A Study of Flow and Loss Processes
at the Ends of a Linear Theta Pinch

Progress Report
for the Period

June 1, 1979 - September 30, 1980

Thomas M. York and Edward H. Klevans

The Pennsylvania State University
University Park, Pennsylvania 16802

June 1980

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Prepared for

The U.S. Department of Energy

under

Contract No. DE-AC02-76ET53018

Formerly EY-76-S-02-4020

NOTICE

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

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

TITLE PAGE	1
TABLE OF CONTENTS	11
LIST OF FIGURES	v
LIST OF TABLES	viii
ABSTRACT	ix
I. INTRODUCTION	1
II. TRANSIENT LOSS FROM A 25 cm LONG THETA PINCH WITH REVERSED TRAPPED FIELDS	4
1. Introduction	4
2. Plasma Column	4
3. Magnetic Field Maps and Transient Flow Initiation	6
4. Radial Profiles of Electron Density, Pressure and Derived Velocity for Various Axial Locations at Several Times in the Loss Event	10
5. The Influence of Column End Formation on Loss Processes	11
6. Rarefaction Wave Phenomenon Identification of an Effective Length of the Plasma Column in the Theta Coil	18
7. Summary of the Observations of Plasma Loss from Within the Theta Coil	21
III. ONE-DIMENSIONAL COMPUTER MODELING OF PLASMA COLUMN BEHAVIOR	22
1. Introduction	22
2. Simulation Results	23
a. Scylla I-C Simulations	23
b. Scylla IV-P Simulations	24
IV. PARTICLE AND THERMAL LOSS PROCESSES AT THE ENDS OF A 50 cm LONG COLLISIONAL THETA PINCH	32
1. Introduction	32
2. Abstract	32
3. Major Outstanding Particle and Thermal Loss Questions	32
4. Determination of Effective Column Length and Minimum Radius of Loss Throat	35
5. Particle Loss--Experiment and Theory	35

6.	Thermal Loss--Experiment and Theory	36
a.	Experimental Determination--Thomson Scatter and Continuum	36
b.	Experimental Determination--Diamagnetic Loop	37
c.	Energy Loss Due to Particle Loss	37
d.	Energy Loss Due to Conduction	37
e.	Comparison of Theory and Experiment	38
f.	Computer Simulation Determination of Thermal Conduction Coefficient	38
7.	Temperature Gradients in the End Region and Thermal Insulation at the End Region Walls	38
8.	Indicated Wave and Flow Velocities During the Loss Event	44
a.	Expansion Wave Velocity	44
b.	Flow Velocity in the Loss Region	44
c.	Flow Velocities at Throat	46
V.	THE INFLUENCE OF ROTATION ON THETA PINCH BEHAVIOR	47
1.	Introduction	47
2.	The 0-D Model of a Rotating Column	47
3.	Experimental and Computational Results	49
VI.	ZERO-DIMENSIONAL MODEL FOR LOSS FROM A THETA PINCH WITH PARALLEL TRAPPED FIELD	58
VII.	MAGNETIC MIRROR STUDIES AND CROWBAR DEVELOPMENT	62
1.	Introduction	62
2.	Abstract	62
3.	Magnetic Mirror Concepts	63
4.	Biot-Savart Analysis of 50 cm Theta Pinch and Comparison with Experiment	65
5.	Flux Conservation Method of Analysis	67
6.	Development of a Self-Crowbarring, Load Isolated Spark Gap	69
VIII.	THOMSON SCATTERING DIAGNOSTIC SYSTEM FOR MEASUREMENT OF CONVECTIVE ELECTRON VELOCITIES	74
1.	Introduction	74
2.	Abstract	74
3.	Velocity Determination from Thomson Scattered Signals	75
4.	Optimization of Signal to Noise Based on Wavelength Examined at Detectors	77

5.	Comparison of Optimized Wavelength and Shifted Peak Techniques	78
6.	Measurements of Density, Temperature and Pressure, and Inferred Plasma Loss Velocity on a Theta Pinch Experiment	79
7.	Thomson Scatter Techniques for the Direct Indication of Flow Velocity	79
8.	Scattering Physics and Data Reduction for Laser Velocity Technique	83
IX.	DEVELOPMENT OF A Nd-GLASS LASER SYSTEM FOR LOW DENSITY DIAGNOSTICS	87
1.	Introduction	87
2.	Technical Introduction	87
3.	Description of Thomson Scattering System Performance	88
4.	Definition of Application of the Diagnostic	90
X.	ZERO DIMENSIONAL MODELING OF FIELD-REVERSED THETA PINCH MACHINES	92
XI.	PARTICLE AND ENERGY LOSS FROM A COLLISIONLESS PLASMA	101
XII.	COOPERATIVE EXPERIMENTAL EFFORTS WITH OTHER LABORATORIES	108
1.	Plasma Pressure Measurements in the ZT-S Toroidal Reversed Field Pinch	108
2.	Particle Loss Measurement in the End Region of the FRX-A Compact Torus	108
3.	Center Cell TMX Plasma Pressure Measurements	109
XIII.	REVIEW OF FACULTY AND STUDENT PARTICIPATION	111
XIV.	PROJECT REFERENCES	112
1.	Reports	112
2.	Publications	113
3.	Presentations	113
	REFERENCES	116

LIST OF FIGURES

		<u>Page</u>
Figure 1	Effective Plasma Column Radii, r_{eff} versus Time	5
Figure 2	Reconstruction of Magnetic Field Structure and Current Sheath Position for $t = 0.8 \mu s$ and $t = 1.0 \mu s$	7
Figure 3	Reconstruction of Magnetic Field Structure, Current Sheath Position, and Ionization and Pressure Fronts at $t = 1.2 \mu s$ and $t = 1.5 \mu s$	8
Figure 4	Magnetic Field Structure, Current Sheath Position and Ionization and Pressure Fronts at $t = 1.7 \mu s$ and $t = 2.0 \mu s$	9
Figure 5	Electron Density Profiles at $t = 2.0 \mu s$	12
Figure 6	Electron Density Profiles at $t = 5.0 \mu s$	13
Figure 7	Radial Profiles of Impact Pressure and Axial Velocity at $t = 2.0 \mu s$	14
Figure 8	Radial Profiles of Impact Pressure and Axial Velocity at $t = 5.0 \mu s$	15
Figure 9	Local Electron Line Densities as a Function of Axial Position for Variable Times	16
Figure 10	Local Electron Line Density as a Function of Time at Several Axial Locations	19
Figure 11	Comparison of Experimental (Piezoelectric) and Computer Simulated Plasma Radius ($B_e = \text{Biot-Savart all } z$) for Scylla I-C	25
Figure 12	Scylla IV-P Midplane Temperatures with Exponential Axial Velocity	26
Figure 13	Scylla IV-P Midplane Energy Line Density with Exponential Axial Velocity	28
Figure 14	Time History of Scylla IV-P Total Electron Inventory (Uniform Profile)	29
Figure 15	Scylla IV-P Exhaust Region Stagnation Pressures at $t = 5 \mu s$	30
Figure 16	Electron Temperature versus Time; Thomson Scatter Results (+) Displayed with O-D Code Results	39

		<u>Page</u>
Figure 17	Axial Distribution of T_e from Thomson Scatter for Several Times in the Column Lifetime	41
Figure 18	Radial Temperature Distribution from Thomson Scatter for Several Times at $Z = 34$ cm	42
Figure 19	Radial Temperature Distribution from Thomson Scatter for Several Fixed Times at $Z = 37$ cm	43
Figure 20	Axial Variation of Flow Velocity at Several Times in the Loss Event	45
Figure 21	Comparison of Mid-Coil Temperature Measurements with Rotational O-D Code Predictions	53
Figure 22	Comparison of Electron Temperature Observations with Code Predictions Including Rotation and Without Rotation, Initial $T_e = 14$ eV	54
Figure 23	Mid-Coil Electron Line Density versus Time, $T_{e1} = 14$ eV and 0.4 μ s Delay Time Included	55
Figure 24	Comparison of Experimental and Predicted Values of Electron Inventory versus Time	56
Figure 25	Indication of Plasma Radii from O-D Code, Luminosity as a Function of Time, with Magnetic Probe and Thomson Scattering Data Points	60
Figure 26	Radial Profiles of n_e from O-D Code and Experiment at $t = 2.04$ μ s	61
Figure 27	Comparison of Predicted and Experimental Magnetic Field Values for Mirror Coils	64
Figure 28	B_z Field on Axis, 50 cm Theta Pinch	66
Figure 29	Comparison of Analytical Methods with Experiment with a Geometric Mirror Ratio of 1.36	70
Figure 30	Geometries of Magnetic Crowbar and Integrated Switch and Crowbar	71
Figure 31	Performance of Integrated Switch and Crowbar: Load Current (Parameters Are Trigger Pin Position, H, and Capacitor Voltages)	73
Figure 32	Scattering Geometry for Velocity Measurement	76
Figure 33	Experimental Geometry and Diagnostics for Flow from Theta Pinch	80

	<u>Page</u>
Figure 34	Density and Temperature History At $z = 13.5$ cm 81
Figure 35	Pressure and Reference Velocity History At $z = 13.5$ cm . 82
Figure 36	Thomson Scatter Layout and Optics Diagram for Electron Velocity Determination 84
Figure 37	Comparison of Velocity from Thomson Scatter with Reference Velocity 86
Figure 38	$n(r)$ versus r 92
Figure 39	B Line Behavior 96
Figure 40	Comparison of Experimental and O-D Predictions of Electron and Ion Temperatures for FRX-B 97
Figure 41	Comparison of Experimental and O-D Predictions of Ion Inventory for FRX-B 98
Figure 42	Comparison of Experimental and O-D Predictions of the Maximum Density for FRX-B 99
Figure 43	The reduced distribution functions $g_0(1/2, v, \tau)$ as functions of velocity at three different values of τ . The vertical arrows indicate the value of the average flow velocity $\bar{v}$ at $s = 1/2$ and the indicated values of τ . (a) At $R = 1.0$, the untrapped distribution. (b) At $R = 1.2$, the trapped (dotted line) and untrapped (solid lines) distributions 103
Figure 44	The ion thermal flux density at $s = 0.51$ as a function of time. The solid lines represent the case $R = 1.0$ and the dashed lines represent $R = 1.2$ 105
Figure 45	The ratio of the thermal flux to the kinetic energy flux at $s = 0.51$ as a function of time. The solid lines represent the case $R = 1.0$ and the dashed lines represent $R = 1.2$ 106

LIST OF TABLES

	<u>Page</u>
Table I. Basic Experimental Parameters	34
Table II. Comparison of Expansion Wave Arrival Times	44
Table III. Comparison of Measured and Characteristic Flow Velocities at the Throat	46
Table IV. Functional Forms for Constants in the Rate Equations .	50
Table V. Active Magnetic Mirror Characteristics	65
Table VI. 50 cm Long Theta Pinch System Characteristics	67
Table VII. Laser (Apollo Model 35, Ruby 6943 Å) Characteristics .	83
Table VIII. Detector Characteristics	83
Table IX. Significant Parameters of the Velocity Measuring Experiment	86

ABSTRACT

Experimental and analytical studies of particle and energy loss at the ends of a linear theta pinch have been carried out. A study of transients occurring in the formation of reversed trapped fields within the coil, and of transients in the end region of a 25 cm long device was completed. A 1-D code has proven to be highly accurate in describing loss events and defining transport mechanisms in different experiments and is described here. A study of loss along field lines in a 50 cm long device has generated new information on loss velocity, axial and radial temperature gradients, and has established an initial effort in understanding thermal loss to the walls. Rotation and parallel trapped fields have been added to the existing 0-D code. A new technique crowbar switch and magnetic field prediction code have been developed. Direct measurement of electron velocity with Thomson scattering was accomplished experimentally. A Nd-glass laser system, frequency doubled, is being developed for low density diagnostics. Theoretical results that accurately predict confinement in FRX devices are described.

