B_{0z} .

Working with relatively cool ($v_{\text{core}} \ll v_0$) yet relatively dense ($n_{\text{core}} \gg n_{\text{ring}}$) core and searching for growth in the range $k_{\perp} v_0 / \omega_p \approx 1$ leads to working with very small $\lambda_D / \Delta x$. In an unmagnetized plasma, $\lambda_D / \Delta x \leq 0.3$ is

numerically unstable; this is readily observable by, for example, loss of conservation of energy. In a magnetized plasma such as ours, with target $(\omega_p/\omega_c)^2 \gg 1$, we should see almost the unmagnetized behavior. Indeed, runs made so far, at the above inequalities, have been plagued by numerical instability, probably due to the thermal core alone.

New work will be done with larger $\lambda_D/\Delta x$ and will use parameters more favorable for physical growth.

Mirror Machine Theory

Turbulent Loss in Mirror Machines

In the past, we have predicted that the plasma lifetime in mirror machines due to loss-cone modes would be several axial bounce periods.¹³⁵ This estimate arose because it was assumed that the plasma scattered into the loss cone is lost in a transit time. Experimental observations have seemingly contradicted this picture because the plasma decay time has generally been of the order of several hundred transit times.

Under certain circumstances, the quasilinear picture may indeed be consistent with the experimental observations. If the distribution function is peaked in a pitch angle nearly perpendicular to the magnetic field, and pitch-angle scattering is negligible, then ions will be lost only when their energy is less than the ambipolar potential. In past experiments, the dominant particle-transport processes have been electron drag, which maintains the pitch angle of the ion, and turbulent diffusion of the ions due to ion cyclotron instability, which primarily affects $v_{\perp}$ and not $v_{\parallel}$. Hence, when ion-ion scattering is small, the electron drag and turbulent diffusion will cause little pitch-angle scattering of a peaked distribution.

Under these conditions, the distribution function (when integrated over $v_{\parallel}$) has a maximum for $\frac{1}{2}mv_{\perp}^2$ of the order of the ambipolar potential $\Phi \approx 3T_e$, where T_e is the electron temperature. The hole in the distribution for energies less than Φ supplies the source of instability. Quasilinear diffusion will diffuse trapped particles into this hole. Alternatively, if either a cold-particle source from charge exchange or an external plasma stream is present, the quasilinear diffusion will cause cold particles to heat and fill in the hole. However, particles in the hole will be lost at the transit time $\tau_L \approx L_p/(e\Phi/m)^{1/2}$, where L_p is the axial scale length. Without a source, the particle lifetime of the trapped plasma, τ_p , will then be of the order,

$\tau_p = \tau_L \frac{n_H}{n_w}$, while the energy lifetime will be of the order $\tau_E = \frac{n_H}{n_q} \cdot \frac{T_H}{T_w} \tau_L$,

where n_H and T_H are the hot-particle density and temperature, and n_w is the warm-particle density that is needed to fill in the ambipolar hole to a level sufficient to stabilize the instability. When an external cold source is present, the particle lifetime can change considerably, but the energy lifetime is unaffected for the same electron temperature. However, if the external source lowers the electron temperature, improved energy lifetimes can be obtained, provided this lifetime is less than the electron drag time.

For more quantitative understanding, consider the model of the distribution in the form,

$$F = \frac{1}{(v_H^2 - v_h^2)} \left[\exp \left(-\frac{v^2}{v_H^2} \right) - \exp \left(-\frac{v^2}{v_h^2} \right) \right] + \frac{n_w}{n_H v_c^2} \exp \left(-\frac{v^2}{v_c^2} \right) \quad (3)$$

Here we associate $\frac{1}{2} m v_h^2 \sim e\phi$, and we seek the minimum energy density in the ambipolar hole that will cause the loss-cone drive to change sign; i.e., we seek the solution of

$$\text{Max}_{\omega^2/k^2} = \int_{\omega^2/k^2}^{\infty} \frac{dv_{\perp}^2}{(v_{\perp}^2 - \omega^2/k^2)^{1/2}} \frac{\partial f}{\partial v_{\perp}^2} = 0 \quad (4)$$

for the minimum of $P = \frac{n_w v_w^2}{n_H (v_H^2 - v_h^2)}$, where P is the ratio of untrapped to

trapped energy density. This minimization with respect to P gives, for this model, the longest possible energy-containment time. The solutions for P and n_w/n_H are given in Fig. 56. The bound on plasma lifetimes are then $\tau_p = \tau_L/\eta$ and $\tau_E = \tau_L/P$ where $\eta = n_w/n_H$.

For 2XII parameters, a typical case of a freely decaying plasma with no external sources, where $T_e = 50$ eV, $T_i = 2$ keV, and $L_p = 50$ cm, gives $x = (3T_e/T_i)^{1/2} = 0.27$, $\tau_L = 4$ μ s, $P = 9 \times 10^{-4}$, and $n_w/n_H = 3 \times 10^{-2}$. Hence, we obtain $\tau_p \equiv \tau_L/\eta = 130$ μ s, and $\tau_E \equiv \tau_L/P = 4.4$ ms.

Here, the particle lifetime is somewhat short compared to experimental results and the energy lifetime somewhat large. However, the apparent observed particle lifetime may be largely due to a cold charge-exchange source, while the energy lifetime may be overly optimized in this example.

In recent 2XIB runs, typical parameters with an external stream present are $T_i \approx 10$ keV, $T_e \approx 0.2$ keV. We then find that $\tau_E \approx 3$ ms, which is comparable to observed lifetimes. The particle lifetime τ_p is not readily determined experimentally because the external stream apparently is an important particle source, but a negligible energy source.

In obtaining our lifetimes, we assumed that Eq. (4) had to be maximized for all ω^2/k^2 . For 2X experiments, where $a_i/R_p \geq 1/3$, and R_p is the radial scale length of the plasma, this is necessary. However, for longer radial scale lengths, the ion-cyclotron drift-cone mode, which is the principal unstable mode, has a maximum in ω^2/k^2 , and hence a smaller fraction of warm plasma is needed for marginal stability. Therefore, as a_i/R_p decreases, longer lifetimes, and ultimately classical lifetimes, may be obtained.

