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STATUS REPORT

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The Present Status and Future Program of the ZT-1 Experiment

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The Present Status and Future Program of the ZT-1 Experiment

Compiled by

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FOREWORD

by

F. L. Ribe

In response to a suggestion by S. O. Dean of the AEC Division of Controlled Thermonuclear Research (Appendix A) an internal review of the Los Alamos Toroidal Z-Pinch (ZT-1) program was initiated in early October 1973. It was intended to give the ZT-1 staff an opportunity to take stock of their research — its past accomplishments and future requirements. Another objective was to determine how the program might be changed in order better to achieve the theoretical goal of the experiment, which is to demonstrate a stable, thermonuclear plasma in toroidal geometry and to understand its properties in order to proceed to a larger scale confinement experiment based on ZT-1 principles.

A review committee was formed under the chairmanship of F. C. Jahoda in order to bring outside opinion and recommendations to bear. The other members of the review committee were J. P. Freidberg, J. C. Ingraham, D. E. Nagle, and K. I. Thomassen. The results of numerous discussions and two formal review sessions are summarized in the Report of the Review Panel (Page 27). The first part of this report presents a discussion of the history, status, and goals of the ZT-1 experiment compiled by the ZT-1 staff.

ABSTRACT

The background, current status, and future program of the ZT-1 experiment are presented. The ultimate objective of the experiment is to formulate the requirements for a fusion reactor using the diffuse toroidal pinch. This type of pinch has toroidal equilibrium and is theoretically fully MHD stable with high total betas, $\leq 30\%$. Measurements of plasma properties include plasma temperatures $(T_i + T_e) > 1$ keV, electron temperature measurements indicate a non-gaussian velocity distribution and electron temperatures < 100 eV, and ion temperatures ≥ 850 eV under some operating conditions. As the theoretical conditions for stability are approached, the pinch is found experimentally to be closer to having complete MHD stability. A critique of a review panel is also included.

THE PRESENT STATUS
AND
FUTURE PROGRAM OF THE ZT-1 EXPERIMENT

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I. INTRODUCTION

This report presents the background, current status and future program of the ZT-1 experiment. The ultimate objective of the experiment is to formulate the requirements for a fusion reactor using a diffuse toroidal pinch. The particular type of pinch being investigated can be characterized as having approximately equal poloidal and toroidal magnetic fields. The toroidal current exceeds the Kruskal-Shafranov limit. Stability is achieved by the close proximity of a conducting wall and the strong shear of the magnetic field; the toroidal magnetic field changes direction in the region near the outside of the pinch. The implications of the field geometry described above are impressive and lead to the advantages of the "reversed field pinch" outlined below:

1. Toroidal Equilibrium. Toroidal equilibrium is achieved in a manner similar to the Tokamak. Radial displacement of the discharge compresses the poloidal field against a surrounding conducting shell and induces an image current in the shell. The resulting transverse field crossed with the toroidal current counteracts the motion.

2. Fully MHD Stable. MHD theory predicts complete stability for all wavenumbers and modes. Stability does depend, however, on the ability to generate the correct field profiles.

3. High Total β . The reversed field pinch is predicted to be stable with a poloidal β as high as 58%. Since the poloidal and toroidal fields are approximately equal a total β of approximately 25% is then possible. This is the highest β predicted for a diffuse pinch having both toroidal and poloidal magnetic fields with the additional advantage of a vacuum region between the pinch and the wall. Pressureless plasma on the outside of the pinch, or current density at the wall is not necessary to support the high β .

4. High Plasma Density. The expected operating range can be greater than 10^{15} cm^{-3} . Limitations to the density will be determined by the experimental parameters.

5. High Plasma Temperature. This type of pinch can be driven by a rapidly rising toroidal current which heats the plasma by implosion heating. The ohmic heating limitations experienced by some of the other approaches should be obviated.

6. Reactor Scaling. Reactor scaling is possible in terms of the β , density, and temperature. Calculations indicate that stability can be maintained against diffusion of the magnetic fields with classical conductivities for reactor time scales.

The reversed field pinch is the only confinement system which has both toroidal and poloidal magnetic fields and all the above advantages.

The purpose of the present phase of the experiment is to investigate the requirements necessary to establish a high-temperature stable reversed-field pinch. The information will lead us to a second stage of the experimental program, ZT-II, to investigate scaling towards a z-pinch reactor.

Section II presents the theoretical justification for the experiment. The experimental background leading up to the present generation of experiments is given in Section III. A description of the experiment and the diagnostics used are given in Sections IV & V, respectively. Experimental results are presented in Section VI and the future program is developed in Section VII.

II. THEORY

A. MHD Stability

The MHD stability theory of diffuse linear pinches was first published by Hain and Lüst in 1958 and has more recently been expounded by Robinson.^{1,2} Robinson shows that in order to confine a plasma of appreciable β , a z pinch must not only contain an axial magnetic field, but this magnetic field must reverse in the outer region of the pinch whereas the total axial magnetic flux must not reverse. Figure 1 shows MHD stable magnetic field distributions satisfying these conditions. The stability analysis is performed using the δW energy principle.^{2,3} We obtain the growth rate of the instability, if any, by solving the normal mode equation of Hain and Lüst. Localized modes of instability can be investigated using the necessary but not sufficient stability condition for stability in Suydam's criterion:⁴

$$s(r) = \frac{8}{r} \frac{dp}{B_z^2 \left(\frac{p'}{p}\right)^2} > -1 \text{ with } P = \frac{r B_z}{B_\theta} \quad (1)$$

Fig. 1. Poloidal magnetic field B_θ , toroidal magnetic field B_z and magnetic pressure p as functions of radius r of a theoretically MHD stable linear configuration.

Asymmetric modes satisfy a more stringent stability condition:⁵

$$\frac{dp}{dr} + \frac{r}{8} \frac{B_z^2}{P} \left(\frac{p'}{p}\right)^2 - \frac{2}{r} \frac{B_\theta^4 B_z^4}{(m^2 - B_z^2/B^2) B^6} > 0. \quad (2)$$

We find that these conditions, when only weakly violated, give rise to highly localized modes of instability.⁶ We obtain the growth rate of symmetric Suydam modes analytically, without having to go through the normal mode analysis.⁷ A more detailed discussion of pinch stability theory is given in Appendix A.

B. Toroidal Equilibrium

The properties of toroidal z-pinch equilibria have been studied using a two dimensional MHD equilibrium code.¹³ For the configurations of the type being examined in the diffuse pinch the toroidal shift calculated by the code is small $\lesssim 5$ mm for the ZT-1 geometry.

Numerical procedures for calculating the MHD stability of equilibria are very useful tools for finding stable configurations not only for one-dimensional but also for two-dimensional toroidal equilibria. As in the linear calculations the general stability test is based upon the energy principle. Optimization studies of one-dimensional linear z-pinch geometries have produced stable reversed field configurations with β_0 values of up to $\approx 58\%$. The corresponding β_0 optimization calculations for the toroidal case involve much more computer time and are not yet complete but stable toroidal configurations have been found with β_0 's of 20%. To date no adverse effects on stability due to the toroidal curvature have been found for the aspect ratio of ZT-1.

C. Field Diffusion

Our one-dimensional two-fluid MHD code⁸ is used to model the observed fast penetration of the magnetic fields in the plasma following initiation of the discharge. Good agreement with magnetic field profiles measured on a linear version of the experiment is obtained by using a diffusion coefficient of the order of five times the Bohm value.⁹ The enhanced diffusion coefficient enters the calculation through an electrical resistivity which is enhanced locally whenever the electron drift velocity exceeds a certain threshold. This is done to replicate the possibility of a microinstability driven by a high current concentration in the plasma. The code is now being used to investigate the penetration of the reverse B_z magnetic field. The basic problem of the diffusion of a pulsed magnetic field in a medium whose diffusion coefficient depends abruptly on the

spatial derivative of the magnetic field has been studied in detail.¹⁰

D. Diffusion and Stability

The survival of stable profiles under the influence of classical diffusion has been examined theoretically using a simple diffusion code as well as the full one-dimensional MHD code. The first unstable modes to appear are Suydam modes localized in the outer region of the pinch. With diffusion alone, the pressure profile then gradually loses its minimum on axis and the central region of the discharge then becomes seriously unstable. This event is found to be delayed under the full MHD conditions and can apparently be avoided altogether by a proper choice of the plasma parameters.¹¹ Assuming a 10 keV plasma and classical Spitzer resistivity, diffusion alone does not seem to be an obstacle to satisfying Lawson's criterion. The question, of course, is whether the anomalous electrical resistivity necessary during the formation of the pinch will become classical once the axial current is spread over the entire radius of the discharge.

E. Implosion Heating

The implosion heating of the plasma has been studied with the one-dimensional MHD code also. The model used indicated the formation of a shock. Such a shock has been observed on streak photographs but its detailed properties are as yet unknown.¹² In any case, the temperatures predicted by the code depend critically on the current and voltage driving the discharge. It has therefore been found necessary to couple the MHD code with the actual z-pinch circuit, including an equation of state to represent the fuses. The current and voltage predicted by this type of calculation is then in good agreement with those observed on the linear version of the experiment.⁹

III. EXPERIMENTAL BACKGROUND

The CTR program at LASL started in 1952 with the z pinch in which a plasma column is confined by the B_0 magnetic field of an axial current. The pure z pinch was quickly found to be unstable. In 1956-1958 a sharp boundary theory was developed which predicted stability for z pinches containing a longitudinal field (B_z) and having a conducting wall close to the pinch.¹³ Experiments at LASL¹⁴ and

elsewhere¹⁵ attempted to confirm these predictions. The general conclusions were as follows:

1. The magnetic fields diffused faster than predicted by classical resistivities, i.e., the resistivities were 'anomalously' high. As a consequence the sharp boundary between the plasma and magnetic field could not be maintained.
2. Several μsec after initiation of the discharge high frequency fluctuations in the magnetic fields were observed.
3. Plasma temperatures were limited to $\lesssim 100$ eV. High energy loss rates (~ 100 J/ μsec) were measured in ultra-violet line radiation from partly ionized impurity ions. The onset of the line radiation, $\gtrsim 4$ μsec in the discharge cycle, was found to be dependent on the impurity concentration of the filling gas.