I. INTRODUCTION

This report presents the results of progress made since the last report in February, 1979, through June of 1980. There are two unique aspects of this report. First, the period of the report was extended due to the transition to fiscal year funding. Second, this period saw the completion of three Ph.D. programs of study and research. This latter point is worth noting, since it reflects the fact that an exceptionally large volume of work is being reported here. Clearly, only a few interesting points from each of these studies will be presented in this progress report; the bulk of the detailed results will be left to thesis reports and journal articles.

This progress report, in a number of ways, can be categorized as being the comprehensive report on the studies of end loss along field lines and from open-ended configurations. There are a large number of new results in this work, and it can be proposed that the physics of these type of end loss has been defined. Further, this report can also be categorized as being the initial report on several new areas of concentration; these were begun much earlier, but now will become the primary focus of this project. Specifically, the emphasis of the study was actually shifted in summer 1979 to the study of plasma wall interactions and the related energy loss, and to the study of Thomson scattering diagnostics that can be used to make local determinations of electron densities in the range $10^{10} - 10^{13} \text{ cm}^{-3}$. Both of these problem areas are of universal interest in fusion plasma physics. The end wall energy loss studies on TMX (and MFTF-B), diverters such as PDX, and PRX-C involve convection along field lines and are of interest in our present and future work. Generally speaking, loss which occurs across field lines in closed field devices has the same fundamental physics of plasma interaction at the wall. The need to study the low density, low energy wall interactions is needed in any case, and this is being pursued.

The reporting of completed work begins with a discussion of transient loss from the 25 cm long theta pinch which initially had reversed trapped fields. Unique results of trapped field closure and dynamics, transient particle loss from within the coil, waves in the end region,

plasma rotation effects, and most importantly, a definition of the formation of an effective end of the plasma column within the coil are presented.

The discussion of the application of a I-D code complete with wall boundary conditions, diffuse profiles, and viscosity is given in section III. Numerous detailed descriptions are given, but in general, there is an excellent prediction of loss events and agreement with available experimental data. These results do appear to allow the desired identification of transport mechanisms and their models that are active in controlling loss events.

The studies of particle and thermal loss in the 50 cm long theta pinch with collisional plasma have produced several exceptional results. There are clear indications of rarefaction waves and their relationship to the definition of the flow velocity history at the ends of the pinch. The proper identification of the significance of sonic velocity has been made. A unique determination of axial temperature variation within the coil and in the end region has been coupled with that of radial variations of temperature and density in the end region. This work established a firm foundation on which to pursue further wall interaction studies.

Significant extensions to our development of definitive and predictive 0-D codes are included in sections V and VI. The effects of rotation have been included and are proving to be highly accurate in predicting transport and loss in the 25 cm experiment. The effects of parallel trapped field are also important aspects in analyzing data from our earlier 10 cm long theta pinch test device.

Important progress was made on two fundamental problems. The development of a simple, inexpensive, and reliable crowbar switch was completed. This will be an important part of present and future work. Further, the accurate prediction of the spatial distribution of magnetic fields in mirrors and mirror type coils added to pinch coils was accomplished. These efforts were under the guidance of Professor J. W. Robinson of the Electrical Engineering Department.

In some ways, landmark work was being accomplished in two new directions with Thomson scattering diagnostics. The principle of high

resolution detection of electron convection velocity was experimentally verified with our ruby system. Analysis, design, and procurement has been accomplished in order to alter the ruby laser system to accomodate a 20-40 J Nd-glass laser which will be frequency doubled for low density diagnostics.

Both principal investigators have been active in carrying out work supportive of research at major fusion laboratories, and brief discussions of these efforts are included in Sections X-XII.

11. TRANSIENT LOSS FROM A 25 cm LONG THETA PINCH WITH REVERSED TRAPPED FIELDS

(Heidrich, Jacoby, Robinson)

1. Introduction

The major aspects of this work have been well documented in earlier reports¹⁻³. Specifically, the general characteristics of the discharge apparatus, the diagnostics, and the phenomenological indications of physical events in the discharge plasma from data observations have been reported. A comprehensive, detailed report of the results of this effort will be presented in the near future in the Ph.D. thesis of J. Heidrich⁴. The present report will focus on several key results that have originated from the analyses of the data, as analysis has been the primary activity during the present report period.

The focus of this study has been two-fold: (1) What are the transient events that occur in and about the end-region of the theta pinch; and (2) How do these events originate from and influence the conditions within the pinch coil? This work has considerable significance at the present time due to the fact that reversed trapped field configurations were formed and these fields were present during the first 2 μ s period of the theta discharge. Due to the low plasma temperatures (15 eV), local probes could be immersed in the plasma. The temporal resolution of all diagnostics was better than 0.1 μ s. A unique opportunity to study the whole range of physical processes occurring during end loss was created and capitalized upon. The necessary facts needed to understand the experiment and some of the more important conclusions will be outlined.

2. Plasma Column Behavior

Diamagnetic loop signals were reduced to indicate effective column radius. The temporal sequence of events and some important phenomenological observations are presented in Figure 1, which graphs r_{eff} as a function of time. It should be noted that pinch occurs at $t = 1.1 \mu$ s, bounce is ended by 2 μ s, and the plasma lifetime is 5 μ s. Detailed consideration will first be given to the period between 0.8 and 2.0 μ s, at which time the reversed trapped field ceased to exist.

Figure 1 Effective Plasma Column Radii, r_{eff} versus Time

3. Magnetic Field Maps and Transient Flow Initiation

Figures 2 through 4 present reconstructions of the magnetic field structure in regions inside and outside the theta coil, along with some other diagnostic indications. Each figure has data for two distinct times; the upper half presents the earlier time. Cross-hatched areas are used to identify regions with reversed trapped flux, i.e. regions having axial components of the magnetic field in a direction opposite to the external magnetic field; $B_z = 0$, at the periphery of these cross-hatched regions. Selected field lines are illustrated by the solid lines; field strengths (kG) are illustrated at arrows on the lines. The positions of maximum azimuthal current density ($j_{\theta \max}$, the position of the current sheath) are shown; the numbers correspond to the magnitudes (A/cm^2).

The magnetic field structure during radial sheath implosion is illustrated in Figure 2. At $t = 0.8 \mu s$, a region of reversed magnetic field extended outside the theta coil. The field structure within this region is illustrated by the field lines drawn. At $t = 1.0 \mu s$ ($0.1 \mu s$ before radial pinch), the region of reversed field had clearly developed into a closed field structure at the end of the coil, to form a compact toroidal geometry. However, the radial field strengths associated with the closed field structure were a factor of 10 less than the strength of the driving field. Therefore, the closed field structure would appear to have had virtually no effect upon the flow of plasma from the coil. A tilt in the current sheath was evident at the edge of, and outside of, the theta coil. The position of this current sheath agreed with that of luminosity observed by side-on framing photographs.

The period after implosion between $t = 1.15 \mu s$ and $t = 2.0 \mu s$ was characterized by reversed trapped field, $m = 0$ column oscillations, plasma rotation and Rayleigh-Taylor fluting of the plasma column (Figures 3 and 4).

The upper half of Figure 3 presents the magnetic field structure $0.1 \mu s$ after pinch. The region of reversed field had moved farther into the end region; it extended to $z = -4$ cm. The magnitudes of the radial fields remained small compared to the driving magnetic field. Inside

Figure 2 Reconstruction of Magnetic Field Structure and Current Sheath Position for $t = 0.8 \mu s$ and $t = 1.0 \mu s$

Figure 3 Reconstruction of Magnetic Field Structure, Current Sheath Position, and Ionization and Pressure Fronts at $t = 1.2 \mu s$ and $t = 1.5 \mu s$

Figure 4 Magnetic Field Structure, Current Sheath Position and Ionization and Pressure Fronts at $t = 1.7 \mu s$ and $t = 2.0 \mu s$

the separatrix the total axial magnetic flux is zero; i.e., the closed magnetic field lines lie inside the separatrix. At $t = 1.5 \mu s$, in the lower half of Figure 3, flow of plasma from within the theta coil had begun. The region of reversed field remained extended to $z = -4.0 \text{ cm}$. Due to annihilation of reversed field, the separatrix moved closer to the axis of the coil. The position of the current sheath indicates that implosion was completed at $z = -5 \text{ cm}$; plane fronts of ionization and pressure existed just beyond $z = -5 \text{ cm}$. The reversed field region had almost dissipated by $t = 2.0 \mu s$ (Figure 4) at which time it was extended to $z = -1.3 \text{ cm}$.

After annihilation of reversed trapped field at $t = 2.1 \mu s$, there was loss of plasma within a forward magnetic field configuration. Diffusion of magnetic field into the plasma column was indicated by both the progression toward vacuum field structure and the decay in current sheath strengths throughout the system.

The phenomenology indicated by local magnetic field measurements is summarized as followed: (1) a distinct closed magnetic field structure formed at the end of the theta coil during sheath collapse; (2) the strength of the radial fields associated with the closed field structure were small compared to the strengths of the driving field, so the closed field did not affect the loss of plasma; (3) no discernable constriction of the flow (throat) was indicated from the position of the current sheath; (4) arrival of diamagnetic plasma by end loss was seen to exclude magnetic field in the end region; (5) gradual movement of the separatrix toward the axis and weakening of field gradients indicated field diffusion.

4. Radial Profiles of Electron Density, Pressure and Derived Velocity for Various Axial Locations at Several Times in the Loss Event

Several interesting features of the loss physics are evident by examination of the axial variations in electron density profiles. These profiles were derived from Thomson scattering determination of density at one radius, and the Abel inverted continuum intensity of light taken

at different chords. It will simply be noted that there was no loss from the coil prior to pinch time (1.1 μ s). For the latest time for which magnetic field was mapped (2 μ s, Figure 4) profiles of electron density are presented in Figure 5. That figure presents data during transient behavior, before quasi-steady loss was established. One of the more interesting observations is the fact that $n_e(-7.5 \text{ cm}) < n_e(-5) > n_e(-2.5)$. In other words, a local peak occurs at -5 cm, which is indicative of a wave or burst of charge in the end region. At a later time (5 μ s, Figure 6) there is a continuous decrease of density values with distance from the coil center. But, in the end region, there is also a definite pattern of mass on axis, mass concentration at higher radii, and low density at $r = 0.5$ cm. This appears to be clear evidence of the diverging magnetic field lines guiding the flow.

The complementary graphs of impact pressure and derived flow velocity, V_z , in Figures 7 and 8, show behavior similar to that indicated by electron density at $t = 2.0 \mu$ s, with $p(-7.5 \text{ cm}) \ll p(-5) > p(-2.5)$.

5. The Influence of Column End Formation on Loss Processes

Electron density profiles were integrated to produce local electron line densities (LELD); these are presented for a series of times in Figure 9. The LELD at $z = +6.25$ and -2.5 cm were constant throughout most of the loss event, whereas those at $z = +12.5$ cm decreased after 2 μ s. Thus, loss of plasma can be concluded to occur primarily in the region $+6.25 < z \leq +12.5$ cm. The large LELD for $z \leq -5.0$ cm after the ionization front passed was concluded to be due to the ionization of ambient background gas. The total electron inventory in the region $-2.5 \leq z \leq +12.5$ cm was obtained by two virtually independent methods. First, the local electron line densities were integrated from $z = -2.5$ to $+12.5$ cm using a linear interpolation. Second, the efflux of electrons, J , was determined from

$$J(t) = \int_0^{r=2\text{cm}} n_e(r,t) V_z(r,t) 2\pi r dr \quad (1)$$

evaluated at $z = -2.5$ cm. The time integrated efflux,

Figure 5 Electron Density Profiles at $t = 2.0 \mu\text{s}$

Figure 6 Electron Density Profiles at $t = 5.0 \mu\text{s}$

Figure 7 Radial Profiles of Impact Pressure and Axial Velocity at $t = 2.0 \text{ } \mu\text{s}$

Figure 8 Radial Profiles of Impact Pressure and Axial Velocity at $t = 5.0 \mu s$

Figure 9 Local Electron Line Densities as a Function of Axial Position for Variable Times

$$\xi(t) = 1.7 \int_{\mu s}^t J(t') dt' \quad (2)$$

was then subtracted from the initial electron inventory.