A quantitative description of this is now being investigated.

Stabilization of Low M-number Interchange Modes in Simple Mirrors by Axially Injected Electrons

We have shown¹³⁶ that a sufficient flux of low-energy electrons injected axially in a simple mirror machine will stabilize low m-value interchange modes. Such electrons, when accelerated by the ambipolar potential, will, in contrast to the familiar process of Debye shielding, contribute positive, perturbed density in regions of positive, perturbed potential. A sufficient number of such electrons reverses the sign of the electric field that has resulted from an ion displacement. To stabilize a mode of wave number k in a slab model, the fractional contribution, α , of the injected electrons to the total electron density must exceed

Fig. 56. Solutions for P and n_w/n_H .

$$\alpha > \frac{|e|\phi}{T_i} k^2 a_i^2 (1 + \epsilon_i)^{-1},$$

where ϕ is the ambipolar potential, T_i is the ion temperature, and $\epsilon_i = \omega_{pi}^2 / \omega_{ci}^2$. To apply this result to cylindrical geometry, $k \rightarrow m/R_p$, where R_p is the plasma radius and m the azimuthal mode number. For reactor-size plasma, this corresponds to a current of 1 A/cm^2 provided the current can be injected where the magnetic field is 1% of the central field.

Stabilizing Mechanisms for Loss-Cone Modes

We have investigated¹³⁷ various mechanisms that might be responsible for the apparent absence of the theoretically predicted drift-cyclotron loss-cone mode in high-density mirror machines when $\omega_{pe}^2 \sim \omega_{ce}^2$:

- Warm plasma outside the trap at 2XII parameters is found to affect the mode only weakly.
- Fanning of the magnetic field is found to stabilize modes sharply resonant in $k_{\perp}$, such as Dory-Guest-Harris, but not to affect instabilities with broad spectra.

We also investigated the possibility of electron orbit diffusion due to the presence of a suggested high-frequency electron instability. Stabilization by this means would explain a number of experimentally observed properties; however, the nonlinear picture is incomplete as discussed.

Electron-Bounce Modes in Mirror Machines

We have investigated the collective oscillations that are possible if the electron-bounce motion is well defined. These oscillations arise near harmonics of the electron-bounce frequency when the axial well for the electrons is nearly quadratic and the axial force is nearly electrostatic. When the wave frequency, ω , matches the ion-cyclotron frequency, then an ion-cyclotron loss-cone instability is possible. This mechanism may be responsible for the onset of ion-cyclotron instability observed in the Baseball II experiment.

To predict instability thresholds, we first calculate the eigenfrequencies of electrons bouncing in an idealized electrostatic and quadratic well. These results, which have been obtained by solving an integral equation for the system, are shown in Fig. 57(a) and (b). In the figures, $\Omega = \omega / \omega_{be}$, where ω_{be} is the radian electron-bounce frequency, $k_{\perp}$ is the perpendicular wave number, and $\lambda_{De} = v_{the} / \omega_{pe}$, $1/2 m_e v_{the} = T_e$. The equilibrium distribution for

this case is $F(E) = (\phi_{\max} - E) \exp(-E/v_{\text{the}}^2)$, where E is the energy per unit mass and $\phi_{\text{M}} = 3v_{\text{the}}^2$. To next order, we include the dissipation arising from the spread of electron-bounce frequencies (a result of the axial magnetic forces on electrons) and the antidissipation that arises from ion-cyclotron damping of the ions in the loss-cone distribution. If we assume $\omega \approx \omega_{\text{ci}} \approx 2\omega_{\text{be}}$, we obtain a necessary condition for the onset of instability.

We have compared the results of our theory with the observed Baseball II threshold conditions. In Table 3, we indicate the relative densities in which instability was observed for a group of experiments in which the primary change in parameters was the axial length of the machine. Here L is the mirror scale length, and L_p is the plasma scale length. The observed threshold densities are compared with our predictions for narrow and spread energy distributions. The predicted thresholds are comparable and somewhat less than the observed thresholds. However, the relative variation of density threshold is more pronounced in experimental than in theoretical results. The theory, which only gives a necessary condition for instability, is consistent with observation, since the prediction is characteristically less than the actual density threshold. At present, we do not know why the

Fig. 57. Eigenfrequencies for (a) even eigenfunctions and (b) odd eigenfunctions.

theory does not give as rapid a dependence with axial length variation. Perhaps a quantitative investigation of the nonquadratic nature of the well can improve the predictions.

Table 3. Comparison between theoretical prediction and Baseball II threshold conditions.

Set No.	$(L/L_p)^2$	T_e/W_i	Experimental observation	Threshold $\omega_{pi}^2/\omega_{ci}^2$	
				Theoretical prediction	
				Peaked distribution	Broad distribution
$W_i = 1.34 \text{ keV}$					
153	11.6	0.016	0.025	0.021	0.029
154	7.4	0.019	0.046	0.027	0.047
155	5.3	0.022	0.071	0.031	0.058
156	4.0	0.022	0.12	0.035	0.068
$W_i = 0.83 \text{ keV}$					
159	4.0	0.031	0.11	0.057	0.090
160	5.3	0.030	0.074	0.053	0.080
161	11.6	0.023	0.031	0.028	0.042
162	4.0	0.023	0.094	0.056	0.084

Quasilinear Model for Mirror Transport

We have developed a model for the evolution of a distribution function, F , that takes into account both classical processes such as electron drag and charge-exchange and turbulent processes as described by quasilinear theory. The basic equations are as follows:

$$\frac{\partial F}{\partial t} = \frac{\partial}{\partial x} D(x) \frac{\partial F}{\partial x} + v_D \frac{\partial}{\partial x} (xF) - v_L(x)F + Q(x),$$

where $x = v_{\perp}^2$. The first term on the right-hand side is the quasilinear diffusion, which will be discussed further below; the second term is the electron drag; the third term is a particle loss rate due to such processes as charge exchange, transit-time losses of particles in uncontained regions of phase space, and estimates of ion scattering losses; and the final term, $Q(x)$, is an

external source term that can arise from neutral-beam injection or an external plasma stream. The distribution F in Eq. (5) is integrated over $v_{||}$ and hence is a function only of $v_{\perp}^2$. The model can be justified when pitch-angle scattering is small and the distribution function is strongly peaked at angles nearly perpendicular to the magnetic field. This is generally the case in mirror experiments. The model has the virtue that one can describe turbulence and classical transport on the same time scale.