These difficulties were considered so fundamental that the z-pinch program at LASL was terminated in 1961 in favor of other approaches.

Since that time further information has been obtained. The toroidal experiment¹⁶ at General Atomic (1963) showed that the fluctuations in the magnetic fields could be suppressed by programming the external fields, e.g., reversal of the B_z field and z current outside the central pinch column. The (1964) observation in Zeta¹⁷ (U.K.) described a quiescent period in the discharge cycle during which approximately classical resistivities were inferred from the diffusion rate of magnetic fields. These latter results encouraged the further examination² of the stability of diffuse magnetic field profiles. Field profiles were then found which are theoretically completely MHD stable and which confine high plasma pressures ($\beta_0 \lesssim 58\%$).

These results initiated the construction of the H3TX (High Beta Toroidal Experiment) at Culham (1969-70). This large programmed pinch experiment¹⁸ is to duplicate under controlled conditions the interesting regime found in Zeta. This experiment is similar to ours at LASL in that it attempts to produce a stable reverse field pinch. The plasma is ohmically heated with the plasma temperature ($T_i + T_e$) limited to $\lesssim 50$ eV which is considerably less than that found in ZT-1. The main characteristics of this experiment and recent results are described in Appendix B.

In addition there are a number of other toroidal experiments being examined. Among these are, of course, the Tokamaks which have lower plasma β than the diffuse pinch. Extensions to the Tokamaks are those attempting to achieve higher betas using elliptical cross sections such as the belt pinch in West Germany and the doublet experiment at Gulf General Atomic. Screw pinch experiments are located in the Netherlands and Japan. These experiments have two fast rising primary currents capable of producing Z and θ pinches simultaneously. The screw pinch relies on force-free currents in the tenuous hot plasma in the outer regions to give some plasma equilibrium and stability.

In (1966) we at LASL reviewed our investigations of z pinches and addressed ourselves to the temperature limitation in the earlier experiments. It was observed that θ pinches are initially heated by a strong shock produced by the rapidly rising B_z magnetic field. Comparisons of the early fast z-pinch experiments, for example Columbus II, with hot Scylla experiments showed that the B_θ 's of the z pinches had been about a factor three less than the B_z 's of θ pinches. This opened up the possibility of heating z pinches in a similar way.

These considerations were tested in the linear z-pinch experiment¹⁹ at LASL in which the magnetic field rose two to three times faster than in current θ -pinch experiments. A new technology to us, that of magnetic energy storage and current diversion, was developed. The technology is described in Section IV. Calculations of plasma pressures from measured magnetic field profiles gave plasma temperatures ($T_i + T_e$) of ~ 750 eV at ion densities of $\sim 3 \times 10^{15}/\text{cc}$. In addition the plasma column exhibited a marked degree of stability for times of the experiment (~ 8 μsec). This linear experiment demonstrated that high temperature, high density, z pinches could be produced. At these temperatures line radiation from impurities is small and the large radiation losses observed in the earlier experiments are reduced. With these encouraging results and with the possibility of obtaining a completely stable high beta plasma the toroidal z-pinch experiment, ZT-1, was constructed (1970-71).

IV. THE ZT-1 EXPERIMENT

The ZT-1 experiment has been specially designed to produce a hot stable plasma. As was described in

Section III many of the difficulties found in early z-pinch experiments can be avoided with a high temperature plasma. To reach high temperatures, high voltage-low inductance techniques have been extended further in ZT-1 than in other z-pinch experiments.

In the ZT-1 experiment the design electric field of 1 kV/cm is routinely achieved. This electric field is a factor 5-10 larger than those in other z-pinch experiments,^{20,21} and a factor 2 higher than that of a proposed high voltage toroidal experiment.²² A considerable effort has been spent to reduce errors and inhomogeneities in the magnetic field. The experiment during the past two and one-half years has been operated with no design change other than modifications to the B_z reversal circuit and the addition of metal-to-metal crowbars to the Z- and θ - circuits.

The toroidal z-pinch device has the parameters shown in Table I.

TABLE I
PARAMETERS FOR ZT-1

Major diameter	76.5 cm
Inside diameter discharge tube	10.4 cm
Aspect ratio	6.8
Initial $\dot{i}_z$	1.4×10^{12} A/sec
Initial $\dot{B}_\theta$ at wall	60 kG/ μ sec
Peak z current	230 kA
Number of voltage feed points	4
Maximum voltage per feed point	$\lesssim 60$ kV
Maximum applied longitudinal electric field	$\lesssim 1$ kV/cm
Energy stored in main capacitor bank	$\lesssim 0.5$ MJ
Longitudinal B_z bias field	< 6 kG
Maximum rate of B_z reversal (as of Oct. 1973)	0.5 kG/ μ sec

In the experiment there are two currents driven by independent power supplies; the main longitudinal current I_z through the plasma column which produces the B_θ confining field, and the azimuthal current I_θ in an exterior winding from which the stabilizing B_z fields originate. These two currents are programmed during the discharge cycle to produce the field profiles required for MHD stability. A representation of I_θ and I_z is shown in Fig. 2. At the top of the figure the radial behaviors of the magnetic fields

Fig. 2. Time sequence of the I_z , I_θ currents and magnetic field distributions in ZT-1.

are shown during a discharge. Note that the time scale is nonlinear. The center two figures show the I_θ and I_z currents. At the bottom of the figure are shown the radial magnetic field profiles and plasma pressure distributions at three selected times in the discharge cycle.

At $\sim 100 \mu\text{sec}$, before the main z-pinch current is initiated a B_z bias field is turned on. About 10 μsec prior to the main z pinch a $\lesssim 15$ kA preionization z current is passed through the filling gas. The main z-pinch implosion then compresses the plasma and B_z bias field about the axis and heats the plasma. Shortly thereafter the I_θ in the external winding is made negative by reversing the voltage across the coil. This produces a reversed B_z field outside the pinch column. Finally at $\sim 3 \mu\text{sec}$ the I_θ and I_z currents are crowbarred.

The I_θ current is driven by two capacitor banks, one provides the initial B_z bias field with the second reversing the B_z field. Programming of the fields is accomplished by varying the magnitude of the voltage, and the timing, of the reverse bank. The I_z current is supplied by a magnetic energy storage system that uses a fuse to transfer the current

to the pinch. Details of the fuse operation can be found in Appendix C. This technique offers the advantage of obtaining very rapid transfer of current to the pinch, since it is a high voltage low inductance system. It supplies current on a time scale necessary for implosion heating to take place and thereby by-passes the ohmic heating limitation of the Culham experiment.

The experiment is designed so that a change from fast to a slow mode of operation can be made quickly. With the fuse and transfer switch the experiment is run in the fast mode, e.g., $\dot{I}_z \approx 1.4 \times 10^{12}$ A/sec. When the fuse is removed and the transfer switch is shorted out the slow mode result, e.g., $\dot{I}_z \approx 3 \times 10^{10}$ A/sec. The period ~ 40 μ sec of the slow mode is then determined by the natural oscillation of the capacitors and inductance.

The ZT-1 experiment is shown in Figs. 3 and 4. Below the torus there is a large 244 cm diameter

coaxial structure, 'the barrel' of 90 cm length. Spacing between the two coaxial conductors is ~ 1.5 mm. Four parallel plate transmission lines connect the top of the barrel to the four fuses. Calculations showed that the coupling inductance between two adjacent fuses was ~ 14 nH. The magnetic energy storage inductor is common to all fuses. Near the bottom of the barrel the radius of the inner conductor is reduced over an axial length of ~ 50 cm. A system of moveable shorts, shown in Fig. 3, allows the radius and thereby the inductance to be varied to match the electrical circuit. Cables to the main z-pinch capacitor banks and switches are connected to the bottom of the barrel. The dimensions of the ZT-1 experiment were determined as follows:

1. The discharge tube diameter and length of each sector were those of the early linear experiment.
2. The major radius was determined by the volt-seconds required by the discharge. It was estimated

Fig. 3. A representation of the ZT-1 experiment identifies the main components.

Fig. 4. The ZT-1 experiment.

that ~ 0.05 V-sec was needed for each 60 cm length of discharge tube. This calls for iron of ~ 420 cm² cross sectional area, assuming a saturation field of 15 kG and a packing fraction of 0.8. To obtain this area it was required to have four sections, with a fuse and feedplate assembly for each quadrant.

A. The Electrical Systems for the Fast Z Pinch

The toroidal experiment can be thought of as four linear systems, 60 cm in length, each driven by a fuse and transfer switch, connected in series and formed into a torus. The discharge current becomes the secondary of a one-to-one current transformer. The primary current I_p from the magnetic energy storage supply passes through a "spark gap transfer switch," through a section of parallel plate transmission line, the feedplate, and to the torus primary. An ideal equivalent transformer circuit is shown in Fig. 5. Part of the primary current, I_p , passes through the inductance L_m and the remainder through L_s . The voltage across the inductor L_m induced by changes in I_m drives the secondary current I_s through the inductor L_s . In 2T-1 the magnetizing current I_m flows on the outside of the primary. This current produces a flux change in the center of the torus which induces an axial electric field in the discharge tube and drives the secondary plasma current I_s . The plasma image current, equal and opposite to I_s , flows on the inside surface of the primary. Without the iron the inductors L_m and L_s are approximately equal. Therefore I_s and I_m are of the same magnitude and the secondary current I_s would be only one half of I_p . Iron cores increase the inductance of L_m by the permeability of the iron. The secondary current I_s then becomes almost equal to the primary current I_p .