As noted previously, the LELD data at $z = +6.25$ cm and -2.5 cm were constant throughout most of the end-loss event. Therefore, based on continuity arguments, the plasma efflux measured at $z = -2.5$ cm was equal to the efflux at $z = +6.25$ cm. Consequently, the efflux measured at $z = -2.5$ cm can be compared to that predicted by the analytic end-loss theories, which calculate efflux from the effective end of an infinitely long coil.

Several theoretical models have been developed to describe the end-loss problem, including both collisional⁵⁻⁹ and collisionless¹⁰ models. The flow in the present experiment was collisional. An early MHD theory due to Taylor and Wesson (TW,5) considered sharp-boundary, steady-flow from a magnetic nozzle. To obtain a unique solution for the plasma efflux, a throat condition requiring that the pressure profile be a continuous monotonic decreasing function of axial position was chosen. This condition yielded a throat, or point of maximum contraction of the plasma, at which the flow was sonic. The resulting plasma efflux was shown to be a function of the density, area, sound speed, and β of the source plasma. Wesson (W,6) developed a sharp-boundary, transient, MHD theory in which plasma flow from the ends of a uniform plasma column was modeled. A similarity solution was found that predicted a rarefaction wave propagating from each end into the plasma column. The flow at the end of the plasma column was predicted to be sonic and significant magnetic constriction of this flow was predicted for $\beta \gtrsim 0.5$. The resulting plasma efflux was constant and again depended on the density, area, sound speed, and β of the source plasma. Later, Freidberg and Weitzer (FW,7) performed a transient MHD analysis that included the effects of diffuse profiles. This theory also predicted a constant plasma efflux. Most recently Brackbill, Menzel, and Barnes (BMB,9) performed a numerical solution to the nonlinear MHD equations for two-dimensional flow from a plasma column with an initially diffuse radial equilibrium. Again, a rarefaction wave propagating into the plasma column from each end was predicted; however,

the resulting efflux was found to be an exponentially decreasing function of time.

The experimentally derived values for efflux of electrons at $z = -2.5$ cm were: $5.0 \times 10^{17}/\mu s$, from the decay of the total integrated electron inventory versus time; and, $6.8 \times 10^{17}/\mu s$ for $2 \lesssim t \lesssim 3.5 \mu s$ and $5.3 \times 10^{17}/\mu s$ for $3.5 \lesssim t \lesssim 6 \mu s$, from the flux calculated using Equation (1). The theoretically derived values for efflux of electrons were obtained using $\bar{\beta} = 0.27$ (the radially-averaged plasma β at $t = 2.0 \mu s$ and $z = +12.5$ cm), $N_{e0} = 4.35 \times 10^{17}/cm$, and $C_0 = 4.1$ cm/ μs . The values derived were: $15.4 \times 10^{17}/\mu s$ from the Taylor-Wesson steady flow theory; $5.0 \times 10^{17}/\mu s$ from the Wesson sharp-boundary, transient flow theory; and $5.0 \times 10^{17}/\mu s$ from the Friedberg-Weitzner diffuse-boundary, transient flow theory. Although $\bar{\beta}$ decreased continually throughout the loss event, the theoretical results are applicable, since they are virtually independent of $\bar{\beta}$ for $\bar{\beta} \lesssim 0.6$. Clearly, the measured efflux agrees well with the transient theories.

6. Rarefaction Wave Phenomenon Identification of an Effective Length of the Plasma Column in the Theta Coil

It is of interest to determine whether evidence exists for the rarefaction wave phenomenon predicted by the transient theories. Both the transient sharp-boundary, flow theory of Wesson⁶ and the transient, diffuse-boundary, flow theories of Weitzner⁸ and Brackbill, et al.⁹, predict that the rarefaction waves move at the cusp velocity,

$$v_c = \sqrt{\frac{C_0^2 v_A^2}{C_0^2 + v_A^2}} \quad (3)$$

Here C_0 and v_A are the sound speed and the Alfvén velocity, respectively, in the undisturbed plasma column. Upon arrival of the rarefaction wave at a fixed axial position in the plasma column, plasma flow is predicted to begin. Consequently, decay in the local electron line density at a given axial position was expected to begin only after arrival of the rarefaction wave at that position. Referring to Figure 10, where the

Figure 10 Local Electron Line Density as a Function of Time at Several Axial Locations

LELD data at $z = +12.5$ cm, $+6.25$ cm, and -2.5 cm are graphed as a function of time, it can be inferred that any rarefaction wave must have existed between $z = +6.25$ and $+12.5$ cm at the end of radial collapse, $t = 1.15$ μ s, since there was virtually no change in the LELD at $z = +6.25$ cm between $t = 1.2$ and 2.4 μ s, when the LELD at $z = +12.5$ cm began to decay.

The position at which a rarefaction wave is expected to have been at $t = 1.15$ μ s can be calculated. Using midcoil plasma conditions at $t = 1.8$ μ s ($T_i = T_e = 14$ eV, $N_i = 3.3 \times 10^{16}$ cm⁻³, and $B_\infty = 12.0$ kG), $C_o = 4.1$ cm/ μ s and $V_a = 7.2$ cm/ μ s; thus, $V_c = 3.6$ cm/ μ s. Using this cusp speed and observing that the LELD at $z = +12.5$ cm began to decay at $t = 2.4$ μ s (arrival of the expected rarefaction wave), the leading edge of the rarefaction wave was expected to be $(3.6 \text{ cm}/\mu\text{s}) \times (2.4 \mu\text{s} - 1.15 \mu\text{s}) = 4.5$ cm from mid-coil at $t = 1.15$ μ s, which is between $z = +6.25$ and 12.5 cm.

The existence of a rarefaction wave between $z = +6.25$ cm and $+12.5$ cm at collapse is also indicated by comparison of the theoretical ratio of the LELD at the effective end of the theta coil (behind the rarefaction wave) to that in front of the rarefaction wave with the experimental ratio. To calculate the line density ratio expected from the analytic transient theories, $\bar{\beta} = 0.65$ (occurring at $t = 1.3$ μ s), was used. A ratio of 0.35 was obtained from the Wesson⁶ theory and 0.45 was obtained from the Freidberg and Weitzner⁷ theory. Before $t = 2.5$ μ s, the experimental ratio obtained by dividing the LELD at $z = +6.25$ cm by that at $z = 12.5$ cm was 0.38, which is in excellent agreement with the theoretical values. This agreement also substantiates the existence of a rarefaction wave between $z = +6.25$ and $+12.5$ cm at $t = 1.15$ μ s.

The effective end of the plasma column can be inferred from these observations. First, the leading edge of a rarefaction wave was at $z = +8.0$ cm at $t = 1.15$ μ s. Second, the theoretical ratio of the LELD at the effective end of the theta coil to that in front of the rarefaction wave agreed well with experimental ratio measured before $t = 2.4$ μ s of the LELD at $z = +6.25$ cm to that at $z = +12.5$ cm. Consequently, the effective end of the theta coil was indicated to be $z = +7.13 \pm 0.88$ cm, where the error was determined by the uncertainty with the $Z = +6.25$ cm and $+8.0$ cm

values. This gave an effective coil length of 10.75 ± 1.75 cm. This appears to establish a basis for the adjustment of theta pinch coil half lengths by approximately one tube diameter in order to compare loss results on different experiments (i.e. $L_{\text{eff}} \approx L - 2D$). With a discharge tube diameter of 9 cm, however, it is more closely matched with $L_{\text{eff}} = [L - 2(0.75)(D)] = 11.5$ cm.

7. Summary of the Observations of Plasma Loss from Within the Theta Coil

By $t = 1.15 \mu\text{s}$, an effective end of the plasma column formed at $z = 7.13 \pm 0.88$ cm from which a rarefaction wave propagated toward midcoil, as predicted by the transient MHD theories for plasma loss. After an initial transient period lasting until $t = 1.5 \mu\text{s}$, a steady flow, driven by an axial pressure gradient, expanded along the magnetic field lines in the region $+6.25 \geq z \gtrsim -5.0$ cm. This expansion led to supersonic flow in the end region. The measured efflux of plasma was consistent with that predicted by analytic, transient, MHD theories.

III. ONE-DIMENSIONAL COMPUTER MODELING OF PLASMA COLUMN BEHAVIOR (Stover)

1. Introduction

The purpose of the one-dimensional (1-D) axial computer modeling program is to develop understanding of the physical processes occurring during the operation of theta pinch devices by comparing experimental measurements with predictions from the codes. The codes which have been developed have been used to describe plasma behavior in the collisional Scylla I-C experiment¹¹ and in the hot collisionless Scylla IV-P¹² experiment.

In previous reporting of this research^{2,3} the basic equations for the model were presented. The plasma is considered to be a two-temperature single fluid which can flow along the discharge axis with a mass-averaged velocity. The equations include: a particle conservation equation; two momentum equations, one each for the radial and axial directions; two temperature equations, one for each species; a magnetic flux equation; and a specified description of the external magnetic field. The following physical phenomena were incorporated in these equations: work done on the plasma arising from motion of the plasma; electron and ion thermal conduction; viscous heating; resistive heating and flux change from resistivity; magnetic field curvature effects; and vacuum vessel sidewall and endwall interaction with the exhaust plasma.

The plasma was assumed to be separated from the driving vacuum magnetic field in a boundary region. Two plasma radial profiles were examined: a uniform profile where the plasma number density is independent of radius, and a diffuse profile where the plasma number density is a function of radius.

During the present reporting period, the influence of ion viscous heating was studied and was found to be very important in Scylla IV-P for $t > 13 \mu s$. Also, the diffuse radial profile was studied with an assumed parabolic profile of axial magnetic field. This is the first such 1-D fluid code, and it enables one to perform a self consistent calculation of ohmic heating, flux diffusion and magnetic curvature effects which result in a $(\underline{J} \times \underline{B})_z$ retarding force. Finally, the interaction of the exhaust plasma with the vacuum vessel sidewalls, neglected in the past,

has been added. Both viscous effects and thermal conduction loss to the walls have been included. Other boundary conditions, including interaction with a fixed temperature background gas and a fixed temperature end-wall have been discussed previously.³ The significant new results are presented in the next section.

2. Simulation Results

a. Scylla I-C Simulations

In a previous report³, which used the uniform density radial profile, it was shown that, up to $t = 7 \mu s$, computer simulations of midplane temperature, integrated on-axis number density, and total particle inventory were found to agree quite well when classical electrical resistivity was included. Ion thermal conduction was found to be negligible, while electron thermal conduction resulted in the heating of exhaust electrons to temperatures slightly higher than that of the ions. Electron temperatures inside the coil were not significantly affected by this thermal conduction. Finally, a rarefaction wave propagated from the end to the center with the cusp speed and arrived at a time which agreed with observations.