The first investigation of Eq. (5) is to use the $D(x)$ one would calculate from straight-line orbit theory. The mode selected was the double-hump mode that oscillates at the lower-hybrid frequency. In this case, only the beam-injected plasma was described by Eq. (5), while the target plasma was assumed to decay in an arbitrary manner. The result of the investigation was that distribution evolves to a marginally stable one

- If phase space is available, and
- If the wave energy oscillates about the marginally stable state at a period proportional to the square root of the input current.

If the phase space is sufficiently restricted, so that the distribution cannot relax to a marginally stable one, plasma buildup from the beam cannot occur.

The disadvantage of the first investigation is that the quasilinear coefficients and growth rates, which were computed with a great deal of precision, are expensive to calculate continuously. Instead, we decided to model heuristically a loss-cone mode and thereby save a large factor in computational cost, time, and storage. The distribution was upgraded to represent the entire plasma, which includes untrapped regions of phase space that are lost in a transit time as well as the target-, beam-, and stream-produced plasma.

Present results indicate that marginal stability arises so that the phase-space hole is continually fed by the turbulent diffusion and that the electron temperature adjusts so that heat loss due to electron cooling and plasma flow are comparable. This model is now being improved.

Beta Limit of Stability Due to Ballooning

Two methods of stabilizing a simple, axially symmetric mirror, line tying and axial feedback, both rely on good electrical communication along the magnetic-field line in the region of the trap. We have considered the stability limitations imposed by ballooning, a condition that impedes electrical communication.

Since it takes energy to bend field lines, there is competition between this energy sink and the energy reservoir due to the bad curvature localized

in the interior of the magnetic trap. Putting it another way, "Can the wave grow before it propagates to the end of the trap?" This competition produces the rough stability criterion

$$\frac{v_{\alpha}^2}{L^2} \geq \gamma_{\text{hyd}}^2, \quad (6)$$

where v_{α} is Alfvén velocity $(\sqrt{B^2/4\pi\rho})$, L is trap length, and γ_{hyd} is the hydromagnetic growth rate $(v/\sqrt{R_c R_p})$, where R_c is the radius of curvature and R_p is the density-gradient distance). When these definitions are incorporated into Eq. (6), maximum β becomes

$$\beta < \frac{L^2}{R_c R_p} \sim 0(1). \quad (7)$$

To determine the precise value of the 0(1) term, we resort to the energy principle. This procedure and detailed results using a normal-mode distribution (Holdren distribution) and a distribution that describes injection at the loss-cone angle are presented in the following paragraphs. The two distributions should bracket the response. In fact, stability criteria are somewhat insensitive to the choice of distribution.

In this model, we assume the trap to be long and thin (i.e., $R_p \ll L$); in which case,

$$p_{\perp} + \frac{1}{2} B^2 = \frac{1}{2} B_{\text{vac}}^2(z), \quad (8)$$

where B is the magnetic field normalized to its maximum value, and $p_{\perp}$ is perpendicular pressure. Note that in this limit, vacuum-field strength is only a function of z , the distance along the magnetic-field line. For simplicity, we assume for the pressure profile at $z = 0$ that

$$p_{\perp}(\psi, 0) = \frac{\beta}{2} (1 - \psi) B_{\text{vac}}^2(0), \quad (9)$$

where $2\pi\psi = \int B \cdot d\mathbf{A}$ normalized so that $0 \leq \psi \leq 1$. Now, with the above normalization, we have

Fig. 58. Holdren distribution (index = n).

$$p_{\perp}(\psi, z) = \frac{\beta}{2} (1 - \psi) B_{vac}^2(0) \frac{Q(B, R)}{Q(1/R, R)}, \quad (10)$$

where $R = 1/B(0)$ and, for Case I, the Holdren normal-mode distribution,

$$Q(B, R) = (2R - 3) \left(\tanh^{-1} x - x + \frac{x^3}{3} \right) + \frac{B + 4}{10B} x^3, \quad x = \sqrt{1 - B} \quad (11)$$

and Case II,

$$Q = 1 - B^2,$$

for injection at the loss-cone boundary.

Equilibrium demands (mirror mode stability) that

$$B^2 + B \left. \frac{dp_{\perp}}{dB} \right|_{\psi} > 0.$$

This condition is trivially satisfied for Case II, provided $R_{vac} > 1$. For Case I, we obtain the relationship between β and R_{vac} shown by the mirror-mode curve in Fig. 58.⁴⁹

To determine stability to ballooning, we use the energy principle, where, in the limit $R_p \ll L$, the energy integral is represented

$$W = \frac{1}{2} \int_{-L}^L (f\xi^2 + g\xi^2) \frac{dz}{L} > 0 \text{ (stability)}, \quad (12)$$

where

$$f = \frac{\psi(B^2 - p_{||} + p_{\perp})}{r^2 B^3} \quad (13)$$

and

$$g = \frac{\psi k}{r B^2} \left. \frac{\partial(p_{\perp} + p_{||})}{\partial \psi} \right|_z, \quad (14)$$

where k is the inverse of the radius of curvature, r is the radial coordinate, $p_{||}$ is the parallel pressure, and ξ is the radial displacement of a flux line.

Stability is determined by numerical solution of the Euler-Lagrange equation

$$\frac{\partial}{\partial z} f \frac{\partial \xi}{\partial z} - g\xi = 0,$$

subject to appropriate boundary conditions. We assume the vacuum field to be of the form:

$$B_{\text{vac}} = \frac{1}{2} \left(1 + \frac{1}{R_{\text{vac}}} - 1 - \frac{1}{R_{\text{vac}}} \cos \left(\frac{z}{L} \right)^n \right) \quad n = 1, 2. \quad (15)$$

Results are given in Fig. 58 for both Cases I and II. The fact that $n = 2$ leads to an improved β -limit is easily understood in terms of the behavior of the bad radius of curvature, which is infinite at $z = 0$ and finite away from the midplane but larger than the minimum value for $n = 1$. Thus, the drive for instability is diminished.