It is essential that the four fuses fire simultaneously. The voltage pulse observed across a

Fig. 5. An idealized equivalent transformer circuit for the z current in the 2T-1 experiment.

single fuse during testing had a half width of ~ 0.5 μ sec, an average jitter of ~ 0.2 μ sec, with an occasional jitter of 0.5 μ sec. In the four-fuse system this jitter would result in a considerable reduction in the total voltage around the torus. The problem was resolved by inter-connecting the fuses with low inductance so that the voltage across any one fuse can not differ much from the others.

At the junctions of the feedplates and primary the currents flowing from the feedplate to the inside surface of the primary must match the azimuthal distribution of the plasma image current density. It has been established that for our z-pinch discharges, compression ratio ~ 2 , B_z on axis ≤ 15 kG, $I_z \approx 200$ kA, $\theta_0 \approx 0.3$ and aspect ratio ≈ 6.8 , the axial current density is distributed uniformly around the minor circumference. To obtain this current distribution the feedplates were modified by cutting out parts of the plates and using shoring bars. Measurements on a test system showed that we have achieved current distributions uniform to within $\leq 2\%$. To further reduce perturbing fields at these junctions, a copper flux conserver surrounds the ceramic discharge and extends 3.5 cm in each direction from the feedplates.

The transfer switches are located in the feedplates. These switches are pressurized and adjusted to fire at a preset voltage. In each feedplate there is also provision for crowbaring by metal-to-metal explosive switches. The winding which produces the B_z longitudinal field is wrapped around the primary. An insulated slot in the primary and feedplate allows fast penetration of this field. At a charging voltage of 17 kV, a 500 G/ μ sec rate of change of magnetic field can be made.

B. Discharge Tube and Pump System

The discharge tube is made of 99.8% fused alumina. The inductance between the inside surface of the discharge tube and the primary must be kept to a minimum; thus an accurate fit was required. As quartz and ceramic tori with tolerances, ≤ 0.010 ", were unavailable the discharge tube was made up of 90 straight pieces of ceramic tubing, as shown in Fig. 6. The ends are ground in a wedge shape and made re-entrant to shield Viton o-rings from the discharge. The torus is evacuated through two 1 cm inside diameter alumina tubes in each quadrant.

Fig. 6. A photograph showing the partially assembled ceramic discharge tube, aluminum primary, and feedplates.

These pump ports are made small to minimize magnetic field perturbations.

A toroidal discharge tube for the ZT-1 experiment using our aluminum washer design has been fabricated. The design is described in Appendix C-8.

The pump system consists of a turbo-molecular pump with a liquid nitrogen trap and a Vac Ion pump. A base pressure of $\sim 3 \times 10^{-10}$ torr in the discharge tube is regularly achieved.

V. DIAGNOSTICS

The diagnostics presently used on the ZT-1 experiment are listed in Table II.

Details concerning the diagnostics are given below.

A. Plasma Density and Temperature Measurements

1. Laser Beam and Polychromator for Thomson Scattering Measurements. Thomson scattering experiments have been carried out on the ZT-1 device to determine the plasma electron temperature and density. The system employs a Korad K-2 ruby laser

TABLE II
DIAGNOSTICS ON ZT-1

Measurement	Diagnostics
A. Plasma characteristics:	
1. Electron density	a. Ashby-Jepcott interferometer. b. Thomson scattering.
2. Electron temperature	a. Differential x-ray absorption. b. X-ray fluorescence spectra. c. Thomson scattering.
3. Ion temperature	a. Doppler broadening of spectral lines. b. X-ray lines.
4. Scattering ion and electron temperatures, pressure balance and magnetic field profiles.	a. Magnetic probes.
B. Plasma stability, energy and particle containment times:	
1. Plasma stability	a. Streak photography. b. $n_e(t, r)$ and $T_e(t, r)$ distributions and stability analysis. c. Sine and cosine coils, giving current centroid and instability wavelengths.
2. Energy balance, I_p , I_{p0} , V_{p0} , I and V_p	a. Rogowski coils, resistive voltage probes and flux loops.

oscillator - amplifier capable of 5 joule pulses with peak power of 250 MW. Quartz lenses focus the beam to ~ 2 mm diameter through the plasma column and into an optical dump. The scattered spectrum is observed at $\sim 90^\circ$ through a quartz window in the discharge tube and a ~ 6 mm aperture in the metal primary. A polychromator with ten $30 \text{ \AA}$ wide channels is used as the detector. This system allows electron temperature measurements to be made over a range of 10 eV to 1 keV. Prism inserts in the aperture in the primary will allow measurements at several radial points in the plasma.

2. Modulated He-Ne Laser Beam and Detector for Plasma Line Density Determination. A He-Ne laser interferometer operated in the 3.39 micron wavelength infrared region is used to measure the plasma electron density. The interferometer is of the Ashby-Jephcott type as modified by Baker et al.²³

3. Monochromator Time Resolved Spectra of Impurity Ionization States for T_e Measurement. Estimates of the plasma electron temperature are obtained from comparison of the solutions to the transient stripping equations with measurements of the lifetimes of successive ionization states of impurities in the pinch. This method assumes that the electron density is known, the ion lifetimes are determined by electron ionization times rather than charge exchange, diffusion, etc. and that the McWhirter²⁴ ionization radiation time criterion $n t > 10^{13} \text{ cm}^{-3} \text{ sec}$ is not satisfied.

4. Polychromator Measurement of Doppler Broadened Spectral Lines. Ion temperatures in the plasma are determined from the Doppler broadening of the HeII 4686 $\text{\AA}$ line. Helium is added, $\lesssim 20\%$ to the initial deuterium gas filling. An eight channel polychromator has been added to the McPherson Model 216 monochromator. A 2 mm diameter cylindrical lens is inserted at the output aperture of the monochromator to diverge the beam to an array of eight light pipes and photomultipliers with wavelength separations of $\sim 1 \text{ \AA}$. This system allows ion temperature measurements over a range of ~ 25 eV to ~ 1 keV. The observed widths of the line are appreciably greater than the instrumental width, Zeeman broadening, and Stark broadening so that only small corrections for these effects are needed.

5. Neutron Measurements. Neutrons from the deuterium pinch discharge are observed with a

calibrated counter to obtain an estimate of the time integrated neutron yield. Plastic scintillator-photomultiplier detectors are used to observe the time behavior of the neutron flux. A paraffin moderated LiI detector is used to confirm neutron production.

6. Differential X-Ray Absorption. A double slit absorption detector for measurement of the soft x-ray emission from the pinch plasma is positioned at one of the pump ports of the torus. Aluminum foils of 6.25×10^{-4} and $1.27 \times 10^{-3} \text{ cm}$ thickness, are the differential absorbers. Assuming the x-ray spectrum is due to bremsstrahlung, electron temperatures are determined from the relative amplitudes of the two signals.

B. Plasma Stability and Containment Diagnostics

1. Streak Photographs. Gross radial motions of the plasma are observed by photographing the light emitted from the plasma through a quartz window in the ceramic discharge tube and a perforated section in the metal primary. The time behavior is recorded with an image converter streak camera.

2. Centroid Probe. The position of the axial current in the pinch discharge is determined by a system of four B_θ sensing coils located on a minor circumference of the ceramic wall at several positions around the experiment. These coils are designed to measure the first spatial Fourier component of the perturbed B_θ field of the discharge. For a linear current in a linear geometry, the response is exactly proportional to the radial displacement of the center of the current distribution.

3. Instability Field Probes. A helical displacement of the pinch current such as that produced by an instability, will give rise to perturbations in both the B_θ and B_z fields. The ratio of the first spatial harmonics of the perturbed B_θ and B_z fields at the primary wall is directly related to the wave number of the perturbation. A set of B_θ and B_z pickup coils is installed in the experiment to determine the wavelength of the $m = 1$ MHD instabilities.

4. Current, Voltage, Flux Loop Measurements. The axial pinch current, I_z , is measured with a Rogowski loop around the minor circumference of the ceramic torus. The axial voltage, V_z , is obtained by measuring the flux change in the iron cores. The energy input is obtained by calculating $\int_0^t V_z I_z dt$ at the terminals. The current in the B_z windings is

measured with a Rogowski loop and the magnetic flux Φ_z with a one turn loop around the minor circumference of the torus.

5. Magnetic Field Probes. Two magnetic field probes are inserted along a minor diameter of the discharge. Each probe contains five coils for the measurement of the B_θ and B_z field components at five minor, different radii. Both the toroidal and poloidal magnetic fluxes and the pitch of the field lines can be determined. With the assumption of pressure balance the radial dependence of the plasma pressure can be determined.

The data are recorded on polaroid film. At present, processing is accomplished with a Hewlett-Packard digitizer, a model 9810A computer with cassette memory, and plotter system. This system is used for all data analysis except stability. Growth rate and radial mode structure of unstable eigenmodes are calculated by processing the digitized data from the magnetic probes on the CDC 6600.

This system is preferred at this stage of the experiment in that it allows for more interaction between the staff and the data. The present time lag in processing the data caused by the limited memory of the Hewlett-Packard computer will be corrected with the recent addition of the tape cassette memory option. When the experiment passes its present stage the data handling system may have to be reevaluated.

VI. RESULTS

The objective of the ZT-1 experiment is to establish experimentally a hot stable diffuse pinch. This section will document what has been accomplished towards achieving this goal. Part 1 deals with the preionization phase. Part 2 documents the plasma temperature and beta. Part 3 presents the electron density measurements; part 4 the electron temperature measurements; part 5 the ion temperature measurements. Part 6 describes some results when the I_z current is crowbarred. Finally, part 7 presents the stability analysis obtained by using the measured magnetic field profiles together with a MHD code to unfold the unstable wavenumbers and growth rates. A discussion of stability and a summary of the results follow.