Simulations during the past year provided several indications. First, for the diffuse profile the rarefaction wave propagated slightly faster than for the uniform profile, arriving at the center almost $1 \mu s$ earlier. This did not lead to more rapid particle loss, however, because the average β was lower for the diffuse profile and because of the $(\underline{J} \times \underline{B})_z$ retarding force. Behavior of on-axis density and midplane temperature were unchanged. Overall, plasma profile effects were not found to have a great significance. Second, exhaust boundary conditions were varied and found to have negligible influence on plasma properties inside the compression coil. Both sidewall interactions and cold background pressure interactions on the exhaust front were examined. Viscous ion heating of the exhaust ions resulting from interaction with the vacuum vessel sidewall was found to be significant (30 eV); however, the upstream influence through the electrons was found to be negligible. Third, computer simulated plasma radii were found to agree reasonably well with experimental

1/e boundaries inside the end plane. Furthermore, experimentally inferred throat behavior inside the end plane was verified for a simulated driving magnetic field profile determined from the Biot-Savart law, assuming a uniform current in the pinch coil (Figure 11). For this case, a throat is formed between 7 cm and 10 cm inside the compression coil and the field decays as the endplane is approached. In the exhaust region the plasma 1/e radius diverges more rapidly than indicated by simulation. These results indicate that there was probably some interaction of exhaust plasma with overrun cold gas and that the driving magnetic field decays inside the compression coil as the endplane is approached.

b. Scylla IV-P Simulations

Scylla IV-P computer simulations were examined with the Scylla IV-P plasma defined by either radially uniform or radially diffuse plasma profiles. These simulation results were found to be strongly dependent on the assumed radial plasma profile, more dependent than the Scylla I-C experiment. The uniform profile Scylla IV-P plasma simulations yielded better overall agreement with experimental results despite experimental evidence indicating that the profile was indeed diffuse.

Midplane electron temperatures with uniform profile are predicted quite well for $t \gtrsim 5 \mu s$, assuming classical electron thermal conduction (Figure 12). Simulated electron temperature was too low when $t < 5 \mu s$, however, particularly near peak magnetic field. This suggests that electron thermal conduction energy loss from the plasma column may be flux limited. Theoretically predicted and experimental total plasma temperature ($T_e + T_i$) agreed rather well until the arrival of the rarefaction wave at midplane, $t \sim 13 \mu s$; simulated plasma temperature then began to decrease too rapidly. Ion viscous heating was examined as a heating mechanism to explain this discrepancy. From this exploration, there evolved an ion viscosity model which allows accurate simulation of both plasma temperature and electron temperature, as shown in Figure 12. The constant, C , characterizes the strength of the ion viscosity, with $C = 1$ representing classical ion viscosity at the center. Exponential decay of this value with axial displacement was required to prevent overheating in the exhaust.

Figure 11 Comparison of Experimental (Piezoelectric) and Computer Simulated Plasma Radius ($B_e =$ Biot-Savart all z) for Scylla I-C

Figure 12 Scylla IV-P Midplane Temperatures with Exponential Axial Velocity

Ion thermal conduction was examined using classical thermal conduction and using an ion thermal flux limiter. As shown in Figure 12, this leads to a rapid drop in ion temperature. As a consequence, we set $Q_1 = 0$ for the remainder of the simulations.

Simulated midplane energy line density also agrees well with experiment using this viscosity model (Figure 13). The simulation dropoff point, associated with significant axial expansion of midplane plasma, agrees well with the 7 μ s experimental value as a consequence of ion viscosity, which tends to smooth out the inward propagating rarefaction wave and significantly shorten the arrival time at the center. The inviscid dropoff point is 13 μ s. Simulated on-axis number density, representing a column average, and total particle inventory were found to agree reasonably well with experiment. End loss flow rates were simulated reasonably well (Figure 14) although the plateau in the total number of particles observed during the first 6 μ s of the discharge, attributed to collimation of the exhaust, could not be reproduced. Inability to simulate this plateau suggests that simulated exhaust front velocity is excessive during the starting transient.

Predicted exhaust plasma properties compared well with the limited experimental data. The simulated exhaust magnetic Reynolds number was sufficiently high, 10^4 , to justify the assumption that the magnetic field lines are convected downstream parallel to the exhaust flow. Furthermore, the electrons are sufficiently magnetized, $\omega_{ce} \tau_e \gg 1$, so that electron thermal conduction to the sidewalls could be neglected. Adopting this model, exhaust electron temperatures determined assuming heat conduction only parallel to the magnetic field into a fixed 5 eV background gas were found to be consistent with estimates inferred from spectroscopic and Thomson scattering diagnostics. Exhaust electron temperatures obtained assuming zero heat conduction to the background gas were found to be too high. Predicted exhaust stagnation pressures which would be measured by a stagnation pressure probe compared overall rather well with piezoelectric pressure probe stagnation pressure measurements with best agreement occurring within 10 cm of the compression coil exit plane (Figure 15). Plasma expansion to the side wall of the exhaust chamber occurred at 40 cm from

Figure 13 Scylla IV-P Midplane Energy Line Density with Exponential Axial Viscosity

Figure 14 Time History of Scylla IV-P Total Electron Inventory (Uniform Profile)

Figure 15 Scylla IV-P Exhaust Region Stagnation Pressures at $t = 5 \mu\text{s}$

the end of the compression coil, consistent with observed plasma-sidewall interaction.

The diffuse profile inviscid energy line density dropoff time compares well with experiment because the rarefaction wave midplane arrival time is only 7 μ s. Following wave arrival, however, both plasma temperatures and energy line density decay too rapidly, at a rate which is greater than that for the uniform profile because of the higher magnetic flux embedded in the diffuse plasma profile. Diffuse profile simulation results improved significantly when ion viscosity and magnetic field curvature effects were included, but the electron thermal conductivity had to be decreased by a factor of 5 below classical to get good agreement with experimental electron temperatures. The field curvature effect through the $(\underline{J} \times \underline{B})_z$ term was very important in reducing the particle loss rate. Nonetheless, decay of total particle inventory occurred slightly rapidly.

Overall comparison of the diffuse and uniform profile Scylla IV-P simulation results indicates that plasma properties can be best simulated for this machine by assuming plasma behavior to be dominated by a dense uniform plasma core with a characteristic number density defined by the on-axis number density.

Considering that $\lambda_i/L \sim 1$ for the Scylla IV-P plasma, it is somewhat surprising that the collisional fluid model adopted here can be satisfactorily used to describe Scylla IV-P plasma behavior. Specifically, the plasma ions can be described as fully isotropic, and ion viscous heating, predicted on small ion-ion mean-free paths, can be used to successfully model ion temperatures. Such fluid-like behavior suggests that the ion cyclotron velocity space instability, predicted to occur in high β devices by Davidson and Ogden¹³, may be excited in the Scylla IV-P plasma column.

IV. PARTICLE AND THERMAL LOSS PROCESSES AT THE ENDS OF A 50 cm LONG COLLISIONAL THETA PINCH

(Jacoby, Heidrich, Robinson)

1. Introduction

Previous reports of this effort^{2,3} have documented bank engineering and the analytical definition of measurable loss variables. During the present reporting period, the experimental work has been completed, data has been reduced and a significant amount of analysis carried out. The details of this work will be reported in the forthcoming Ph.D. thesis of B. Jacoby¹⁴. A brief summary of some of the more important aspects of the experiment and of the results will be presented.

2. Abstract

The plasma was generated with a 40 mT D₂ fill in a 3.8 cm radius discharge tube; 80 percent z-preionization was followed by a main discharge that produced a 23 kG peak field in 4.65 μ s. The electron density and temperature in the column at the end of a dynamic implosion was characterized by $1.5 \times 10^{16} \text{ cm}^{-3}$ and 20 eV, respectively. This was followed by adiabatic compression simultaneous with the particle and energy loss of interest. The diagnostics employed in this experiment were Thomson scattering, continuum spectroscopy, local magnetic field probes, local pressure probes, and diamagnetic loops. Axial temperature and density profiles were mapped from the coil into the end region. At positions in the end regions 9 and 12 cm from the coil end, plasma wall contact occurred; a radial scan of temperature and density using Thomson scattering and spectroscopy was made to clearly identify thermal loss to the discharge tube walls.

3. Major Outstanding Particle and Thermal Loss Questions

Problems that remain to be resolved in order to understand loss physics require knowledge of: (1) velocity of plasma leaving the system, and whether it is related to sound velocity, Alfvén velocity, or cusp velocity; and (2) energy loss. Regarding the latter, there are several

questions relating to: (1) conduction mechanisms--gradients in Z or R ; (2) plasma interactions with discharge tube walls, and (3) Hobbs and Wesson's¹⁵ prediction of sheath inhibition of thermal loss.

Data that had been gathered in earlier experiments were not complete enough to clarify the basic physics, but have served to orient this study. Specifically, the most complete results were reported from several different devices. Scylla I-C¹¹ was a 1 m long collisional experiment. There were: (1) data from diamagnetic loops located axially along the coil; (2) axial holography, and (3) local pressure measurements. A 50 cm long theta pinch experiment was conducted at G.E. Research Laboratory.¹⁶ There were measurements with: (1) axial Thomson scattering; (2) center plane diamagnetic loop; and (3) image converter camera photographs of plasma diameter at axial positions. The 25 cm long theta pinch results reported in part II of this work were carried out with initial reversed trapped fields, but the results are informative for loss physics studies, in general.

The data needed to identify loss physics will now be outlined. In order to determine radial and axial density variations in the coil and end region, we used: (1) Thomson scattering on-axis; (2) continuum spectroscopy for radial density variation; and (3) Thomson scattering for radial variation in the end region. The radial and axial temperature variations were determined with: (1) small radial variation presumed in the coil; (2) Thomson scattering for axial variation; and (3) Thomson scattering for radial variation in the end region. The energy line density decay in the coil was indicated by: (1) an axial survey of diamagnetic loops; and (2) Thomson scattering with continuum spectroscopy to get $\int 3/2 NkT 2\pi r dr$. In order to determine particle inventory decay in the coil, we used: (1) Thomson scattering with continuum spectroscopy to get $\int N 2\pi r dr dz$; and (2) pressure probe measurements to get flux from the coil. Finally, to clarify electron conduction energy flux to the discharge tube walls, we measured: (1) Thomson scattering for axial variation both in and outside of the coil; and (2) Thomson scattering for radial variation in the end region. The basic parameters that characterized the experiment are given in Table I.

Table I. Basic Experimental Parameters

- I. Geometry

Coil Length: 50 cm Coil I.D.: 10.5 cm Tube I.D.: 7.62 cm
- II. Preionization System: RF Coils Followed by a Z-Discharge
 - A. RF Coils: Number of coils - 2
 Location - 5 cm from Z electrodes
 Ring frequency - 20 mhz
 - B. Z Discharge: Half cycle time - 5 μ sec
 Peak current - 24.2 kA
 Type of circuit - Marx
 Equivalent capacitance - 2.33 μ F
 Equivalent charging voltage - 36 kV
 Discharge path - 3 ft.
- III. Main Bank: Delay from end of P.I. pulse - 5.0 μ sec
 Charging voltage - 18.0 kV
 Total system capacitance - 232.4 μ F
 Total system inductance - 24.5 nH
 Coil inductance - 18.6 nH
 Peak driving magnetic field - 23.2 kG
 Peak current - 1.05 MA
 Quarter cycle time - 4.75 μ sec
 Half cycle time - 10.0 μ sec
- IV. Fill Gas: Deuterium at 40 mT
- V. Plasma Parameters in Coil: Peak temperature ($T_e = T_i$) - 37.4 eV
 Peak electron density on axis -
 $5.02 \times 10^{16} \text{ cm}^{-3}$
 Preionization fraction - 68 percent
 Implosion time - 0.80 μ sec
 Column 1/e radius - 0.90 cm
 Plasma on axis - 0.32

4. Determination of Effective Column Length and Minimum Radius of Loss Throat

Diamagnetic loop data were taken at axial positions of $z = 0, 6.5 \text{ cm}, 12.6 \text{ cm}, 18.4 \text{ cm}$ and 21.7 cm . Graphs of the effective excluded flux radius,

$$\pi r_{\text{eff}}^2 B_{\text{vac}} = \Phi_{\text{excluded}} \quad (4)$$

for variable axial positions showed definite throat formation. Using a spline fitting interpolation routine, the minimum position was determined to lie between 18.4 cm to 18.7 cm from midcoil. Accordingly, an average value of 18.55 cm was indicated as the axial throat position.