In conclusion, for a vacuum-mirror ratio of less than four and for a vacuum-field shape of $n = 2$, the ballooning mode does not lead to β -limits severely less than that obtained for optimum injection ($\beta \approx 0.85$).

Ballooning Interchanges in a General, Large-Aspect-Ratio Magnetic Trap

The attempt has been made to extend the large-aspect-ratio theory for an axisymmetric system (see the preceding article) to the general nonaxisymmetric case. We have carried the work far enough to get a general, sufficient condition for stability against ballooning interchanges, a condition which reduces in the axisymmetric case to the already known necessary and sufficient condition. The condition in question (as in the axisymmetric case) is stated in terms of the behavior of one-dimensional, Euler-Lagrange solutions on the individual flux lines. Unfortunately, it is not yet in a suitable form for numerical calculation. The main difficulty at this point is not so much in the stability analysis as in the determination of the unperturbed equilibrium. We do have, at least, a complete system of lowest-order equilibrium relations (in the large-aspect-ratio limit) that would serve in principle to determine the equilibrium uniquely.

Charged-Particle Motion, Adiabaticity, Etc.

On the Motion of Charged Particles in Periodically Varying Magnetic Fields

We have considered a motion in vacuum magnetic fields of charged particles with charge q , mass m , that is derivable from a vector potential $\underline{A}(\underline{x}) = A(x, z)\hat{y}$; where $\hat{y}$ is a unit vector in the y direction, and A is independent of y and is periodic, or nearly periodic, in z . An approximate theory has been developed that is appropriate to the situation where the velocities in the x, y directions are small compared to that in the z direction. We have shown that to the lowest significant order (with z playing the role of the usual time variable) the motion in the x, y plane is equivalent to that of a particle moving in a one-dimensional potential $\psi(x)$ given by

$$\psi(x) = \left(\frac{q}{mc} \right)^2 \frac{1}{4E} \langle A^2 \rangle ,$$

where E is the total energy of the particle, and $\langle \rangle$ denotes an average over the z variation of A .

This theory has been applied to a particular field configuration that is considered to be a possible way of transporting low-energy ion beams.¹³⁸

Excellent agreement was found between the theory and the results obtained by solving the exact equations numerically.

A first-order correction to the theory has also been obtained.

Diffusion in Velocity Space Associated with Nonadiabatic Changes in the Magnetic Moment of a Charged Particle

Numerical and theoretical studies have indicated that in the vicinity of a point on a line of force where the magnitude of the magnetic field is an extremum, the magnetic moment μ of a charged particle experiences a nonadiabatic change. Because the effect is localized, we can, in a simple fashion, incorporate a term representing this nonadiabatic feature in a kinetic equation.

We then find that nonadiabatic charges give rise to an effective collision term in the bounce-averaged, guiding-center, kinetic equations in the form of a diffusion in μ space. Estimates of the diffusion constant suggest that, as the energy of the particles increases, this diffusion is more important than classical diffusion. Thus, the behavior of magnetic confinement systems employing injection of energetic neutral beams may be strongly influenced by this effect, which of course serves to enhance loss rates.

Superadiabaticity and Area-Preserving Mapping

The concept of superadiabaticity¹³⁹ may be important in determining plasma life times for situations where jumps in the magnetic moment μ contribute the major loss mechanism. We know from earlier work¹⁴⁰ on related phenomena that superadiabaticity and area-preserving mapping are intimately connected. We have shown that, to the same order to which jumps in μ are calculated, the mapping of (μ, ψ) space, where ψ is the phase angle associated with cyclotron motion, is area preserving. Using this fact allows one to write down the following set of equations that govern the change in μ and ψ as the particle passes through the region where the nonadiabatic jump occurs:

$$\begin{aligned}\mu_{n+1} - \mu_n &= A(\mu_{n+1}) \cos \psi_n \\ \psi_{n+1} - \psi_n &= B(\mu_{n+1}) - \frac{\partial A}{\partial \mu_{n+1}} \sin \psi_n,\end{aligned}$$

where the suffix n denotes the numbers of times the particle passed through the central region. The variation of A and B with μ depends on the particular magnetic-field configuration under study, but the general form of the equation depends on the area-preserving nature of the change.

We have considered the application of equations of the above form to mirror machines and have shown that island structures like those found by Lieberman and Lichtenberg¹⁴⁰ exist with the following implications:

- That a "superadiabatic loss cone" exists, i.e., that there is a pitch angle above which, in the absence of collisions, all phase-space trajectories remain inside the machine, but below which there exist trajectories that take a particle into the ordinary loss cone.
- That there is, furthermore, a lower pitch angle below which all phase-space trajectories eventually lead out of the machine.

Nonadiabatic Particle Behavior in Magnetic Wells

It is well established, from both analytical and computational work, that a particle moving in a magnetic well experiences jumps in its magnetic moment μ near the point of minimum magnetic field B on its guiding-center trajectory. These jumps are of the form $\Delta\mu \propto \exp(-1/\epsilon)$, where ϵ is of order of the ratio of gyroradius to a field scale length. With mirror experiments moving toward confinement of higher-energy particles (with larger gyroradius) in finite- β fields (for which mid-machine B and scale length are smaller than in the same machine operated at $\beta = 0$), the theory of nonadiabatic jumps is of renewed interest.

An analytic method for calculating jumps in two-dimensional vacuum fields was developed by Hastie, Hobbs, and Taylor¹⁴¹ and improved upon by Howard¹⁴² and Krushkal.¹⁴³ We have extended this approach to apply to nonvacuum and three-dimensional (e.g., minimum- B) fields and have considered its validity.