1. Preionization of ZT-1. The preionization energy source is four 15 μ F capacitors that can be

charged to a maximum of 10 kV. Each capacitor drives one quadrant of the torus, giving a maximum of 40 kV around the torus. The current is limited to 18 kA by an external inductance.

Measurements have been made of the electron density and magnetic field distributions. The electron density as a function of time is obtained with a helium-neon laser coupled cavity interferometer. The error resulting from the unconfined plasma that enters the pumping ports is assumed negligible. The electron density is shown in Fig. 7 for a B_z field of 2.5 kG, deuterium pressure of 30 mTorr, and several capacitor bank voltages. To facilitate time comparisons, the preionization current at 6 kV is also displayed. The dashed line on the graph indicates 100% ionization assuming a uniform electron density. Magnetic probes are used to determine the $B_\theta(r)$ profile. The ten coils are mounted in 8 mm diameter ceramic tubes which are then inserted into the plasma through a pumping port 90° from the one used for the density measurement. When the probes are inserted 5 cm into the discharge for the first time, the electron density is increased by about 25%. After 10 cleanup discharges the presence of the probe cannot be detected within the experimental error. When the I_z preionization current passes through zero, at 15 μ sec, very little trapped magnetic field is measured on axis (≈ 100 G). Unless otherwise noted all of the results discussed in this report are obtained with the main z-pinch current starting

Fig. 7. Preionization current (upper trace) and laser interferometer fringe shift produced by the preionization electron density.

at the end of the first half-period of the preionization current and the preionization bank voltage adjusted to produce 100% ionization at this time. During the preionization, hard x rays are detected. In Fig. 8 the signal from a fast-scintillator x-ray detector is superimposed on the plasma current for two different preionization currents. The increased period, T , of the current in the bottom trace is achieved by doubling the series inductance in the preionization circuit. The same peak current is maintained for the two cases. The gas is deuterium at 30 mTorr and the B_z bias field is 2.5 kG. In both cases, the x-ray emission starts at peak current $T/4$ with the maximum occurring at about $(3/8)T$. The time shift in the x-ray signals in the two examples indicates that the x-ray emission may be associated with the reversal of voltage on the z pinch rather than a specific time interval required for acceleration of the electrons. X-ray films show a nearly uniform radiation intensity around the outer major circumference of the torus with more intense radiation at the four feedplates. From lead-absorption measurements, the x-ray energy is ~ 400 keV. The total peak voltage around the torus is only 30 kV before gas breakdown; once the preionization current starts to flow, the voltage around the torus drops to ~ 2 kV. Insertion of a magnetic probe 6 cm into the discharge reduces the x-ray intensity below the sensitivity of the detectors.

Fig. 8. X rays generated during the preionization current cycle. The x-ray bursts occur after preionization peak current and have photon energies in the range of several hundred keV. The x rays are usually not observed during the main current pulse.

2. Plasma Temperature. The plasma temperature ($T_i + T_e$) is calculated from the pressure profiles by means of the equation

$$T_e + T_i = \frac{1}{Nk} \int_0^R 2\pi r p dr, \quad (3)$$

where N is the total line density assumed to be constant and equal to the initial line density and p is the plasma pressure determined from the magnetic probe measurements. In addition, the temperature is assumed independent of radius. β_0 as defined by the Bennett relation is,

$$\beta_0 = \frac{200 \int_0^R 2\pi r p dr}{I_z^2}. \quad (4)$$

Integration of the plasma pressure profiles leads to the data shown in Figs. 9 and 10. The plasma temperatures ($T_i + T_e$) are high, 1-3 keV, and indicate that we have been successful in achieving high temperatures by the fast rate of rise of the z current designed into 2T-1. The low temperature limitation seen in ohmic heated z-pinch experiments has therefore been surpassed. The temperature shows an inverse dependence on filling pressure. However, no clear dependence of the temperature on the initial bias magnetic field is evident over the range from 2500 to 4000 G.

The field configurations having the lowest β_0 , ~ 0.4 , and most constant value of β_0 as a function of time, while also having a positive pressure gradient near the axis, are obtained with $B_{z0} = 4000$ G and either 2 or 5 mTorr filling pressure.

3. Electron Density. The electron line density has recently been measured by He-Ne laser interferometry. The laser beam passes through a quartz section of the discharge tube located 5.3 cm away from the pump ports. During pinch formation the electron line density increases in fair agreement with that expected from the pinch radial compression. The density then remains almost constant during most of the current cycle, ~ 6 μ sec.

The determination that the electron line density is constant and equal within experimental error to

Fig. 9. The β_0 as a function of time for several starting conditions.

Fig. 10. The plasma temperature ($T_i + T_e$) as a function of time for several starting conditions.

the initial line density establishes the plasma temperatures calculated from the plasma pressure, Section VI-2 above. When the ZT-1 experiment is run in the fast mode with fuses the initial values of $T_i + T_e$ should then be between 1 and 5 keV, as shown by Fig. 10.

4. Electron Temperature.

a. Differential soft x-ray measurements.

An estimate of the electron temperature can be obtained using the differential soft x-ray technique. The signals are characterized by a large amplitude pulse which can be interpreted as being due to an initial electron temperature of about 1 keV which rapidly decreases to ~ 100 eV in about 2 μ sec or as a burst of ~ 10 keV x rays resulting from runaway electrons. This technique is sensitive to electron temperature greater than 100 eV and therefore can only place an upper bound of 100 eV.

b. Measurements by Thomson scattering.

Thomson scattering measurements are being made to make a better determination of electron temperature. A plasma volume, 8 mm long and 2 mm in diameter, located 1 cm from the minor axis of the machine, is

viewed at an angle of 90° from the incident laser beam. Two detectors have been used. The first has four channels located at $65 \text{ \AA}$ intervals and the second ten channels at $32 \text{ \AA}$ intervals. The k-vector, important for the interpretation of the results, has both radial and poloidal components but no toroidal component. Striking differences are observed between the scattered spectrum for the slow and fast modes of operation. Figure 11 shows the data taken in the slow mode. The time indicated is in μ sec and is measured from the initiation of the I_z current. The temperature is obtained from a least square fit to a gaussian. The data are typical of many shots taken in the slow mode, and the electron temperature varies from 10 to 50 eV, depending on the time of the measurement. The density, typically $3 \times 10^{15} \text{ cm}^{-3}$, obtained by comparison with Raleigh scattering in nitrogen, is as expected from compression of the filling gas.

Figure 12 shows data obtained in the fast mode with the four channel detector. The solid squares and the dashed data points have been measured on two

Fig. 11. Thomson scattering spectrum taken with the slow mode of operation. The temperature is given in eV.

Fig. 12. Thomson scattered spectrum taken with the fast mode of operation. Two different shots are displayed.

separate shots. The solid curve is the computer's attempt to fit a gaussian to the solid squares. Clearly, the temperature obtained from this fit is not realistic. The dashed curve is a higher order fit to the two measurements as well as to other shots. It is seen to be symmetric about the laser line at 6943 Å. It should be noted that the parameter $\alpha = (K\lambda_D)^{-1}$ is much smaller than one in this experiment where λ_D is the Debye length. The dip in the middle of the scattered spectrum of Fig. 12 is

somewhat suspect because considerable signal must be subtracted from the observed signal, due to instrumental scattering on the channel centered on the laser line. Recent measurements using eight of the ten channel system has confirmed that the spectrum is indeed not gaussian in the fast mode.

c. Discussion of the Thomson scattering results. The wave number and frequency of the double humped feature shown in Fig. 12 coincides with the dispersion relation of Bohm-Gross modes, see Fig. 13, assuming an electron temperature of 30 eV. A 35° scattering experiment will help to resolve this question. Whatever the phenomenon is, it appears that it must be associated with electrons. Ion oscillations or waves are orders of magnitude lower in frequency. The distorted spectrum is observed for times ranging from 0.75 μ sec to 5 μ sec in the

Fig. 13. Plot of the dispersion relation for hot electron plasma waves.

discharge. Since the Landau damping of these waves is large a strong driving mechanism would have to be present. There is experimental evidence for runaway electrons in the plasma.

d. Possible consequences of low electron temperatures. The low electron temperature ~ 30 eV, has possibly two important effects on the z-pinch performance.

(1). The azimuthal magnetic fields diffuse rapidly towards the axis. During this field diffusion magnetic energy is transferred into plasma energy by resistive heating. A preliminary analysis is being made on the plasma heating and its effect on pinch stability and equilibrium.

(2). After the axial current has diffused to the axis the plasma resistivity must be low in order that plasma heating and field diffusion will not continue at an excessive rate. It may turn out that the high resistivities are a result of microinstabilities and turbulence. With the wide range of parameter space available to us in ZT-1, see Section VII, the onset and scaling of an enhanced resistivity can be examined.

5. Ion Temperature. A mixture of 20% He and 80% D at 15 mTorr has been used as the filling gas. The Doppler broadening of the 4686 He II was measured as a function of time and converted to an ion temperature. Preliminary results from one discharge are shown in Fig. 14 together with the calculated

$(T_i + T_e)$ from pressure balance. With an electron temperature of ~ 40 eV given by Thomson scattering there is then fair agreement among the three measurements $(T_i + T_e) \sim 200\text{--}400$ eV from pressure balance, $T_i \approx 400$ eV for Doppler broadening and $T_e \sim 40$ eV from Thomson scattering. The discharge was run in a mode in which the plasma temperature was predicted to be of this magnitude. More recently ion temperatures as high as ~ 850 eV have been measured.