Continuum radiation profiles along chords were also taken at axial positions of $z = 0 \text{ cm}, 6.5 \text{ cm}, 12.6 \text{ cm}, 18.7 \text{ cm}$, and 28 cm . This data was then Abel inverted to get a relative continuum profile as a function of radius. Since the continuum is Bremsstrahlung, one has

$$n_e^2 / \sqrt{T_e} = kC(r) \quad (5)$$

where $C(r)$ is the value of relative continuum radiation measured and K is the proportionality constant. Presuming that $T_e^{1/4}$ does not vary significantly over the plasma column cross section, then a relative density profile can be arrived at¹⁷

$$n_e = (T_e)^{1/4} [C(r)]^{1/2} \quad (6)$$

The relative density profile so derived was least squares fitted to a Gaussian profile. The resulting Gaussian radii indicated that a throat formed at a position of 18.7 cm .

5. Particle Loss--Experiment and Theory

Using continuum profiles to obtain relative density profiles, and Thomson scatter results to normalize these density profiles, the total particle inventory in the coil could be determined. Thomson scattering was performed at a number of axial positions in order to map the time history and axial profiles of densities and temperature at $r = 0$. With

the knowledge of n_e and T_e , the relative continuum profiles were normalized at each of the axial positions where data were taken. With absolute density profiles available, the total particle inventory in the machine as a function of time was found from

$$N(t) = 2 \int_0^{L_{\text{eff}}} dz \int_0^{3.81 \text{ cm}} 2\pi r n_{\text{exp}}(r, z, t) dr \quad (7)$$

where L_{eff} is the machine effective half length from the throat position. $N(t)$ was graphed as a function of time to determine the decay and loss factor.

End loss theories⁵⁻⁸ presume a constant magnetic field and constant source conditions, with the exception of the work of Brackbill, et al. This is reasonably satisfied during the period between 4 μ s to 7 μ s in this device. During this period, the magnetic field undergoes moderate increase and decrease about its peak value, and the plasma is not heated or compressed.

The total particle inventory did decay with a distinct exponential character, and an e-folding time of $\tau_{\text{exp}} = 5.18 \mu$ s. To compare with theoretical results, an end loss parameter⁷ χ was determined as

$$\chi = \tau_p / \frac{L}{2} \sqrt{\frac{m_1}{2(T_e + T_i)}} \quad (8)$$

For the 50 cm theta pinch, $\tau_p = 5.18 \mu$ s, $L/2 = 18.6$ cm, $m_1 = 3.34 \times 10^{-24}$ gm, $T_e = T_i = 33.4$ eV, and $\chi_{\text{exp}} = 2.23$. The average beta on axis, β_a , at midcoil for this period of time was $\beta_a = 1.86$. A theoretical χ from Brackbill's code⁹ was determined to be $\chi_{\text{theo}} = 2.6$, giving best agreement.

6. Thermal Loss--Experiment and Theory

a. Experimental Determination--Thomson Scatter and Continuum

As noted above, absolute density profiles were available. Presuming constant temperature in radius, the temperature from Thomson scatter was used to evaluate

$$E_T(t) = 6 \int_0^{L_{\text{eff}}} dz kT(z, t) \int_0^{3.81} \pi r^2 n_e(r, z, t) dr \quad (9)$$

where $E_T(t)$ is the total energy in the machine, l_{eff} is the effective machine length and the discharge tube radius was 3.81 cm. Performing these integrations, graphing the result on semi-log axes and then least squares fitting the result to an exponential produced a decay time, $\tau_{E_1} = 3.02 \mu\text{s}$.

b. Experimental Determination--Diamagnetic Loop

The energy line density as a function of time can be derived from the diamagnetic loop signal when the magnetic field outside the plasma column is known as a function of time. Briefly

$$E_L(t) = \frac{3}{2} \pi \int_0^R 2r \frac{1}{8\pi} [B_{\text{vac}}^2 - B_{\text{in}}^2(r)] dr \quad (10)$$

$$E_L(t) \approx \frac{3\pi}{2\pi} B_{\text{vac}} \int_0^R [B_{\text{vac}} - B_{\text{in}}] 2r dr \quad (11)$$

$$E_L(t) \approx \frac{3}{8\pi} B_{\text{vac}} S_{\text{Dia}}(t) \quad (12)$$

where E_L is the energy line density, $B_{\text{in}}(r)$ is the field inside the plasma column, and $S_{\text{Dia}}(t)$ is the diamagnetic loop signal. Using the diamagnetic loop signal at the midcoil, and fitting the resulting energy line density to an exponential, results in a decay time of $\tau_{E_2} = 3.04 \mu\text{s}$.

c. Energy Loss Due to Particle Loss

As previously developed³,

$$\tau_{E_p} = \frac{3}{5} \tau_p \quad (13)$$

where τ_E is the energy decay factor and τ_p is the particle decay factor. Using the experimental result for particle loss on a τ_p of 5.18 μs , $\tau_{E_p} = 3.11 \mu\text{s}$.

d. Energy Loss Due to Conduction

With densities of $2 \times 10^{16} \text{ cm}^{-3}$ and temperatures of 30 eV, the transport processes in the plasma column are collisional. Thus, for energy loss due to thermal conduction

$$\left. \frac{dE}{dt} \right|_{th} = 2 \int_0^{3.81} 2\pi r dr K_{lle} \left. \frac{\partial T_e}{\partial z} \right|_{z=l_{eff}} \quad (14)$$

where

$$K_{lle} = 3.1 \times 10^9 \frac{T_e^{5/2}}{2nA} \frac{\text{erg}}{\text{eV-cm-sec}} \quad (15)$$

K_{lle} is the electron thermal conduction coefficient along magnetic field lines. Using Thomson scattering results for n_e and T_e and continuum profiles for column radii, the equations above were evaluated. The decay time for energy due to thermal conduction is $\tau_{Eff} = E_{TOT}/(dE/dt)_{th} = 2.52 \mu s$.

e. Comparison of Theory and Experiment

The theoretical value of energy loss due to convection and conduction is $\tau_E = \tau_{Ep} \tau_{Eth}/(\tau_{Ep} + \tau_{Eth}) = 3.07 \mu s$. The average value measured was $\tau_E = 3.03 \mu s$, so the agreement is good. It can be expected that in the thermal loss from this device, no anomalous processes are active.

f. Computer Simulation Determination of Thermal Conduction Coefficient

A zero-dimensional computer code¹⁸ was used in conjunction with experimental studies to examine the time dependence of column averaged quantities. It was found that the time history of the column temperature was sensitive to changes in the numerical value of the thermal conduction coefficient, K_{lle} . Thus the history of temperature provided by Thomson scatter results was graphed with the predicted history from code results. The latter was done for three cases: K_{lle} , $2 \times K_{lle}$, $3 \times K_{lle}$, $1/2 \times K_{lle}$, and $1/3 \times K_{lle}$. As can be seen in Figure 16 the value K_{lle} gives the best agreement.

7. Temperature Gradients in the End Region and Thermal Insulation at the End Region Walls

The electron temperature on center line was measured with Thomson scatter diagnostics at axial positions from midcoil into the end loss

Figure 16 Electron Temperature versus Time; Thomson Scatter Results (+)
Displayed with O-D Code Results

region. Results are presented in Figure 17. It should be noted that the temperature decreases with axial location, for $z > 8$ cm.

Hobbs, and Wesson¹⁵ analytically showed that the presence of a Debye sheath at walls could provide a thermally insulating barrier due to the limitation of electron flux to the wall. They found two limiting cases for energy flux to the wall:

$$Q = \frac{1}{4} n_e \sqrt{8 kT/m} 2kT (0.16) \text{ at } \Gamma = 0 \quad (16)$$

and

$$Q = \frac{1}{4} n_e \sqrt{8 kT/m} 2kT (0.351) \text{ at } \Gamma = \Gamma_e \quad (17)$$

where m is the electron mass and Γ is the ratio of secondary electron emersion flux to primary electron flux. Γ_e is the value of Γ when space charge limiting occurs.

At a position $z = 37$ cm from midcoil, the loss plasma reached the walls of the discharge tube. Thomson scattering was performed at $r = 0$ cm, 1.1 cm and 2.0 cm for $z = 34$ and $z = 37$ cm; electron temperatures are presented in Figures 18 and 19. From this information, an estimate of the thermal energy conducted to the walls was arrived at as

$$\frac{dE}{dt} \approx K_{lle} \frac{dT}{dz} 2\pi r_t L \quad (18)$$

where r_t is the discharge tube radius, L is the length of wall the plasma contacts and K_{lle} is the electron conduction coefficient along field lines. Using average experimental values it is indicated that

$$\frac{dE}{dt} \approx 10^{22} L (\text{eV/s-cm}) \quad (19)$$

Using the flux formula for $\Gamma = 0$, since this provides the lower flux limit appropriate for this plasma,

$$\left. \frac{dE}{dt} \right|_{\text{sheath}} \approx 10^{23} L (\text{eV/s-cm}) \quad (20)$$

The flux indicated by experiment is lower than that allowed by a sheath, which was to provide a lower limit on flux. However, the notion of sheath reduction of thermal flux is related to considerations of mean

Figure 17 Axial Distribution of T_e from Thomson Scatter for Several Times in the Column Lifetime

Figure 18 Radial Temperature Distribution from Thomson Scatter for Several Times at $Z = 34$ cm

Figure 19 Radial Temperature Distribution from Thomson Scatter for Several Fixed Times at $Z = 37$ cm

free path, i.e. collisionless sheaths, which are not correct here. Also, there are indications that sheath effects on thermal flux are limited to $\tau_0/\tau > 1$, where τ_0 is the characteristic time for an electron to translate across the space between walls at $x = \pm L$. For times, τ , long compared to τ_0 , no sheath effect is expected and normal thermal conduction will take place. That, in fact, seems to occur, as there is little discrepancy between the computer code with classical thermal conductivity and the experimental results. The code used $T_e = 0$ at walls and appears to be a correct specification, with no sheath effect indicated.

8. Indicated Wave and Flow Velocities During the Loss Event

a. Expansion Wave Velocity

The expansion wave which moves into the pinch from the end is predicted to propagate at the cusp speed noted earlier,

$$v_c = v_A c / \sqrt{v_A^2 + c^2} \quad . \quad (21)$$

The expansion wave velocity has been determined experimentally from decay of line density, and the results are presented in Table II.

Table II Comparison of Expansion Wave Arrival Times

<u>Axial Position</u> <u>(cm)</u>	<u>Experimental Wave</u> <u>Arrival Time (μs)</u>	<u>Theoretical Wave</u> <u>Arrival Time (μs)</u>
2.5	0	0
18.7	1.6	1.05
12.6	2.1	2.10
6.5	3.7	3.15
0	4.2	4.10

b. Flow Velocity in the Loss Region

The plasma convection velocity as it escapes from the coil region and expands into the end region is presented as a function of axial position in Figure 20. Plasma velocity was determined from $V = (P_{\text{impact}} - n kT/nm)^{1/2}$.

Figure 20 Axial Variation of Flow Velocity at Several Times in the Loss Event

Note that the behavior is characterized by increasing then decreasing velocity with distance at any given time. This is indicative of expansion and subsequent interaction with background gas. The changes with time are indicative of one-dimensional, unsteady gas dynamic flow processes.

c. Flow Velocities at Throat

The throat position had been determined to be at $z = 18.6$ cm. The velocity (measured) was determined from pressure probe and Thomson scatter measurements and is compared with several characteristic velocities for the plasma in Table III.