The method starts from the exact differential equation for the time variation of μ ,

$$\frac{d\mu}{dt} = f_1(\mu, \underline{r}) \cos \psi + f_2(\mu, \underline{r}) \cos 2\psi + f_3(\mu, \underline{r}) \sin 2\psi, \quad (16)$$

where ψ is the angle between $\underline{v}_\perp$ and $\nabla_\perp B$, the projections of the velocity and field gradient onto the plane perpendicular to $\underline{B}$. If we substitute in the right-hand side of Eq. (16) the lowest-order terms in gyroradius expansions ($\underline{r}$), $d\psi/dt$, and μ about the guiding-center trajectory, and drop the $\cos 2\psi$, $\sin 2\psi$ terms [since they can be shown to lead only to contributions to $\Delta\mu$ of order $\exp(-2/\epsilon)$], then the change μ is reduced to quadrature. The integral is performed by deforming the contour into the complex plane; the dominant contribution then comes from the region near the zeros of B .

The differential equation for μ is of the form of Eq. (16) even for three-dimensional, nonvacuum fields, provided that $\underline{J} \times \underline{B}$, where $\underline{J}$ is current density, is parallel (or anti-parallel) to $\nabla_{\perp} B$. [This is true, for example, in a P(B) equilibrium.] More generally, one must add a term of the form $f_4 \cos \bar{\psi}$, where $\bar{\psi}$ is the angle between $\underline{v}_{\perp}$ and $\underline{J} \times \underline{B}$.

We have shown that $\Delta\mu$ is completely determined by the behavior of the magnetic field strength as a function of arc length s in the neighborhood of its complex zeros. In particular, we have shown that, near the zeros of B , the curvature (which is included in f_4) can be simply related to the form of $B(s)$ in those regions.

By considering the higher-order terms in the expansion of r and $d\psi/dt$, we have shown that the expression for $\Delta\mu$ obtained by the above procedure is the first term in a double expansion in powers of ϵ and pitch angle, not merely in powers of ϵ as is often supposed. Fortunately, the expansion in pitch angle converges rapidly, so that the first term is a good approximation.

We have also considered extension of the method to calculation of jumps in the second adiabatic invariant (J).

Application of Nonadiabatic Jump Theory to Mirror Machines

We are applying the theory described in the preceding article to model magnetic fields that represent mirror machines. In particular, we have considered three models, two representing axisymmetric nonvacuum fields, and the third representing a three-dimensional vacuum field. Specifically, we have considered

- An axisymmetric magnetic field of the form $B_z \propto 1 + z^2 + \alpha r^2$, where r, z refer to cylindrical coordinates and α is a free parameter;
- A long, thin, finite- β equilibrium plasma in an axisymmetric mirror field¹⁴⁴; and
- A hyperbolic cusp with superimposed uniform field, $B_x = x$, $B_y = -y$, $B_z = \text{const.}$ This field is considered as a model for MIRICLE¹²³ and as a prototype for a minimum-B configuration because the field lines fan in a fashion qualitatively similar to that in Baseball or Yin-Yang mirror fields.

In considering the field strength as a function of position along a field line and analytically continuing into the complex plane, we find that the fields considered all have singularity structures that are more complicated than the simple cusp and multipole fields considered by previous authors.^{141,143,145} In particular, in the neighborhood of the axis in the

first two models, a zero and a branch point of B occur sufficiently close together that they cannot be evaluated separately in performing the integral described in the preceding article. If, however, we consider either a field line far enough away from the axis that the singularities may be considered well-separated, or one close enough to the axis that the singularities may be considered merged [the criterion being whether the integral $(e' mc) \int B ds/v$ between singularities is large or small], then we may explicitly evaluate $\Delta\mu$. Comparing with values obtained from orbit calculations,³² we find agreement to within about 30% if we examine $\Delta\mu$ values for a specific gyroradius. If we ask for the gyroradius (or energy) corresponding to a specific value of $\Delta\mu$, agreement is within a few percent.

Considering the long, thin, equilibrium model, we find that, near the axis, where the singularities of B may be considered merged, the exponential factor in $\Delta\mu$ varies as $(1 - \beta)/v$ for small pitch angles.

In considering the cusp plus uniform- B_z field model, we find that the radius of curvature, which appears in the integrand of Eq. (16) of the preceding article, has branch points separate from the zeros of B . In the lowest-order theory, these branches would contribute to $\Delta\mu$. We also find, however, that expansion of $d\psi/dt$ to higher order brings in a nonoscillating term that is not present in the more symmetric fields. Inclusion of this correction removes the branch contribution and also somewhat raises the contribution from the zeros of B . The calculation illustrates that it will be necessary to consider such corrections to $d\psi/dt$ in evaluating $\Delta\mu$ for minimum- B fields.

In addition to calculating specific models, we have explored the usefulness of a quadratic fit to magnetic-field strength as a function of arc length along a field line. We find that such a fit matches orbit results for a linear multipole field much better than the analytic expression of Hastie, Hobbs, and Taylor,¹⁴¹ which is based on a quadratic fit to the magnetic field seen by a particle as a function of time. We have applied such a fit to the axisymmetric mirror model described above, and find that, in comparison with the expression obtained using the exact equations, the gyroradius which gives rise to a specific $\Delta\mu$ can be obtained to within about 20%. We are now considering this approximation in connection with minimum- B fields.

Adiabaticity Limits to rf-Augmented Magnetic Mirror Confinement

In examining the effect of adiabaticity and superadiabaticity limitations on the use of rf-augmented magnetic mirror confinement,¹⁴⁶ we have shown that the scaling of the region over which the rf fields are applied to maintain a

given level of adiabaticity is such that, although the fields decrease as resonance is approached, the total rf energy stored in the resonance region remains constant. Assuming that the dissipation is proportional to the energy stored, we conclude that the external energy supplied is not reduced from the energy requirements on nonresonant rf containment. In fact, the weak additional scaling required to maintain containment by superadiabaticity implies that resonant rf containment requires more applied power. The stochastic heating, which results from the small phase-uncorrelated energy changes that occur on each pass through resonance when superadiabaticity is not satisfied, is such that only a small improvement in the field strength required for containment can be made by operating in this mode.