These results from ZT-1 run in the fast mode are to be compared with those taken of discharges with the slow mode. Here $T_i + T_e$ was ~ 72 eV from pressure balance, $T_i \approx 40\text{--}50$ eV from Doppler broadening, and $T_e \approx 20$ eV from Thomson scattering. The strong heating produced by the fast rising z current is again evident.

6. Observations of I_z Crowbarred. A number of discharges have been made with the z current crowbarred at peak current. As described earlier there is a metal-to-metal explosive switch in each of the four feedplates. The z currents were sustained by the crowbars with $1/e$ decay constants between $35\text{--}36$ μsec for the first 10 μsec and dropped close to zero at ~ 50 μsec . Without crowbars the z current passes through zero at $11\text{--}12$ μsec . On one discharge, the $1/e$ decay of the plasma current was calculated to be as high as ~ 130 μsec for the first 16 μsec in the discharge cycle. If these decay constants are interpreted in terms of an inductance and a resistance the electron temperature assuming classical resistivity would be ~ 50 eV. The good agreement with the Thomson scattering measurements, $40\text{--}50$ eV, is probably fortuitous but indicates again that the effective resistivities must be decreased if the pinch lifetimes are to be increased.

7. Stability.

a. Stabilized Pinch Without B_z Reversal.

This section will document what has been achieved towards obtaining a stable pinch. The results that follow are obtained with the fast mode of operation with an initial $\dot{I}_z$ of 1.4×10^{12} A/sec. Slow mode results are presented only for a comparison. During the past two years ~ 150 fast discharges have been made and several hundred in the slow mode. In this report a few typical discharges will be discussed. To be stable against pressure-driven modes the pressure gradient near the axis should be greater than or equal to zero. Figure 15 shows that this can be

Fig. 14. A comparison of the ion temperature measured by Doppler broadening with the plasma temperatures $(T_i + T_e)$ calculated from pressure balance. If the electron temperature is included this shows fair agreement between the measurements.

Fig. 15. Smoothed plasma-pressure profiles calculated from measured magnetic-field distributions for the fast mode of operation at 2-, 5-, and 10-mTorr deuterium gas pressures. Positive pressure gradients near the axis, as required for stability, are observed for 2 and 5 mTorr and the general shape is maintained for the duration of the current pulse.

achieved when ZT-1 is operated in the fast mode. With 4 kG B_z bias field and filling pressures of 2 or 5 mTorr, the pressure profiles have the necessary gradient near the axis. The general shape is maintained for 8 μ sec after which time the fields become too small to measure accurately. The current passes through zero at 11.5 μ sec.

The fact that the pinch is stable against gross kink modes can be seen in the reproducibility of the magnetic-field data shown in Fig. 16. The data were taken from a series of discharges at 5 kG B_z bias field.

The magnetic probes were positioned to measure B_z for B_θ across the diameter of the discharge on two successive discharges. Within the experimental error, the magnetic-field profiles are reproducible and well defined up to 6 μ sec. Analysis was not carried further in time because of the diminishing plasma current. As the magnetic field is not reversed on the outside of the pinch, this configuration is predicted by MHD theory to be unstable to radial modes localized around the pitch minimum at ~ 3.8 cm. Streak photographs show evidence of some instability taking place. So that, while a constricted discharge is maintained on a gross scale,

Fig. 16. Reproducibility and symmetry of probe measurements in the fast mode discharge.

indicating that a toroidal equilibrium is attained, these localized modes may be the cause of the losses observed in the energy balance calculations. The reproducibility can be destroyed by lowering the bias field.

b. Stabilized Pinch with B_z Reversal. The following results were obtained with a rate of B_z reversal of 250 G/ μ sec as measured without plasma. Figure 17 shows a comparison of radial distributions of B_z , B_θ , and pitch ($P = r B_z/B_\theta$) with and without the externally applied reverse B_z field. Apparently, the plasma conductivity is high near the wall since the B_z reversal compresses the plasma and trapped magnetic field. This increases the B_z on axis and moves the B_θ flux lines inward. The resulting equilibrium prevents the zero in B_z from moving away from the wall more than a few millimeters. Figure 18 shows the comparison of the streaks and I_z and I_θ currents with and without B_z reversal. The reversing field is applied at the start of the pinch implosion. Streak photographs are taken across a diameter. Luminosity is an indication that plasma is touching the wall.

Fig. 17. Comparison of B_z , B_0 , and the magnetic field line pitch ($p = rB_z/B_0$) with and without an externally applied reverse B_z magnetic field. Because of the high plasma conductivity the reversal has compressed the plasma, increasing the B_z on axis and shifting B_0 inward. The resulting equilibrium then prevents the zero in B_z from moving away from the wall more than a few millimeters.

The MHD stability program, for the stabilized pinch, and for the reversed B_z pinch are shown in Fig. 19. The calculations are based on measured B_0 and B_z profiles. Cylindrical geometry and ideal MHD are assumed. K is the axial wavenumber of the $m = 1$ instability and r is the minor radial position. The horizontal lines indicate wavenumbers searched for unstable modes. The lines $g = 0$ represent the roots of the function g appearing in the potential energy integral $\int [d\xi_r/dr]^2 dr$, where ξ_r is the radial component of the displacement from equilibrium. The other terms in the integral are always positive.

Instability thus requires that g be negative over at least part of the plasma radius. This negative region is the one enclosed by the $g = 0$ lines in the figure. The shaded areas correspond to unstable eigenmodes. Their amplitudes are drawn in proportion to their growth rates. The single-hatched areas correspond to current driven modes and are typical of pinches involving a minimum in the pitch. The cross hatched modes are pressure driven modes. The fastest growth rate for these cases is of the order of $\sim 2 \times 10^6 \text{ sec}^{-1}$. It is clear from the analysis that the reversed field pinch has fewer unstable modes with reduced growth rates when compared to the stabilized pinch without reversal. Reversal of the B_z field outside the pinch has had a remarkable effect on pinch stability. Using the measured field profiles the time history of the predicted stability of the reversed field pinch is shown in Fig. 20. For this case the unstable wave numbers are identified as solid horizontal lines with the width at half maximum of the eigenmode shown by the thick portion of the line. The short horizontal lines on the ordinate indicate wave numbers found to be stable. The triangles and circles represent roots of the functions f and g , respectively, appearing in the energy integral. The hatched portion of the abscissa represents Suydam unstable radii. Note that there is no longer a minimum in the pitch. The fastest growth times are 40, 60, and $0.7 \mu\text{sec}$ for the three times shown. The profiles indicate that the discharge goes unstable at time $t \approx 6 \mu\text{sec}$, in coincidence with the onset of luminosity in the streak photograph. The growth rates are much slower and the unstable wave numbers much fewer before $6 \mu\text{sec}$ than for the non-reversed B_z pinch. In fact, during the first $6 \mu\text{sec}$, the stability of the pinch is improving in time.

The sudden disruption, therefore, seems to be due to a change of the magnetic field profiles, perhaps due to diffusion, leading to an unstable configuration rather than the slow growth of an early instability.

8. Discussion of Stability. As previously stated the objective of the ZT-1 experiment is to establish experimentally a hot stable z pinch. The magnetic field and plasma pressure profiles necessary for stability are determined by MHD theory. During the course of the experiment we have made progress towards the understanding of z pinch stability and

Fig. 18. Comparison of streak photographs taken with and without reverse B_z . Note that the streak photograph with reversal is significantly fainter with a marked decrease in the bright filamentary structure seen without reversal.

Fig. 19. The MHD stability diagrams, (a) for the stabilized pinch without reversed B_z , (b) for reversed B_z . Note the great reduction in number of unstable wave numbers when the B_z is reversed.

Fig. 20. Streak photograph and stability diagram of a reversed B_z pinch at times $t = 4, 6$, and $8 \mu\text{sec}$. The fastest growth times for the unstable modes at 4 and 6 μsec are 40 and 60 μsec and appear to be increasing with time. At 8 μsec the pinch suddenly becomes unstable with growth times of 0.7 μsec .

the factors which are important to the successful production of stable profiles.

Early in the research program of ZT-1 it was established that the plasma pressure profiles deduced from measured magnetic field distributions had positive gradients close to the axis. This is one of the requirements for MHD stability. With a correct pressure profile having been formed about the discharge axis our attention was focused in programming the fields necessary for stability.

The behavior of ZT-1 can be characterized by operation at low and high B_z bias fields.

a. At low B_z bias fields the β_0 's are too high and the pinch is unstable. A reversed field will not stabilize this pinch. If the β_0 's could be reduced, however, stability might be achieved. There is some evidence that a reduction of the initial degree of preionization of the filling gas has the effect of extending the lifetime.

b. At high B_z bias fields the β is lower. There are data that suggest that after an initial instability a period of relative stability follows. Plasma energies remain high with streak photographs being relatively without evidence of light at the walls.

The quiescent phase observed at high bias fields may be similar to that seen previously in Zeta in which a stable regime was established spontaneously. We have not as yet determined any detrimental effects to a pinched plasma that rapidly passes through a period of instability. The plasma energy density appears to remain relatively high and no large increase in plasma impurity content is seen.

The timing and phasing of the magnetic fields has turned out in other experiments to be crucial to establishing stable z pinches. In ZT-1 we had an imbalance in the rates of rise of the B_z and B_θ fields which may have made stable profiles difficult to find. The experiment is now being modified to alleviate this imbalance by reducing the rate of rise of z current and slowing down the onset of instabilities to gain time for the present B_z reverse system to establish stable profiles. Another alternative is to increase the rate of rise of the B_z reverse field.