Table III Comparison of Measured and Characteristic Flow Velocities at the Throat

Time (μ s)	V(measured) (cm/ μ s)	V(Alfven) (cm/ μ s)	V(sonic) (cm/ μ s)	V(cusp) (cm/ μ s)
2.0	4.11	9.07	16.5	7.95
3.0	7.71	11.7	15.2	9.27
4.0	8.66	13.9	14.1	9.90
5.0	11.6	17.8	13.0	10.5
6.0	12.4	19.8	11.9	10.2
6.5	11.2	19.2	11.5	9.87

It can be observed that: (1) the Alfven speed is not close to the measured speed; (2) sonic speed agrees with measured speed at later times, possibly indicating a "choked throat" condition in the classical sense; and (3) the cusp speed is in best agreement at earlier times and overall comes closest to the measured values. In general, it appears that loss at early times occurs at the cusp speed as a transient, and with time there is the progression of events to allow loss to occur at sonic speed in the steady state case.

V. THE INFLUENCE OF ROTATION ON THETA PINCH BEHAVIOR (McCowan)

1. Introduction

Rotation of plasma about the axis has been observed in theta pinches since 1961¹⁹⁻²⁵. Analyses have used a parameter, α , to represent the ratio of the rotational energy of an ion at the edge of the plasma to the thermal energy of an ionized atomic ion and electrons. In most of these cases the ratio of rotational energy to thermal energy, $\alpha < 1$. However, in the recent experiment reported by Heidrich⁴, the observed rotation was sufficiently large that the parameter $\alpha = m_i a^2 \omega^2 / 2T > 1$, where a is the plasma radius, ω is the rotation frequency, m_i is the ion mass, $T = T_i + 2T_e$ is the plasma temperature in energy units, and Z is the atomic number. For values of α this large, rotation makes a significant contribution to the radial pressure balance and therefore influences the radial profiles of the density and/or the magnetic field. To determine the importance of plasma rotation on the behavior of macroscopic plasma parameters, notably N , the total ion inventory, and T , the effect of rotation has been incorporated in the zero-dimensional (0-D) model of Stover, et al.¹⁸ (hereafter referred to as I).

We will first discuss the extension of the 0-D model to include plasma rotation. Also, since the experiments were performed with helium, atomic number corrections are introduced. Simulation results are then obtained and compared with experimental results.

2. The 0-D Model of a Rotating Column

The development of a 0-D model to describe the behavior of a linear theta pinch has been presented⁹. The notation adopted here is the same as that used in I, and the presentation is limited to the extensions to include the effects of rotation and non-hydrogenic ions.

The model consists of five first order differential equations. Four of the equations are derived from expressions for the time changes of electron and ion temperature, the total particle inventory, and the magnetic flux within the plasma. The fifth equation is obtained by assuming

radial pressure balance. The pressure balance equation, including the effect of rigid body rotation, is

$$\frac{B_e^2}{2\mu_0} = \frac{B_i^2(r)}{2\mu_0} + n(r)T + m_i \omega^2 \int_r^a n(r') r' dr' \quad (22)$$

where $n(r)$ is the ion density and B_e and $B_i(r)$ are the applied and internal magnetic fields. Solution of equation (22) for the density profile requires specification of the internal magnetic field profile. In I a parabolic field rising from $\zeta_a B_e$ on the pinch axis to B_e at $r = a$ was chosen. This form is retained for the present work. It is then possible to convert equation (22) to a differential equation and solve for $n(r)$ to obtain

$$n(r) = C_1 + C_2 r^2 - (C_1 + C_2 a^2) e^{-\alpha(1-r^2/a^2)} \quad (23)$$

where C_1 and C_2 can be expressed as

$$C_1 = \frac{2(1 - \zeta_a)^2 B_e^2}{\mu_0 m_i \omega^2 a^4}$$

$$C_2 = \frac{2\zeta_a(1 - \zeta_a) B_e^2}{\mu_0 m_i \omega^2 a^2} + \frac{4(1 - \zeta_a)^2 B_e^2 T}{\mu_0 m_i \omega^2 a^4}$$

For $\alpha \ll 1$, equation (23) reduces to equation (22) in I.

Following the method developed in I, but with the use of equations (22) and (23), and allowing for atomic number greater than one, the following set of equations is obtained:

$$\begin{aligned} \frac{dA_p}{dt} = & \frac{1}{k_5} \left[\frac{k_2}{B_e} - \frac{k_1(1 - \zeta_a)}{B_e} \right] \frac{dB_e}{dt} + \frac{k_3}{k_5} \left[-ZT_e \left(\frac{1}{\tau_{th}} \right) - T_i \left(\frac{1}{\tau_{th}} \right) - \frac{2}{3} \frac{(Z\epsilon_e + \epsilon_i)}{\tau_p} \right. \\ & \left. + \frac{(2T_e + T_i)}{\tau_p} + \frac{4\pi n(1 - \zeta_a)^2 B_e^2}{3\mu_0 n A_p} \right] + \frac{\bar{n}}{k_5 \tau_p} + \frac{8\pi k_1(1 - \zeta_a)^2 \eta_{\perp}}{k_5 \mu_0 A_p} \quad (24) \end{aligned}$$

$$\frac{dT_e}{dt} = (T_i - T_e) \frac{S}{\tau_{eqi \rightarrow e}} - T_e \left(\frac{1}{\tau_{th}^e} \right) - \frac{1}{\tau_p} \left(\frac{2}{3} \epsilon_e - T_e \right) - \frac{2T_e}{3A_p} \frac{dA_p}{dt} + \frac{4\pi\eta (1 - \epsilon_a)^2 B_e^2}{3\mu_0^2 n A_p^2} \quad (25)$$

$$\frac{dT_i}{dt} = (T_e - T_i) \frac{S}{\tau_{eqe \rightarrow i}} - T_i \left(\frac{1}{\tau_{th}^i} \right) - \frac{1}{\tau_p} \left(\frac{2}{3} \epsilon_i - T_i \right) - \frac{2T_i}{3A_p} \frac{dA_p}{dt}, \quad (26)$$

$$\frac{d\epsilon_a}{dt} = \frac{8\pi(1 - \epsilon_a)n_a}{\mu_0 A_p} - \frac{(1 + \epsilon_a)}{A_p} \frac{dA_p}{dt} - \frac{(1 + \epsilon_a)}{B_e} \frac{dB_e}{dt}, \quad (27)$$

and

$$\frac{dN}{dt} = \frac{-N}{\tau_p}, \quad (28)$$

where the shape factor is given by

$$S = \frac{2\pi}{\bar{n} n_a A_p} \left[\frac{(C_1 + C_2 a^2)^2 a^2}{4\alpha} (1 - e^{-2\alpha}) - \frac{C_1 a^4 (C_1 + C_2 a^2)}{\alpha^2} (\alpha + e^{-\alpha} - 1) \right. \\ \left. - \frac{C_2 a^2 (C_1 + C_2 a^2)}{\alpha} (1 - e^{-\alpha}) + \frac{C_1^2 a^6}{6} + \frac{C_1 C_2 a^2}{2} + \frac{C_1^2 a^2}{2} \right] \quad (29)$$

$\bar{n}$ and n_a are the average and on-axis densities, and $A_p = \pi a^2$ is the plasma cross sectional area. The coefficients ℓ_1 to ℓ_5 , which are rather complicated algebraic expressions, are shown in Table IV. The temporal behavior of T_i , T_e , ϵ_a , A_p , and N is obtained by numerically integrating equations (24) through (28) using Hamming's predictor-corrector fourth-order integration procedure.

3. Experimental and Computational Results

The theta pinch being discussed consisted of a 25 cm discharge coil with a 10.5 cm i.d. discharge chamber initially containing helium at 100 mTorr. The magnetic field peaked at 19.7 kG after a quarter cycle time of 4.6 μ s. Peak average densities of approximately 10^{16} cm^{-3} and peak temperatures of 18 eV were achieved. Thermal conduction was relatively unimportant because the electron thermal conduction time $\tau_{th}^e = 50\tau_p$.

Table IV. Functional Forms for Constants in the Rate Equations

$$\begin{aligned}
\ell_1 &= \frac{-16(1 - \alpha_a)B_e^2 T^2}{\mu_o m_i^3 \omega_a^6} (e^{-\alpha} - 1) - \frac{4B_e^2 T e^{-\alpha}}{\mu_o m_i^2 \omega_a^4} - \frac{4(1 - 2\alpha_a)B_e^2 T}{\mu_o m_i^2 \omega_a^4} - \frac{2\zeta_a B_e^2}{\mu_o a^2 m_i \omega^2} \\
\ell_2 &= \frac{16(1 - \zeta_a)^2 B_e^2 T}{\mu_o m_i^3 \omega_a^6} (e^{-\alpha} - 1) + \frac{8(1 - \zeta_a)B_e^2 T e^{-\alpha}}{\mu_o m_i^2 \omega_a^4} - \frac{8\zeta_a(1 - \zeta_a)B_e^2 T}{\mu_o m_i^2 \omega_a^4} \\
&\quad + \frac{2(1 - \zeta_a^2)B_e^2}{\mu_o m_i \omega_a^2} \\
\ell_3 &= \frac{16(1 - \zeta_a)^2 B_e^2 T}{\mu_o m_i^3 \omega_a^6} (e^{-\alpha} - 1) + \frac{4(1 - \zeta_a)^2 B_e^2 T e^{-\alpha}}{\mu_o m_i^2 \omega_a^4} + \frac{4(1 - \zeta_a)B_e^2 T e^{-\alpha}}{\mu_o m_i^2 \omega_a^4} \\
&\quad + \frac{2(1 - \zeta_a)B_e^2 T e^{-\alpha}}{\mu_o m_i \omega_a^2} - \frac{4\zeta_a(1 - \zeta_a)B_e^2}{\mu_o m_i^2 \omega_a^4} \\
\ell_4 &= \frac{-24(1 - \zeta_a)^2 B_e^2 T}{\pi \mu_o m_i^3 \omega_a^6} (e^{-\alpha} - 1) - \frac{4(1 - \zeta_a)^2 B_e^2 T e^{-\alpha}}{\pi \mu_o m_i^2 \omega_a^4} - \frac{8(1 - \zeta_a)B_e^2 T e^{-\alpha}}{\pi \mu_o m_i^2 \omega_a^4} \\
&\quad - \frac{2(1 - \zeta_a)B_e^2 T e^{-\alpha}}{\pi \mu_o m_i \omega_a^2} + \frac{8\zeta_a(1 - \zeta_a)B_e^2 T}{\pi \mu_o m_i^2 \omega_a^4} - \frac{(1 - \zeta_a^2)B_e^2}{\pi \mu_o m_i \omega_a^2} \\
\ell_5 &= \frac{\ell_1(1 + \zeta_a)}{A_p} - \ell_4 - \frac{n}{A_p} + \frac{2\ell T}{3A_p}
\end{aligned}$$

where τ_p is the particle confinement time; and ion and electron temperature were nearly equal since $\tau_p = 100\tau_{eq}$, with τ_{eq} the equilibration time.

The choice of initial conditions for the 0-D simulations was complicated by the absence of axially averaged data and the initial existence of reversed trapped magnetic field. The reversed field, a remnant of a theta preionization discharge, was annihilated 2 μ s after the initial application of the driving magnetic field. The experimentally determined plasma parameters at 2 μ s were used as the initial conditions for the 0-D modeling.

Spectroscopic data was obtained for the electron line density $N_e(a) = \int_0^a 2\pi n(r,z) r dr$ and for the electron temperature $T_e(a)$ at midcoil, quarter coil and several exhaust region positions. These data suggest that at $t = 1.5 \mu$ s after the initiation of the main bank a rarefaction wave is launched from an axial position just inside the quarter coil and arrives at the midcoil at $t = 2.4 \mu$ s. The implications of the data analysis are that there is an effective length of a source plasma of approximately 12.5 cm and the region between quarter coil and the end is a guide field region. For the computer simulations we have chosen a plasma length of 12.5 cm.