General Theory

Flute Instability of a Pellet Expanding in a Magnetic Field

If laser pellet expansion is to be a useful method for starting up mirror plasmas that are to be sustained by neutral beam injection, the plasma must expand across field lines to a dimension comparable with that of the neutral beam. Using a snowplow model for the expanding pellet,¹⁴⁷ it can be shown that for Baseball II-T parameters, an unperturbed pellet should expand only to a radius of 0.1 cm; but it can also be shown that the expanding but decelerating shell is unstable to a Raleigh-Taylor instability that should lead to fluting across field lines.

To follow the instability into the nonlinear regime, we have written the equations for planar and cylindrical snowplows in Lagrangian variables and have demonstrated that, in the range of wave numbers for which the instability can grow appreciably before the snowplow turns around, the Lagrangian equations reduce to a set of linear equations previously derived by Ott¹⁴⁸ to describe the nonlinear evolution of a gravitating sheet mass. These equations may be solved exactly, and the solutions unfolded into Eulerian variables to allow a determination of the shape of the field-pellet interface as a function of time. An initially sinusoidal perturbation steepens until cusps are formed; after this time, the Lagrangian transformation and the snowplow model break down.

Since cusps form when the perturbation amplitude is still small compared to the maximum extent of the unperturbed, expanded pellet, it is important to determine the evolution after cusp formation. To this end, we plan to pursue numerical solutions to the hydromagnetic equations.

Space Charge in Charge-Changing Cells

As part of our support for the neutral beam program, we are studying problems associated with the transport of charged beams. One such problem can arise in the passage of low-energy ion/atom beams through charge-changing cells (i.e., cells filled with a low-pressure gas or vapor that enables the conversion of beam components to another charge state). In a typical cell, the background plasma formed from ionizing and/or from charge-transfer collisions can affect the properties of the neutral beam, particularly its divergence angle. We are developing a code to predict the space charge in such cells.

In the typical cells, the ion mean free path is larger than the transverse dimensions, and an ion created in the gas will fall freely to the wall under the action of the electric field. Plasma electrons with energies less than the plasma sheath are effectively trapped and thermalize. Such a situation is described by the Tonks-Langmuir equation,¹⁴⁹ first derived for a low-pressure discharge. We have written a code to integrate this equation in one dimension for Cartesian coordinates for given values of beam current, voltage, dimension, and cell size (the cell wall is assumed to be at ground potential). To date, we have successfully run the code for problems where the fractional space-charge imbalance is greater than about 10^{-5} , and we are extending it to the lower values expected in many cells. This code has also been used to predict the performance of an electrostatic scheme for isotope separation with lasers.

Runaway Electrons in an Impure Plasma

We have extended the Kruskal-Bernstein theory¹⁵⁰ of runaway electrons in an infinite, homogeneous plasma subjected to a uniform electric field so that it applies to multiply ionized, multiple-species plasmas.¹⁵¹ The runaway rate was found to be proportional to

$$E^{-3(1+Z)/16} \exp \left\{ -(4E)^{-1} - [(1+Z)/E]^{1/2} \right\}$$

Here, E is the electric field strength measured in units of $-4\pi e^3 n (\ln \Lambda) / m v_0^2$, where e , n , m , and $\sqrt{3} v_0$ are the electron charge, number density, mass, and rms thermal velocity, respectively; Z is the effective ionic charge; and $\ln \Lambda$ is the Coulomb logarithm. The proportionality constant may depend on Z but not on E . The runaway theory of Lebedev¹⁵² was also extended to $Z \neq 1$. Connor and Hastie¹⁵³ have independently performed a similar calculation.

Generation of Negative Ions from Alkali-Coated Metal Surfaces

An analysis of the surface-plasma negative-hydrogen ion source developed by Belchenko *et al.*¹⁵⁴ has led to a hypothesis¹⁵⁵ for negative-ion formation by atom collisions with the cesiated cathode. In this model, a near-monolayer of cesium is formed on the tungsten cathode. The collision of an energetic (few-eV) neutral atom with the surface forms an intermediate CsH^- molecular configuration, from which an H^- ion rebounds. In its qualitative formulation, the model indicates that negative ions will form in any tungsten-alkali-hydrogen system.

A quantitative analysis of this system requires an accurate knowledge of the system energetics. In collaboration with M. Gardner and A. Karo of the LLL Chemistry Division, we are performing a Hartree-Fock calculation of the energetics of alkali-hydride diatomic systems. These calculations will be extended to compute the energetics of hydrogen-alkali surface interactions.

The Ionization States of Carbon in the Baseball II-T Laser-Heating Experiment

The irradiation of polystyrene pellets in the Baseball II-T CO_2 laser-heating experiment has generated states of ionization in carbon up to C^{5+} and C^{6+} . To achieve these ionization states requires ionization of the helium-like C^{4+} configuration. Because of the large energy gap between the helium-like C^{4+} states and the C^{5+} state, the spectrum of ionization states in this region is a sensitive measure of both the electron temperature and the density history of the pellet.

Using the electron temperature and density histories from the LASNEX code,¹³¹ we have calculated the ionization states for different electron temperatures and pellet expansion velocities. By comparing these calculated results with the observed ionization fractions, we have concluded that the pellet is burning hotter than 100 eV.

Derivation of the Plasma Wave Equation by a Variational Principle

A complete electromagnetic description of an inhomogeneous plasma requires the use of the Vlasov-Maxwell equations. For an inhomogeneous plasma, the linearized Vlasov-Maxwell equations lead to the integro-differential equation,

$$\nabla \times \nabla \times \underline{E} = \frac{\omega^2}{c^2} \underline{\epsilon} \cdot \underline{E},$$

where $\underline{\epsilon}$ is a tensor integral operator. The variational method used to derive this equation is based upon the construction of a quadratic form that represents

the rate of energy production, which we show to be symmetric for the field amplitudes. The variation with respect to amplitudes produces the correct integral equation in intrinsically symmetrical form. The integral equation may be approximated for long wavelengths by a differential equation whose self-adjoint nature is directly exhibited. We use the formalism to study the effects of temperature gradients on finite- β stabilization criteria.

Geometric Optics in Space- and Time-Varying Plasmas

We have extended the theory of geometric optics in space- and time-varying plasmas reported last year² to include internal sources. The calculation proceeds by deriving the far field for a point monochromatic source. This is matched asymptotically to the geometric optics field, and the result is used to generate the field due to a distributed source and the velocity-space diffusion tensor for a fluctuating source.