9. Summary of Results. The following statements can be made on the performance of ZT-1 experiment when operated in the fast mode:

a. Magnetic probe measurements show that under some conditions toroidal equilibrium is achieved.

b. Plasma pressure profiles are hollow as required for stability.

c. The measured β_0 's can be made to lie within MHD stability criteria.

d. With no reversal of the B_z outside the pinch stability calculations show that the pinch is unstable on the outer periphery. Streak photographs appear to confirm this. With B_z reversal the pinch, if not yet stable, is closer to having MHD stability in that the numbers and their growth rates are reduced. The streak photographs show that the wall light is much reduced.

e. Plasma temperatures ($T_i + T_e$) > 1 kev are inferred from plasma pressure profiles.

f. Electron temperature measurements indicate a non-gaussian velocity distribution and a low electron temperature < 100 eV.

g. Preliminary ion temperature measurements indicate an ion temperature in agreement with the temperature calculated from the plasma pressure.

VII. THE GOALS AND PROGRAM OF ZT-1

The central goal of the experiment is to demonstrate that MHD stable profiles can be established in the plasma. The experiment should delineate the requirements for establishing stable profiles, and then identify the cause, if stability cannot be maintained with time. The last requirement is necessary if limitations to the concept of reverse field pinches are to be understood, as well as to establish priorities for future work. Obstacles that may develop as the program progresses may be removed as our understanding of plasma physics improves.

Goals that should be reached within the time scale of June 1974 are as follows:

1. Establishment of internal consistency between the diagnostic results, so that the basic parameters of the experiment n_e , T_e , T_i can be verified.

2. Identification of programming techniques required to establish stable profiles.

3. Once stable profiles are established to identify whether pressure driven modes or current

driven modes are leading to instability within the time scale predicted by diffusion.

The results to date show that partial stability can be achieved, in that slow growth rates can be programmed into the pinch. However, at 8 μsec very rapid growth rates become evident. Since the time scale for the onset of these instabilities is so short it is experimentally difficult to establish a cause for their occurrence. Goal C of the program is then to be directed toward slowing down the growth rate of the instabilities by lowering the magnetic fields, termed "derating" the experiment. Coincident with derating, the rate of rise of the I_z and I_θ current can be modified to bring them into balance. The overall range of parameters is expected to be: $\dot{I}_z$ 0.4 to 1.5×10^{12} A/sec; I_z 50 to 200 kA; $\dot{B}_z$ 0.5 to 1.0 kG/ μsec and finally 5.0 kG/ μsec . The lower range of $\dot{I}_z$ and I_z is consistent with the requirement to retain some degree of implosion heating, so the plasma temperature should be in an intermediate range between 100 to 500 eV. (In the Culham experiment $\dot{I}_z$ is 4×10^{10} A/sec.) The above parameter range is readily accessible with the present machine. Details of the required modification can be found in Appendix C. The stable time against diffusion with derated operation is expected to be ~ 40 μsec . Goal C is expected to achieve this time scale.

The future program, beyond June 1974, would be directed toward establishing longer time scales. If

B_θ becomes too high because of diffusion and the resulting ohmic heating in the plasma, then emphasis can be directed towards techniques designed to reduce B_θ . If the stable profiles are lost due to radial diffusion the time scale must be increased by programming techniques.

In summary, we have an experiment which can be operated over an impressive range of parameters, from duplicating the slow ohmically heated experiments to the fastest rates of rise of z current in the world. The diagnostics have been advanced to the point where plasma properties can readily be determined and the measured magnetic field distributions can quickly be compared with MHD stability theory. We now have the opportunity to establish those regimes of importance to the stable diffuse pinch.

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APPENDIX A STABILITY THEORY

In order for the linear diffuse pinch to be MHD stable, the energy integral δW must satisfy the condition²

$$\delta W = \frac{\pi}{2} \int_0^{r_{\text{wall}}} \left[f \left(\frac{d\xi}{dr} \right)^2 + g \xi^2 \right] dr > 0,$$

where

(A-1)

$$f = r \frac{(kr B_z + m B_\theta)^2}{m^2 + k^2 r^2},$$

$$g = \frac{2 k^2 r^2}{m^2 + k^2 r^2} \frac{dp}{dr} + \frac{1}{r} (kr B_z + m B_\theta)^2 \frac{k^2 r^2 + m^2 - 1}{m^2 + k^2 r^2} + \frac{2 k^2 r}{(m^2 + k^2 r^2)^2} (k^2 r^2 B_z^2 - m^2 B_\theta^2),$$

for all possible perturbations $\xi(r)$ and axial wave numbers k . In these expressions, B_θ is the azimuthal magnetic field and B_z is the axial field. The pressure gradient dp/dr follows from pressure balance:

$$\frac{dp}{dr} = - B_z \frac{dB_z}{dr} - \frac{B_\theta}{r} \frac{d}{dr} (r B_\theta). \quad (\text{A-2})$$

We minimize δW most conveniently by using Suydam's method of completing squares.³ The energy integral is written as the sum of quadratic terms in ξ . Then if any of the coefficients multiplying these terms is negative, the configuration is unstable. A magnetic field configuration can thus be tested for stability in a few seconds computer time.

We obtain the growth rate of the instability, if any, by solving the normal mode equation of Hain and Lüst.¹ In the incompressible case, this equation reduces to:²⁵

$$[a(r\xi)'] - b\xi = 0,$$

where

$$a = \frac{r(\omega^2 \rho + F^2/\mu_0)}{k^2 r^2 + m^2}, \quad (A-3)$$

$$b = \omega^2 \rho + \frac{F^2}{\mu_0} - \frac{2B_\theta}{\mu_0} \left(\frac{B_\theta}{r} \right),$$

$$+ \frac{2mr}{\mu_0} \left[\frac{FB_\theta}{r(k^2 r^2 + m^2)} \right],$$

$$- \frac{4k^2 F^2 B_\theta^2}{\mu_0^2 (k^2 r^2 + m^2) (\omega^2 \rho + F^2/\mu_0)},$$

$$F = kB_z + \frac{mB_\theta}{r},$$

and ω is the growth rate. The boundary conditions are:

$$\xi(r_{\text{wall}}) = 0$$

$$\xi'(0) = 0 \text{ for } m = 1$$

$$\xi(0) = 0 \text{ for } m > 1.$$

A difficulty in creating theoretically stable profiles such as the one shown in Fig. 1 is to satisfy Suydam's criterion over the entire radius of the discharge. Instead of constructing stable profiles from given $B_z(r)$ and $B_\theta(r)$, we therefore start from $B_z(r)$ and $s(r) > -1$ as independent variables. Suydam stability is then automatically satisfied. $B_z(r)$ in Fig. 1 is simply a cosine function shifted upwards to satisfy the positive B_z flux condition.

APPENDIX B

THE CULHAM HBTX EXPERIMENT

The HBTX (High Beta Toroidal Experiment) is designed to produce stable magnetic field and pressure profiles. The main characteristics of the experiment are shown in Table B-I.

TABLE B-I
DESIGN PARAMETERS OF HBTX

Discharge tube diameter	12 cm
Major diameter	2 meters
Z current	$\lesssim 380$ kA
Rise time of Z current	7-10 μsec
B_z bias field	$\lesssim 8$ kG
Rise time of reverse B_z field	$\lesssim 4-7$ μsec
Crowbar time of Z and θ pinches	2-3 μsec

Toroidal reversed field pinch configurations have been established in this experiment, without instability or wall contact with $\beta_\theta \sim 0.6$, and $n \approx 10^{16} \text{ cm}^{-3}$.²⁶ The pinch is ohmically heated and plasma temperatures ($T_i + T_e$) of $\lesssim 50$ eV are reported.²⁷ For

peak plasma currents of 50 kA the plasma is stable for 30-40 μsec - the classical lifetime of the field configuration. The data suggest that neutral gas in the core is necessary for final stability. The time variation of the radial electron density and temperature distributions are in agreement with results of numerical simulation. The energy confinement time of 12-15 μsec and the particle confinement time which is somewhat longer can be explained on a classical basis.

The Culham group's interpretation of their results is that the lifetime of reversed field configurations depends upon diffusion of the magnetic fields which causes the configuration to change into an unstable one. The nature of this diffusion process prevents stable operation at currents of more than 100 kA and the attainment of higher temperatures and longer lifetimes. They feel that diffusion is the central problem for future research on the High Beta Toroidal Experiment.

APPENDIX C ENGINEERING

During the development of the ZT-1 experiment several special components and circuits had to be designed and tested. The following items have been developed:

1. Magnetic Energy Storage and Current Transfer system. If the z pinch is to be heated by a fast rising magnetic field a high voltage, low inductance energy source is required. We have used the technique of magnetic energy storage and current transfer as shown in Fig. C-1. Here a ~ 20 kV, capacitor bank and switch is connected to an inductor and current interrupter, a copper fuse. When the capacitor switch is closed current I_p flows through the inductor and fuse as shown in the lower half of the figure, and rises to ~ 0.6 MA. The fuse melts, evaporates, and becomes a relatively high resistance. The storage inductor tends to maintain the current. When the voltage across the fuse reaches a predetermined value it is switched across the load, a linear

z pinch is the example. The current I_s through the load then rapidly rises to approximately equal I_p . When I_s equals I_p the voltage across the fuse drops close to zero the current then rings out with the LC frequency of the circuit.

A numerical analysis was made of the behavior of two fuses interconnected with an inductor. A maximum test of the required coupling was made by varying the fuse cross sections so as to introduce a timing difference between the fuse voltages approximately three times the measured jitter time. With an inductance of 10 nH coupling and two fuses, the voltage characteristics for both fuses were within 1% of each other. Experimentally we find the voltages do follow each other to $< 5\%$.