Although the code was written to describe average plasma behavior in the source, it is possible to use it for comparison with mid-coil observations. To do this we delay particle loss until the rarefaction wave arrives, then allow the density to decay with the average column decay rate. Convective energy loss is similarly delayed. Thermal conduction losses are unimportant. For this type of study, the initial conditions were chosen to be mid-coil values at $t = 2 \mu$ s. An initial plasma radius of 1.5 cm was used, the initial electron line density was $4.4 \times 10^{17} \text{ cm}^{-1}$, and the initial electron and ion temperatures were varied from 13 eV to 15 eV. The rotation frequency was deduced by several different methods to be $\omega = 3 \times 10^6 \text{ rad/sec}$. For the particle loss time we used

$$\tau_p = \frac{L}{2} \left[\frac{m_i}{2(T_e + T_i)} \right]^{1/2} \frac{\chi}{h(t - 2.4)}$$

where $h(t - 2.4)$ is a step function which gives the desired delay in particle loss, and χ is a scaling parameter which was set equal to 2.3, a value which is in close agreement with other pinch experiments⁹.

A comparison of observed mid-coil electron temperature behavior with computer simulations is shown in Figure 21. The sensitivity to the choice of initial electron temperature is clear. Both the 14 eV and 15 eV initial conditions give reasonable agreement with the data. The temperature rise is the result of ohmic heating and compression. The primary effect of an initial temperature increase is to exclude more magnetic field from the interior. This is reflected in the values of $\zeta = B_z/B_e$, where B_z is the on-axis field. This leads to a slightly greater ohmic heating input per particle.

The significance of ζ is more dramatically illustrated in Figure 22, where the $T_e = 14\text{eV}$ case is shown with and without rotation. Without rotation present the ohmic heating is not sufficient to cause the observed temperature rise.

The comparison of simulation electron line density with data is shown in Figure 23. The observed loss rate is somewhat faster than that predicted by the code. To achieve agreement with the data, a value of $\chi = 1.78$ would be needed. This led to electron temperatures which dropped off too rapidly at later times.

The influence of the choice of resistivity has been examined for an initial temperature of 13eV. The classical cross field resistivity²⁶ was used in the earlier runs; when this was doubled, the particle loss rates were not significantly altered, and the peak electron temperature was increased from 16eV to 16.5eV. The reason for this small effect is that radial expansion of the column introduced a cooling effect which compensated for the extra ohmic heating. From the available data it is not possible to accurately identify the value of the resistivity.

The behavior of the total electron content in the coil, plus an additional 2.5 cm in the exhaust, has been determined experimentally from pressure probes and from spectroscopic measurements. The results are shown in Figure 24. To obtain the theoretical value it was assumed that the electron content can be written $N = N_1 + N_2$, where N is the number

Figure 21 Comparison of Mid-Coil Temperature Measurements with Rotational O-D Code Predictions

Figure 22 Comparison of Electron Temperature Observations with Code Predictions Including Rotation and Without Rotation, Initial $T_e = 14$ eV

Figure 23 Mid-Coil Electron Line Density versus Time, $T_{e1} = 14 \text{ eV}$ and $0.4 \mu\text{s}$ Delay Time Included

Figure 24 Comparison of Experimental and Predicted Values of Electron Inventory versus Time

in the source (12.5 cm), and N_2 is the number between the quarter coil and 2.5 cm outside the coil. It has been found experimentally that for $2 \mu\text{s} < t < 4.5 \mu\text{s}$ the values of N_2 were approximately constant. During this time, the line density at quarter coil was approximately constant while the line density at mid-coil was decreasing. For $t > 4.5 \mu\text{s}$ the density throughout the coil decayed with a time constant τ_p . In order to calculate the behavior of N_1 , average initial values of T_e and line density were used. These values were obtained by taking the average of mid-coil and quarter coil values. The simulation results are consistent with experimentally observed values. The influence of rotation and initial temperature are noticeable, but not strong.

In summary, the comparison of computer simulations with experimental data suggests that rotation plays an important part in explaining temperature behavior. Also, particle loss is consistent with a model in which the plasma source is a column of 12.5 cm length, not the 25 cm length of the actual coil.

VI. ZERO-DIMENSIONAL MODEL FOR LOSS FROM A THETA PINCH WITH PARALLEL TRAPPED FIELD

(McCowan)

An experiment had been carried out in a 10.5 cm long pinch²⁷ where a parallel trapped field was present. This resulted in an annular plasma column of 6 cm length after implosion. The inner boundary of the annulus diffused to the axis in approximately 1 μ s. The zero-dimensional code of Stover, et al.¹⁸ was altered to treat this problem and to evaluate the plasma behavior after collapse; this was needed in order to compare the behavior observed using a Twyman-Green axial interferometer.

The numerical model consists of six equations including:

1. particle conservation
2. electron energy conservation
3. ion energy conservation
4. radial pressure balance
5. rate of change of the magnetic flux at the inner and outer boundaries

A number of assumptions were incorporated into the analysis. These included:

1. A sharp boundary was used to describe the plasma density.
2. Radial diffusion was computed using a parabolic B field in the plasma. (We note that this was not consistent with assumption 1, but it greatly facilitated computation.)
3. The resistivity $\eta_{\perp}$ was assumed to be larger at the inner boundary than at the outer boundary. Specifically, we took

$$\eta_{\perp} = \eta_{\perp}^{cl} \left[\left(1 + \frac{a_o - r}{a_o - a_i} \right) (C_1 - 1) \right]$$

where a_i and a_o are the inner and outer radii, $\eta_{\perp}^{cl}$ is the classical resistivity, and C_1 is a constant. The reason for this choice of $\eta_{\perp}$ is that the inner boundary was observed to diffuse to the center rapidly, while the outer boundary moved only a small amount. Physically, it is thought that radial oscillations lead to a higher density gradient at the inner boundary than the outer boundary and this, in turn, leads to a high diffusion rate at the inner boundary. Use of a large value for

$n_{\perp}$ at a_1 is a convenient technique to introduce this effect. It has been found that a value $C_1 = 3.8$ results in a_1 reaching the center at the observed time of 1 μ s after implosion.

The initial conditions were taken at the end of implosion, 1 μ s after firing the main bank. The following values were used:

$a_0 = 2.1$ cm	(magnetic probe data)
$\frac{a_1}{a_0} = 0.75$	(ratio of inner to outer radius luminosity)
$T_i = 2.88$ eV	(snowplow implosion model)
$N_e = 1.6 \times 10^{18}$ cm ⁻³	(snowplow mass pickup)
$z = \frac{B_i}{B_e} = 0.616$	(radial pressure balance)

where B_i is the internal field in the plasma. The behavior of the plasma radii as predicted by the code and as indicated by luminosity are shown in Figure 25. The general behavior is in reasonable agreement.

After the plasma diffuses to the axis, it is possible to compare measured fringe shifts with predicted fringe shifts. To do this we converted sharp boundary profiles to Gaussian profiles with the form

$$n(r) = n_0 e^{-r^2/r_0^2}$$

with n_0 obtained at $t = 2.0$ μ s after implosion from interferometer measurements, N determined from the 0-D code, and r_0 determined from

$$n_0 \pi r_0^2 L = N$$

Using $n_0 = 2.75 \times 10^{16}$ cm⁻³, $N = 6.54 \times 10^{17}$, and $L = 6$ cm we obtain $r_0 = 1.12$ cm. Comparison with experiment is shown in Figure 26. The overall agreement is seen to be reasonable, with the code underestimating the particle content and plasma radius.

It is concluded that the code provides a reasonable model to use in the overall interpretation of the phenomenology, and particularly the interpretation of the Twyman-Green interferometer results.

$$\eta_{\text{inner}} = 3.8 \times \eta_{\text{classical}}$$

Figure 25 Indication of Plasma Radii from O-D Code, Luminosity as a Function of Time, with Magnetic Probe and Thomson Scattering Data Points

Figure 26 Radial Profiles of n_e from Q-D Code and Experiment at $t = 2.04 \mu\text{s}$

VII. MAGNETIC MIRROR STUDIES AND CROWBAR DEVELOPMENT (Robinson, Veglia, Mead)

1. Introduction

The earlier reported⁴ work had involved the development of active mirror coils for addition to the 50 cm long theta pinch, the use of inserts as passive mirrors, and the prediction of mirror fields by numerical studies based on the use of the Biot-Savart relationship. That work comprised the efforts which were reported in the M.S. thesis of J. Veglia²⁸ in August, 1979. There were two problems that remained to be resolved in the development of mirror fields: (1) accurate predictions of fields in the mirror region; and (2) development of a satisfactory crowbar switch. This mirror effort was to be the test-bed for crowbar development for the main bank switches, as the techniques of crowbarring used by Los Alamos and NRL were both too complex to operate reliably and too costly to fabricate. Generally, both of these problems have been solved with novel, unique approaches and this work will be summarized here.

2. Abstract

The problem of generating optimum magnetic mirror fields at the ends of a 50 cm long theta pinch experiment to study particle flow and loss effects has been investigated. A combination of active and passive mirrors was developed to produce 2-3:1 field ratios for a 23-kG pinch. Biot-Savart and potential field prediction solutions for the magnetic field distribution were compared with experimental measurements in 2-5 cm long mirror coils for the 50 cm long pinch. A crowbar system parallel to that of the main coil discharge resulted in the development of a new concept crowbar switch. The internal arc is drawn in series with the circuit discharge, and is magnetically drawn to contact a third electrode on the circuit discharge return. The capacitor bank is isolated from the inductive load, eliminating ripple in the discharge current. Tests have been made with a 28 μ F bank charged to 18 kV which peaks at 170 kA in 4 μ s. Ripple for the magnetic mirror crowbar is less than five percent and has a 1/e time of 45 μ s.

3. Magnetic Mirror Concepts

There are two basic points that clarify the thrust of the present work: (1) local diagnostics used to study mechanisms of particle and energy loss require detailed knowledge of local $\vec{B}$ field values; and (2) collisional loss flow differs from collisionless. There are two different approaches to the experimental development of more intense magnetic fields at the ends of linear devices. They will now be described.

Passive mirrors involve area reduction at the ends of the device. The concept is put in the form of ratios, as

$$\frac{B_{\text{mir}}}{B_{\text{mid}}} < \frac{A_{\text{mid}}}{A_{\text{mir}}} = \frac{R_{\text{mid}}^2}{R_{\text{mir}}^2} \quad (30)$$

where mid refers to midcoil, or values within the theta pinch, and mir refers to values at the mirror. The problems are that, on the average,

$$B_{\text{mir}}/B_{\text{mid}} \text{ (e.g. 1.1)} < A_{\text{mid}}/A_{\text{mir}} \text{ (e.g. 1.4)}$$

and flux concentrates at outer radii.

Active mirrors involve independent current discharge through a coil at the end. The concept for a single turn coil can be expressed for on-axis magnetic field as²⁹

$$B_z(z) = \frac{\mu_0 I}{L} K_b(z, \frac{L}{A}) \quad (31)$$

where $K_b = \text{fn}(\text{coil aspect ratio, axial position})$. The problem is that prediction of fields from the main coil with the added end coil fields is not linear. There are several methods of solution: analytical solution (empirical)²⁹; analytical solution with constant current density along the coil; Biot-Savart numerical solution³⁰; and potential field solution with appropriate boundary conditions²⁸.

Using single turn mirror circuitry, the active mirror coils listed in Table V were fabricated and tested. The analytical solution outlined by Knoepfel²⁹ is compared to the experimental fields generated in the field coils alone in Figure 27. It can be concluded that: (1) theory is satis-

a) Radial Variation of B_z Fields for a 2.54 cm Mirror Coil

b) Radial Variation of B_z Fields for a 5.08 cm Mirror Coil

Figure 27 Comparison of Predicted and Experimental Magnetic Field Values for Mirror Coils

Figure 28 B_z Field on Axis, 50 cm Theta Pinch.

factory within the single turn, constant diameter coil; and (2) $B_z = f(R)$, or flux concentration near the wall is significant.