The general initial-value problem for a source-free plasma is solved in the geometry optics approximation, and the associated kinetic equation is derived.

EXPLORATORY RESEARCH: THE GAS-EMBEDDED Z-PINCH

Introduction

During the report period, we conducted a small exploratory program designed to investigate the concept of constraining the growth of instabilities in a Z-pinch by embedding the Z-pinch in a mass of high-density, low-temperature, deuterium gas. The program consisted of computations and experimental studies of Z-pinches that were initiated either by a relativistic electron beam or by exploding tubes.

Electron-Beam-Triggered Z-Pinch Experiment

Our experimental program directed toward using a relativistic electron beam to produce a gas-embedded Z-pinch used available hardware.² The experimental apparatus is shown schematically in Fig. 59. The vacuum diode is charged by a triggered Van de Graaf machine (an Ion Physics FX-25 charged to 2.6 MV). The electrons are produced by field emission at the tip of the cathode and are accelerated across a 5-mm vacuum gap toward a 0.025-mm-thick, Ti-foil anode that is thin enough to let electrons pass through but thick enough to contain the discharge chamber's 100- to 200-kPa hydrogen-gas fill.

Fig. 59. Electron-beam-initiated Z-pinch experiment.

The parameters of the electron-beam pulse are approximately 1.5 MeV, 20 kA, and 30 ns. A small, 20-kV, 10- μ F, capacitor bank is directly connected across the discharge chamber, and the discharge is triggered by the electron beam. The anode of the discharge is a graphite button, its cathode the Ti foil; the axial length of the discharge is 40 mm. There are 18 return-current bars separated by viewing windows for diagnostics, and the low-inductance, flat-plate line connecting the capacitor bank to the discharge chamber is insulated with plastic sheets.

To achieve an energy deposition of 1 eV or so per atom, the beam was focused to a 1-mm diameter, giving a current density $j \approx 10^6$ A/cm². Prior to firing the electron beam, the capacitor bank was charged to a voltage that was 0.5 to 0.9 of the measured breakdown value. Then, the pinch was initiated by firing the electron beam. Figure 60 shows the beam current and magnetic field B_θ in the pinch region, and Fig. 61 shows typical pinch current and B_θ waveforms.

Image-converter cameras were used to photograph (with a 10-ns shutter speed) the pinch discharges side-on through the Lucite pinch insulator. Since the primary radiation in the visible region of the hydrogen spectrum comes from the Balmer series, the photographs primarily record light coming from plasma regions having a temperature $T \approx 0.5$ to 1 eV. Spectroscopic studies are incomplete at this time.

Fig. 60. Electron beam current and Z-pinch field.

Fig. 61. Z-pinch current and field.

Roughly speaking, the photographs showed three modes of pinch formation, depending on the gas pressure:

- A helical-like shock structure at high pressure ($p \geq 760$ Torr H_2),
- Mass accretion at $p \sim 500$ -Torr H_2 , and
- A straight conducting channel at $p \sim 50$ - to 100-Torr H_2 .

At high pressure ($p \geq 760$ Torr H_2), the helical-like shock structure observed by Smärs is seen (Fig. 62). Here, following Smärs, we interpret the luminous regions as shock waves launched by a tightly pinched column that is undergoing kinking. At high pressures, beam propagation is erratic (as seen in Fig. 62), and formation of the pinch appears to be strongly influenced by streamer-breakdown phenomena.

At pressures of ~ 500 -Torr H_2 , mass-accretion appears to occur. The plasma column remains relatively cold ($T \approx 1$ eV) and grows in radius as the current increases. A typical example is shown in Fig. 63. Here, as time increases, the luminous region gets larger and brighter. In some shots, a contraction observed late in time (300 to 500 ns) indicates some repinching.

At pressures of 50- to 100-Torr H_2 , the electron beam propagates without appreciable instability to form a straight conducting channel ~ 1.5 mm in diameter, approximately as indicated

Fig. 62. Kinking Z-pinch at 1520-Torr H_2 .

Fig. 63. Mass-accretion mode at 500-Torr H_2 .

at 0.18 μs in Fig. 64(a). By 0.40 μs , the light from the center regions of the pinch has decreased to nearly zero, indicating that the temperature has increased above several eV. At 0.55 μs , wisps of light reappear that are suggestive of shock waves driven by a kinking pinch column. In Fig. 64(b), taken under the same conditions as Fig. 64(a), part of the column appears to have deformed into a helix. Figure 64(b) also shows that half of the column apparently remained in a mass-accretion mode. The observation that part of the column pinches and part remains at several eV indicates that the sensitivity of pinch formation to initial conditions is similar to that found in numerical calculations.¹⁵⁶

At 100-Torr H_2 , where the initial channel is straight and of well defined size, the pinch temperature can be estimated from the Bennett relation,

$$I^2(A) = 2 \times 10^{-9} n(\text{cm}^{-3}) a^2(\text{cm}) T_B(\text{eV}).$$

Taking na^2 to be constant (in the mass-accretion mode $T \approx \text{constant}$ and $na^2 \approx I^2$) as found by Smärs and in numerical calculations,¹⁵⁶ the Bennett

Fig. 64. Z-pinch at 1-Torr H_2 , where (a) shows a typical shot, and (b) shows helix formation at $t = 0.36 \mu\text{s}$.

temperatures T_p for the times t shown in Fig. 64(a) are:

t (μs)	T_p (eV)
0.18	3.3
0.40	15.1
0.55	22.2

Thus, it is quite reasonable in Fig. 64(a) for the light to decrease for $t > 0.18 \mu s$ as the plasma becomes fully ionized.

It appears from our test results that the way in which the conducting channel is formed can strongly influence the subsequent development of the pinch. The two possible resultant pinch modes are shown in Table 4. At high

Table 4. Gas-embedded Z-pinch modes.