The advantages of this energy supply include the following:

- a. A low voltage and relatively high-inductance capacitor-switch system energizes the circuit.
- b. The inductance of the load can be made small, ~ 25 nH. The inductances then of capacitors, switches and cables do not enter in the determination of current rise times.
- c. When the discharge current has risen to its maximum value the voltage across the discharge tube can be made small. This occurs if the voltage transfer is made when the capacitor voltage is small. A low voltage reduces the possibility of a second discharge breakdown near the wall. In early high voltage z-pinch experiments this breakdown limited the maximum voltage that could be applied. We have not seen any evidence of a wall breakdown using the transfer system.

The disadvantages of the system are as follows:

- a. The system is inefficient. Only about one quarter of the stored energy is transferred to the load. At this stage of the experiment the transfer efficiency is not important but will become so if the experiment is to increase in size.
- b. The copper fuse must be replaced after every discharge. This has turned out to be important to the ZT-1 experiment which has four fuses. The number of discharges per day has been limited, ~ 6 per day. We now have developed a packaged fuse which allowed a shot every ten minutes. A transfer

Fig. C-1. The magnetic energy storage and current transfer system. The electrical circuit is shown in a, with the currents and voltages in b.

capacitor circuit, see this section, is under test which will replace the fuses.

2. Fast B_z Reversal Circuit. The present circuit for the B_z reversal is shown in Fig. C-2. The B_z winding is the load, inductance $\approx 40 \mu\text{H}$, on the extreme right of the figure. On the left is a Marx circuit (including the capacitors $C_{1,2,3}$) which provides the slow forward bias B_z field. Immediately to the right is a crowbar switch, SW_4 , which is closed just before the main z pinch and prevents further energy transfer from the slow bank. Still further to the right is the Marx circuit with capacitors $C_{4,5}$ for the fast reverse B_z field. The low inductance 1Ω resistor isolates the reverse bank from the crowbar switch SW_4 . Finally the switch SW_8 or SW_9 crowsbars the load.

3. Derating of the Z circuit. The overall range of the experimental parameters can be increased by either modifying the present fuses or by installing resistors. Changing the width of the fuses will vary the voltage and current of the transfer. Resistors can be installed in series with the storage inductance in each quadrant together with the removal of the transfer switches. With resistors the fuses

are not used and the repetition rate at which the experiment can be run will be markedly increased.

4. Field Distortion Spark Gaps. Field distortion spark gaps have been developed to accommodate the wide voltage range required in the experiment. These gaps are fired in the cascade mode, that is breakdown is initiated from the distortion electrode to a main electrode by a trigger pulse. Breakdown from the distortion electrode to the opposite main electrode results from overstressing when the distortion electrode approaches the voltage of the first main electrode. Distortion gaps are successfully operated over voltage ranges up to $\sim 20:1$ and with peak voltages of 40 kV.

Simultaneous breakdown of both halves of such gaps is possible if the trigger circuit rise time is short enough. Operation in this mode would provide an almost infinite voltage range. This operating mode is still not perfected.

5. Transfer Capacitor Circuit. The transfer capacitor circuit has been designed to obtain rapid rates of current transfer into a load, requiring expensive fast capacitors for only part of the total energy storage. Components have been tested and

Fig. C-2. Circuit diagram of the B_z energy supply. The B_z winding of inductance, $\approx 40 \mu\text{H}$, on the right of the figure is driven by the forward bias bank on the left with crowbars and reverse banks shown in the center.

have been assembled into a circuit which drives a static inductive load. When this test is completed the inductive load will be replaced by a linear z-pinch discharge.

6. Fuse Development. A development program has resulted in a fuse that can be used on ZT-1 and also on the proposed increased energy level ZT-S experiment. The final design is a disposable package that consists of a hairpin shaped 1 mil thick copper coil separated by a single 60 mil sheet of ABS plastic and sandwiched between two layers of sand. The fuse package can absorb 20 kJ of energy without rupture, can be mounted in an inverted position, and produces no burning at the electrical connection.

7. Metal-to-Metal Explosive Switch. A low inductance crowbar switch has been designed, tested and installed in the four feedplates of ZT-1, Fig. C-3. Its performance approached the design expectations, i.e., self-inductance ~ 3 nH and resistance $\lesssim 5 \mu\Omega$. Closure time is $\sim 11.0 \pm 0.3 \mu\text{sec}$ where $t = 0$ is defined as the start of current in the bridgewire of the detonator.

In tests of this switch the initial crowbar currents ranged between 180 to ~ 330 kA with L/R decay times of ~ 1.2 ms without burning. A number of discharges of ZT-1 have been crowbarred with the predicted performance of the electrical components.

8. A Metal Toroidal Discharge Tube. A toroidal discharge tube for ZT-1 using our aluminum washer

Fig. C-3. A cross-section view of the metal-to-metal explosive crowbar switch installed in the feedplates of ZT-1.

Fig. C-4. A cross-section view of the metal toroidal discharge tube installed in the ZT-1 primary.

design has been fabricated. In this design of a metal wall²⁸ on which high electric fields, ~ 1 kV/cm, are to be applied, the wall is subdivided such that the voltage between adjacent conducting surfaces is less than the running voltage of an arc.²⁴ Experiments have shown that this voltage is ~ 25 V. In our present design, the discharge tube is fabricated from a stack of aluminum washers, 0.010" thick, with adjacent surfaces anodized for insulation. Our tests on a linear tube of this construction showed that electric fields $\lesssim 1.3$ kV/cm and currents $\lesssim 0.45$ MA could be successfully applied.

A toroidal metal discharge tube for ZT-1 has been fabricated, Fig. C-4. Each washer, ~ 0.010 " thick, is tapered to match the major radius of the primary when packed in series. Also, each washer is subdivided 40 times in azimuth so that a voltage of 1 kV/turn can be applied. This latter subdivision allows B_z to be varied in the experiment as required for stability.

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REPORT OF THE REVIEW PANEL ON THE DIFFUSE TOROIDAL Z PINCH

(ZT-1)

November 27, 1973

Panel Members:

F. Jahoda (Chairman)

J. Freidberg

J. Ingraham

E. Kemp

D. Nagle

K. Thomassen

I. INTRODUCTION

This report summarizes the findings and recommendations of the internal review panel formed by Dr. Fred Ribe in response to a request by Dr. Stephen Dean, AEC-DCTR, that program guidance be given to the ZT-pinch experiments. (See Dean letter, Appendix A')

Although the letter from Dr. Dean makes an analogy with the Staged Theta Pinch Review Panel, a distinction between that panel and the present one should be noted. We are concerned with a program which is considered a primary backup to Scyllac (as opposed to the Staged Theta Pinch which is part of the main line Scyllac effort). Thus, as stated in the charter instructions themselves, the more general question of "the role of Z pinches in the over-all program" must also be addressed.

A fundamental point agreed on by the panel is that the rules for judging a back-up experiment should be somewhat different from those applying to the main line experiments. The panel feels that a back-up program should be judged on the progress made in implementing and investigating various avenues of approach towards a well-defined final goal, rather than judged against a detailed list of specific milestones which might render the program inflexible. This point is especially important since

a backup experiment has, almost by definition, a less well-defined route to the break-even experiment.

In sitting in judgment on our colleagues we have tried hard to utilize effectively the opportunity which our proximity gave us for detailed and searching inquiry into the ZT program. In general, this interaction has tended to reveal more understanding, more data, more thought by the ZT group than indicated in either the formal presentations or written material. In fact the panel criticizes the group for inadequate communication, including lack of publication in refereed journals, of their achievements and state of progress at any given time to the rest of the plasma physics community.

The experiment has been underway for about three years, and disappointingly slow in producing results. Recent progress has been more rapid and the results are encouraging. It is felt that there is a solid theoretical basis for the experiment, good engineering support, an increased rate of understanding the experimental results and some clear directions and goals for the future.

The panel is unanimous in its feeling that while some measure of progress in attaining the final goals of the experiment can be made by July 1974, an accurate and honest evaluation of the long

term prospects of the ZT program could be made only after a period of 18 months (i.e., July 1975).

The specific recommendations made in this report are mostly in line with those proposed by the ZT group itself, but the specific dates have been set by the panel. That portion which is required by July 1, 1974 represents a substantial achievement in itself and will require a concentrated effort by the entire group if the schedule is to be met. The panel has suggested a very significant final goal of the experiment: confinement of a 1 keV plasma with $n > 10^{15} \text{ cm}^{-3}$ for 40 μsec . Such an achievement by July 1975 would, in our view, merit a greatly expanded effort on toroidal Z pinches.

II RATIONALE FOR THE DIFFUSE TOROIDAL Z PINCH PROGRAM

There are both good theoretical and good experimental reasons for choosing the particular confinement and heating schemes utilized in the ZT experiment.

1. Theoretical Rationale. MHD stability is an important ingredient in choosing favorable magnetic configurations. This is particularly true for high- β systems, where the results of many years of experimental experience indicate that on the time scales of interest almost all the important behavior (with the exception of the implosion phase) is described by MHD.

The predictions of MHD theory constitute the most important justification for the ZT experiment. Theoretical calculations in both one and two dimensions indicate that magnetic field profiles exist which are stable to all modes included in the MHD model. This statement cannot be made either for the Tokamak or Scyllac configuration.

The stable ZT profiles are axisymmetric, with confinement and toroidal equilibrium at high total β ($\sim .2$) provided by the poloidal field and stability provided by a toroidal field which reverses on the outside. Qualitatively, stability against localized modes is accomplished by high shear and stability against kink modes is achieved by wall stabilization.

2. Experimental Rationale. Considerable experimental evidence indicates that the predictions of the theory can be achieved in certain circumstances. In particular, the quiescent period of the Zeta experiment at Harwell conformed to the stable

magnetic configurations just discussed, although at the time of that experiment the theory was not yet known. In addition the linear Z pinch at Los Alamos indicated that stable profiles could be obtained at high temperatures for the 8 μsec before end loss terminated the experiment.

On the basis of Zeta the Culham laboratory built the HBTX experiment. The goals of this experiment were to increase the density from the Zeta value to 10^{15} cm^{-3} and to have experimental control of the field profiles (which occurred purely by accident in Zeta). The Culham group has shown that field programming can be used to achieve stable profiles. A very encouraging recent result is that once the stable profiles are achieved, field diffusion is near classical. The disappointing feature of the Culham experiment is the low electron and ion temperature ($T \sim 30 \text{ eV}$). These low temperatures are uninteresting for CTR purposes and the slow joule heating method probably cannot overcome the radiation barrier at 100 eV.

The important difference between HBTX and ZT is the method of heating. By using implosion heating it is possible to obtain quite high temperatures in the ZT experiment ($T \sim 1 \text{ keV}$). High temperature, obviously needed for a fusion reactor, also more easily satisfies the condition, $(v_{\text{drift}}/v_{\text{sound}}) < 1$, thus eliminating at least some current-driven instabilities.

In summary, there is very strong theoretical justification for the ZT program. In addition there is considerable experimental evidence, mainly at low temperatures, which indicates that field programming can be used to obtain stable profiles. The aim of the ZT program is to develop programming procedures, consistent with the requirements of implosion heating, to obtain a stable plasma at thermonuclear temperatures.

III. STATUS AND PROBLEMS

The ZT-1 experiment has already been moderately successful in its aim of achieving stable profiles at high- β and high plasma temperature. Values of β_0 ranging from 0.4 to 0.6 have been obtained with ion temperature exceeding 1 keV at early times. Corresponding densities are in excess of 10^{15} cm^{-3} , but the electron temperature appears to be below 100 eV in all cases.

The profiles for these cases are grossly stable for the first 4-8 μsec , but all are theoretically unstable to localized modes with growth times of tens (to 50) of microseconds. The effect of these localized modes on energy and particle transport is not known; it may or may not be serious. Of definite concern is the loss of gross stability on the 4-8 μsec time scale, a loss which may be occurring because the profiles are changing anomalously fast. After early time agreement, some time prior to this loss of stability a discrepancy develops between the energy input and the energy content of plasma and field which has not been resolved.

Techniques for converting probe data to profiles of field and pressure and making rapid assessments of stability have been developed, adding considerably to the understanding of the experiment. In general, the theoretical aspects of this program have been adequately addressed and increased understanding and progress now await further experimental results.

One of the major achievements of this program is the advanced engineering design which produces the fast rising fields that heat the plasma and create an equilibrium. A very sophisticated energy storage system and feed arrangement was required and has been implemented. Recent improvements now allow much more rapid operation with an attendant increase of information. Significant results should be forthcoming in the months ahead owing to these changes and to the addition of new diagnostics and improvement of older diagnostics. (See Appendix B⁴)

Failure to achieve stable profiles thus far can be attributed to various causes. First, theory indicates that stable profiles at the higher values of β_0 are very sensitive to changes in the profile. Second, arbitrary profiles cannot be programmed experimentally since only a limited number of parameters can be varied. Some changes, such as large increases in the risetime and magnitude of the reversed B_z field require extensive modifications. Third, fast magnetic field diffusion, perhaps arising from localized MHD instabilities or low T_e , appears to rapidly destroy gross stability of profiles. This occurs either by changes in the profile itself or by plasma heating that raises β_0 beyond the stable limit. Nonetheless, gross stability has been achieved for times long compared to characteristic

growth times for kink modes (0.1 μsec). With the improved diagnostics and many machine variables yet to explore, one can be enthusiastic about the potential of the experiment.

IV. GOALS AND RECOMMENDATIONS

The primary goal of the ZT-1 experiment is the achievement of a long confinement time at high temperature and high β . A significant achievement, one which would merit a greatly increased level of effort, would be to confine a plasma with a temperature of ~ 1 keV and density $> 10^{15} \text{ cm}^{-3}$ for at least 40 μsec .

The panel feels that since a well-designed machine, adequate diagnostic means and an experienced, capable staff now exist, this goal, if it is to be achieved, must be reached in the next 18 months.

In FY '74 substantial progress should be demonstrated. The panel would therefore require that the entire parameter range available without major modification of the present machine be explored by July 1, 1974 including

1. Decrease in $I_z(\text{max})$ and $\dot{I}_z$.
2. Decrease in $I_z(\text{max})$ but not $\dot{I}_z$.
3. Increase of B_z in two steps to 500 G/ μsec and to 1000 G/ μsec . At the end of this search a clear direction must be apparent for attaining the above primary goal in FY '75.

It is suggested that this exploration can be speeded up by relying only on some key diagnostics bearing on stability to check reproducibility and identify those conditions where the full range of diagnostic measurements is most useful. It is essential that the rate at which data analysis proceeds does not limit the rate at which the data is accumulated.

The panel recognizes that Items 1 and 2 above will lower the temperature already achieved. Hopefully, however, they will further increase stability and add significantly to the understanding of remaining physics problems (Appendix C⁵). Pursuit of this schedule should also determine the most effective manner to pursue the major modifications projected for FY '75 in order to achieve the stated goals. As presently contemplated, these modifications include both the further increase of B_z to 5000 G/ μsec and the installation of a larger ceramic tube to reduce diffusion effects and study the scaling with size.

In summary the panel feels that recent results on ZT-1 are encouraging, that it is appropriately regarded as the primary backup program at Los Alamos

and that it be pursued, subject to periodic review, with vigorous efforts.

APPENDIX A'

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

September 25, 1973

Dr. Fred Ribe,
Director
P-15 Division
P.O. Box 1663
Los Alamos, New Mexico 87544

Dear Fred:

In the course of this past year, through the combined efforts of Los Alamos, DCTR, and the Staged Theta Pinch Review Panel, program guidance has been established for the theta pinch program. Similar guidance has not yet been provided for the ZT-1 experiment.

It would be useful, at this time, for us to come to a mutual understanding of the role of z- pinches in the overall program and our expectations for the ZT-1 in particular. We might well begin in a way similar to our early interactions on the Staged Theta Pinch, i.e., LASL preparation of an internal program plan, followed by a presentation and discussion with DCTR staff, leading to a finished document. The document would contain mutually agreeable specific goals for FY 74. A particular aspect which should be prominent in the stated goals is progress toward the experimental verification of the theoretical equilibrium and stability of the reversed z pinch configuration by the end of this fiscal year. This procedure should give us a method for determining the value of continuing this program beyond the present fiscal year.

I look to Ken Moses to interact with you and Jim Phillips in arriving at a reasonable time schedule for this exercise.

With best regards,

A handwritten signature in cursive script, appearing to read "S. Dean".

Stephen O. Dean,
Assistant Director for
Confinement Systems
Division of Controlled
Thermonuclear Research

cc: J. Phillips
K. Moses

APPENDIX B'
DIAGNOSTICS

The diagnostic capabilities of the pinch group have recently been commendably increased and are well documented in their report. They offer reasonable opportunities for cross-checks that will greatly add to the confidence in the quoted plasma parameters. The panel wishes to stress, however, that it is important that the greater quantity of different diagnostics does not of itself hinder the rate at which machine discharges are accumulated by taking too much time either for set-up or data analysis. It would be desirable to settle on one diagnostic that bears directly on stability and is easily analyzable, in order to rapidly guide parameter searches for those operating conditions that most merit complete study by the full range of measurements.

Several further desirable diagnostic actions can be suggested, nevertheless. Their implementation is recommended to the extent that they can be accomplished without impeding the speed with which the search for stable profiles is pursued.

1. The panel is concerned by the great reliance on internal magnetic probes. Reproducibility of other data with and without probes inserted should be repeatedly checked. Scans of density vs radius with the laser interferometer would be useful, especially if they can be coupled with radial temperature distributions to check pressure profiles.

2. Neither results on ion temperatures from neutron measurements, nor on k-values of unstable modes from instability probes, are documented, though the measurement capability for both is stated, and both techniques could supply important information.

3. The ion temperature measurement by Doppler broadening should be extended to other impurity lines, in order to determine what kind of scaling, if any, is necessary to relate the impurity ion temperature to deuterium. Clues to the ion heating mechanism may be obtainable from the scaling at early times before any ion-ion equilibration occurs.

4. Pressure probes at the walls would establish the correct base line constant for the pressure gradients and might register whether plasma losses occur during the formation phase.

5. The non-gaussian distribution of the laser scattering may well be an important general phenomenon when energetic electron currents exist, that has been missed by other experimenters. A test of the Bohm-Gross wave explanation by looking for plasma radiation emitted at the electrostatic wave frequency (far-infrared) would be of very great interest. Certainly at least the scattering at another k value (as planned at 35°) should be carried out.

6. Further efforts to improve the quality and interpretation of streak pictures should be made. Future ZT devices would benefit from increased optical access, e.g. several streak camera locations, despite some degradation in magnetic field homogeneity.

We reemphasize that these suggestions should be implemented only when no interference with the search for stable profiles will occur.

APPENDIX C'

PLASMA PHYSICS

Many interesting plasma physics questions arise in connection with the diffuse Z pinch, some of which apply also to other toroidal experiments. Several have been alluded to in the main text, all have been recognized in one form or another by the ZT group. We append an incomplete list here of problems that need to be addressed by both theory and experiment in order to guide the program effectively in the longer range future.

1. What instability mechanism is responsible for the initial fast diffusion of B_0 ?

2. Does the additional plasma heating produced by this magnetic field diffusion in the setting-up phase necessarily produce values of β_0 too large for stability, and if so, how can the excess energy be non-destructively dissipated?

3. Why doesn't the reversed B_z show similar rapid diffusion?

4. Why does the electron temperature remain low? Do runaway electrons play a role? What is the cause and significance of the non-Maxwellian electron velocity distribution indicated by the laser scattering?

5. What is the significance, if any, of slowly growing localized modes?