Mode	Criteria
Mass-accretion or discharge-channel	$T \approx \text{constant}, na^2 \approx I^2$
Pinch	$na^2 \approx \text{constant}, T \approx I^2$

pressures ($p \geq 760$ Torr H_2), the electron beam propagates erratically, occasionally forming several channels. The growth of pinch current (μs , possibly, the propagation of the electron beam) in this pressure range is probably strongly influenced by the streamer phenomena of electric field concentration and photo-ionization. At present, no information is available on either the mass of the pinch ($\sim na^2$) or the temperature in any pressure range studied. The existence of a pinch is inferred from the similarity to Smärs' results¹⁵⁷ at high pressure and from the disappearance of light at low pressure (100 Torr).

Again following Smärs, the helix-like structure that appears in Fig. 64(b) has grown to a radius $\xi_H \approx 1.5$ mm at $t = 0.36 \mu s$. Similar results have been seen on other shots. This observation may be compared with the secular growth prediction¹⁵⁸ modified for $I = I_0 t / \tau$.¹⁵⁹ The predicted helix size is

$$\xi = \left(\frac{3\pi^2}{4} \frac{r_p^2}{r_c^2} \frac{\rho_p}{\rho_g} \frac{eT_B \tau_c}{m_p \tau^2} \right)^{1/3} t^{4/3},$$

where m_p is the pinch radius, ρ_p is the density of the pinch, r_c is the radius

of a high-conductivity, low-pressure corona, and ρ_g is the density of the surrounding gas.

For Fig. 64(b), $\tau = 0.76 \mu s$, $I_0 = 64 \text{ kA}$, and (estimating $r_p \approx 0.05 \text{ cm}$, $r_c \approx 0.1 \text{ cm}$, and $\rho_p/\rho_g \approx 5$) the predicted helix radius is $\xi = 3.9 \text{ mm}$. The theory in this case overestimates ξ_{obs} by roughly a factor of 3. As described earlier, the theory generally overestimates ξ_{obs} by factors of 3 to 10. Figure 65 shows a comparison of predicted and experimental helix radii for pinches formed at 100-Torr H_2 .

The importance of the kink mode in restricting feasible regimes for controlled fusion may be estimated using the theory of Ref. 158. If we assume that the acceptable energy loss by shock heating of the gas by the kink motion is equal to the plasma energy, the stability factor N is¹⁵⁹

$$N \approx \frac{6}{\pi} \left[\frac{\rho_g (r_c/r_p)^3}{\rho_p k^2 r_p^3} \right]^{1/2},$$

which is shown for the Smårs experiment and for one-dimensional code calculations to be $N \approx 70(\rho_g/\rho_p)^{1/2}$. Thus, modest values of ρ_g/ρ_p may be sufficient to achieve $N \geq 100$ required for fusion feasibility.

Studies of Exploding Tubes to Initiate

Z-Pinch

In addition to the experiments triggered by electron beams, exploding tubes were investigated as a possible means of containing the high-density gas and of providing rapid fuzing of the high-current supply for the pinch. Flash x-ray pictures of the exploding tubes confirmed our numerical code calculations of the dynamics.¹⁶⁰ No evidence of high-temperature Z-pinches was seen in these first experiments, but the experiments are being redesigned and rebuilt on the basis of improved dynamics calculations.

Fig. 65. Observed and predicted radius vs time of the helix formed by the kink instability. The data points were taken at $p = 100\text{-Torr } H_2$, and charging voltage $V_0 = 4.5 \text{ keV}$.

Numerical Modeling

The formation of a thermonuclear Z-pinch in dense gas had been investigated earlier¹⁵⁶ by numerical modeling in one dimension. Pinch formation was found to be possible (if an appropriate initial conducting channel was provided) using a model that treated dissociation and ionization of the gas by the Saha equation and that described the plasma by MHD equations that included thermal and electrical conductivity and radiation losses.

This year, we used this model plus the following assumptions to investigate the effects of α -particle heating:

- That α -particles lose energy to the plasma by classical collisions with time constant τ_c , and
- That α -particles are lost out the end of the pinch by VB drift with time constant τ_d .

The α -particle lifetime evaluated for each Lagrangian zone is given by $1/\tau_\alpha = 1/\tau_c + 1/\tau_d$.

Fig. 66. One-dimensional calculation of a gas-embedded Z-pinch, including α -particle heating. The energies U_n (neutron), U_B (magnetic), and U_p (plasma) are in 10^5 J/cm²-radian. T_i is the ion temperature in keV, and ρ_0/ρ_p is the ratio of the initial pinch density to the density at $r = 0$.

Results of a typical calculation

are shown in Fig. 66. For this calculation, an initial conducting channel 10 cm long with $T = 1$ eV, $r_0 = 0.047$ cm, and $\rho_0 = 0.1$ g/cm³ was assumed to be formed in cold DT with $\rho_0 = 0.1$ g/cm³. The channel was heated to $T = 390$ eV in 2.25 μ s by a resistive-pinch preheat. At $t_s = 2.25$ μ s, a capacitor ($C = 0.1$ μ F) with internal inductance $L = 50$ nH and charged to $V = 50$ MV was switched on and crowbarred at peak current $I = 30$ MA. At $t - t_s = 0.45$ μ s (corresponding to a lifetime $N = 400$ sound transits), $Q = (U_n + U_\alpha)/(U_B + U_p) = 4.2$.

New effects are introduced by α -particles. As T_i approaches 10 keV in Fig. 66, α -particle heating becomes dominant, rapidly brings T_i up to the 50-keV range, and causes expansion

(ρ_0/ρ_p increasing) of the pinch for constant current. At $t \sim t_s = 0.4 \mu s$, the system is approximately in steady state, with $dU_\alpha/dt \approx 14 \times 10^5 \text{ W/cm} \cdot \text{rad}$, $\tau_c \approx 10\tau_d$, and $U_p = 1.20 \times 10^5 \text{ J/cm} \cdot \text{rad}$. If the plasma is assumed to flow through the pinch at sound speed, the α -particle energy release and plasma energy loss are approximately equal for a length $L \approx 20 \text{ cm}$. This result suggests that a self-sustaining, flow-through Z-pinch may be possible with about the above parameters.

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SECTION 5. TALKS AND PUBLICATIONS

TALKS

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