Table V. Active Magnetic Mirror Characteristics

Voltage (kV)	18.0	
Capacitance (μF)	28.0	
Total source inductance (nH)	97.6	
Coil radius (cm)	4.45	
Coil length (cm)	2.54	5.08
Coil inductance (cm)	100.6	79.7
System resistance (M Ω)	8.39	8.25
Maximum current (amps)	1.98×10^5	2.11×10^5
Maximum magnetic field (kG)	25.9	25.3
Risetime (μs)	3.7	3.7
Damping coefficient $\alpha(\text{s}^{-1})$	2.117×10^4	2.327×10^4

4. Biot-Savart Analysis of 50 cm Theta Pinch and Comparison with Experiment

The Biot-Savart numerical method is carried out in the following fashion. First, assume an axial distribution of current in the theta pinch coil, using distributions given by Knoepfel²⁹ (Bardotti) for theta pinch coil without mirrors. Second, apply the Biot-Savart law by integrating over the current distribution for each field point within and outside the coil. Note that the boundary conditions presume a steady-state solution (field lines penetrate the theta pinch coil).

The advantages of the technique are: (1) it is conceptually simple; and (2) details are available for simple geometries. The disadvantages of the technique are: (1) current distributions are not known for more complex geometries; and (2) calculated flux lines are not necessarily parallel to conducting surfaces. A comparison of the different techniques for the case of the 50 cm theta pinch (Table VD) are shown in Figure 28 without mirrors. It can be seen that near the coil end there are considerable differences between the calculations and experiment. Because of these instances a more accurate technique was felt to be needed.

Table VI. 50 cm Long Theta Pinch System Characteristics

Theta pinch coil length	50 cm
Theta pinch coil i.d.	10.5 cm
Total capacitance	232.4 μ F
Charging voltage	18.0 kV
Bank inductance	24.5 nH
Coil inductance	18.6 nH
Peak field	23 kG
Peak current	1.05 MA
Quarter cycle time	4.7 μ s
Half cycle time	10.0 μ s

5. Flux Conservation Method of Analysis

A brief outline of the method can be described as follows. First, assume that conducting surfaces are parallel to flux lines. We then define flux $\psi(r,z)$ to be zero at $r = 0$ and constant on conducting surfaces. We specify flux on nonconducting surfaces, or specify planes $z = \text{constant}$, to be surfaces of symmetry. We then solve

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial z^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} = 0 \quad (32)$$

Subject to the above constraints. We now apply the method to simulation of flux lines in theta pinches with mirror fields. First we define: A , magnetic vector potential; J , current density; r, θ, z , cylindrical coordinates; B , magnetic flux density; and ψ , magnetic flux. We make the assumptions:

$$J_z = J_r = A_z = A_r = 0 ; \quad (33)$$

$$\frac{\partial}{\partial \theta} () = 0 ; \quad \nabla^2 A_\theta = -\mu_0 J_\theta \quad (34)$$

$$\nabla \times A = B, \text{ i.e. } B_r = -\frac{\partial A_\theta}{\partial z}, \quad B_z = \frac{1}{r} \frac{\partial}{\partial r} (r A_\theta) \quad (35)$$

The flux ψ is assumed to be zero at $r = 0$. Thus

$$\psi(r) = \int_0^r 2\pi r' B_z dr' \quad \text{for some } z \quad (36)$$

or in differential form:

$$\frac{\partial \psi}{\partial r} = B_z (2\pi r) \quad (37)$$

Similarly for some r :

$$\psi(z) = -\int_0^z 2\pi r B_r dz' + c \quad (38)$$

or in differential form:

$$\frac{\partial \psi}{\partial z} = -2\pi r B_r \quad (39)$$

Consequently:

$$\frac{\partial^2 \psi}{\partial z^2} + \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} = 2\pi r (\nabla^2 A) = -2\pi r \mu_0 J \quad (40)$$

Though currents can be included, assume that $J = 0$ so that

$$\frac{\partial^2 \psi}{\partial z^2} + \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} = 0 \quad (41)$$

This is the same as requiring that $\nabla^2 \psi = 0$ except for the sign of the third term.

We then utilize the finite difference representation of the solution as follows. Assume an array of points as shown below:

For the general point Q, the equation

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{\partial^2 \psi}{\partial z^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} = 0 \quad (42)$$

can be represented by values of ψ at Q, A, B, C, D.

$$A = \frac{A + B + C + D}{4} - \frac{A - B}{8N} \quad (43)$$

where $n\Delta$ is the distance of Q from the axis. For a plane of symmetry, replace C with D. Define ψ to be zero on the axis. Iterative application of the finite difference formula, with boundary conditions specified, leads to a flux map. B may be expressed in terms of finite differences such as

$$B_{z(n+1/2)} = C \left(\frac{\psi_{n+1} - \psi_n}{n + 1/2} \right) \quad (44)$$

A comparison of this technique and Biot-Savart with the fields generated in a 50 coil with passive inserts is shown in Figure 29. There is excellent agreement of experiment with the flux conservation method.

6. Development of a Self-Crowbarring, Load Isolated Spark Gap

The conventional types of crowbars that have been developed are: (1) knife edges driven through dielectric sheet; (2) ferrite loaded gaps, which present high inductance to trigger pulse and low inductance to discharge; (3) multi-channel breakdown with fast rising pulse on trigger pin; and (4) vacuum gaps.

A drawing of a new crowbar design utilizing a magnetically driven arc is shown in Figure 30(a). In this figure, which is conceptually simple, it is easy to visualize the following significant points: (1) the arc forms in series with load; (2) arc is magnetically driven by load current to close crowbar circuit; and (3) after crowbarring, separate arcs carry load and source currents. An integrated switch and crowbar configuration is shown in Figure 30(b).

(a) $r = 0$ cm (b) $r = 3$ cm

Figure 29 Comparison of Analytical Methods with Experiment with a Geometric Mirror Ratio of 1.36

Figure 30 Geometries of Magnetic Crowbar and Integrated Switch and Crowbar

An analog simulation of the integrated switch and crowbar is presented in Figure 31. This performance is in agreement with experimental tests. The advantages of the new crowbar system are: (1) low ripple without low inductance; (2) no auxiliary timing or pulsing circuits; (3) peak current equals load current; (4) closing time is insensitive to geometry and operating current; (5) power is dissipated in non-critical regions; and (6) it is rugged and inexpensive. The disadvantage of the new crowbar system is that there is increased system inductance.

Figure 31 Performance of Integrated Switch and Crowbar: Load Current (Parameters Are Trigger Pin Position, H, and Capacitor Voltages)

VIII. THOMSON SCATTERING DIAGNOSTIC SYSTEM FOR MEASUREMENT OF CONVECTIVE ELECTRON VELOCITIES

(Jacoby, Peterson)

1. Introduction

The possibility of accomplishing direct measurement of electron convective velocities has application in a number of problems of current interest. Convection of flow from confined plasmas in open ended field reversed devices (FRX), mirror machines (TMX, MFTF) and divertors (PDX) are some examples. These are also important applications in the studies of the physics of loss^{1,2,3} now being completed, and the subsequent studies of plasma-wall interaction being planned.

This research effort has focused on the problems associated with velocity determination using Thomson scattering techniques in the limiting conditions, i.e. where signals are small because of velocities being smaller than electron thermal speed or low electron density. These conditions are characteristic of loss-divertor situations where wall conditions are important. Previous work that has been reported², has been directed to the identification of technique, particularly as it can result in the optimization of signal to noise ratio (SNR). Such considerations are being reported in a journal publication³¹.

During the present reporting period, there has been the application of these techniques to an experiment where reference diagnostics were used to provide verification of the velocity indications from Thomson scattering. A brief outline of these results will be presented.

2. Abstract

A method of measuring convective electron velocities using Thomson scattering techniques in a diagnostic system which optimizes signal-to-noise ratio has been designed and evaluated. The output signal is related analytically to the thermal speed. The method is evaluated with reference to shifted peak techniques. The method was applied to the well understood convection of plasma from the ends of a theta pinch coil which was 11 cm long and 10.5 cm in diameter; $N_e \approx 10^{16} \text{ cm}^{-3}$ and $T_e \approx 10 \text{ eV}$. Maps of fields and plasma in the coil and end region were accomplished with magne-

tic and pressure probes; these diagnostics allowed prediction of loss velocities for comparison. Scattered signal magnitudes are compared to predictions; detector and stray light are identified in this proof-of-principle evaluation of a new diagnostic.

3. Velocity Determination from Thomson Scattered Signals

A schematic of the laser beam-detector geometry with respect to the convecting plasma is shown in Figure 32. The details of the analysis were reported earlier. However, a brief recapitulation will identify the difference of scattered signals, from

$$P_s d\lambda d\Omega = \frac{P_i r_{oe}^2 d\Omega L}{2\sqrt{\pi} \sin \theta/2} \frac{c}{a} \frac{d\lambda}{\lambda_i} \left[1 - \frac{3.5\Delta\lambda}{\lambda_i} + \frac{c^2 \Delta\lambda^3}{4a^2 \lambda_i^3 \sin^2 \theta/2} \right] \exp\left\{-\frac{1}{a^2}(w/k - V')^2\right\} \quad (45)$$

where $w/k = c\Delta\lambda/2\lambda_i \sin \theta/2$ and $V' = 1/(2 \sin \theta/2)(\beta - 1) \cdot \underline{v}$. The above equation can be simplified if we presume a 90° scattering angle θ and $\hat{i} \cdot \underline{v} = 0$. Then the difference in signals from two detectors is

$$\frac{P_{s1} - P_{s2}}{P_{s2}} = \exp\left\{-\frac{2\Delta\lambda}{\lambda_i} \frac{cV_b}{a^2}\right\} - 1 \quad (46)$$

and since,

$$I \propto P_s d\lambda d\Omega \quad (47)$$

we get

$$\therefore \frac{I_{s1} - I_{s2}}{I_{s2}} = \exp\left\{-\frac{2\Delta\lambda}{\lambda_i} \frac{cV_b}{a^2}\right\} - 1 \quad (48)$$

It can be seen that since $a = \sqrt{2kT_e/m_e}$, the electron temperature is needed to evaluate V_b .

We can more clearly identify the velocity dependence if we presume

$$\frac{2\Delta\lambda}{\lambda_i} \frac{cV_b}{a^2} \ll 1, \quad (49)$$

Figure 32 Scattering Geometry for Velocity Measurement

then

$$\frac{I_{s1} - I_{s2}}{I_{s2}} = \frac{2\Delta\lambda}{\lambda_1} \frac{cV_b}{a^2} \quad (50)$$

This shows a direct dependence on V_b .

4. Optimization of Signal to Noise Based on Wavelength Examined at Detectors

Presuming that the detectors will be photomultipliers, the noise from the photoemissive process is $I_n = \sqrt{I_{sig}} eG/\tau$ due to Poisson statistics of photo-emissive processes. Then

$$\frac{S}{N} = \frac{(I_{sig1} - I_{sig2})}{2\sqrt{I_{sig1,2}} eG/\tau} \quad (51)$$

where τ = pulse time and G = tube amplification.

We can optimize signal to noise through choice of λ_s or $\Delta\lambda$. Assuming $2\Delta\lambda cV_b/\lambda_1 a^2 < 1$, we expand the exponential

$$\therefore S/N \propto e^{-1/2} a^2 (c\Delta\lambda/\sqrt{2} \lambda_1)^2 \frac{2cV_b \Delta\lambda}{a^2 \lambda_1} \quad (52)$$

So, optimization of S/N with respect to $\Delta\lambda$ gives $\Delta\lambda = \lambda_1 \sqrt{2} a/C$ and the S/N ratio then becomes

$$\frac{S}{N} = \frac{\sqrt{2} V_b}{a} e^{-1/2} \sqrt{\frac{w_i r_o^2 n_e L d\Omega T d\lambda n}{\sqrt{2\pi} h a}} \quad (53)$$

The optimized signal to noise with Bremsstrahlung added can also be determined. This noise results from fluctuation in Bremsstrahlung level. The ratio of Bremsstrahlung to laser signal is $2.09 \times 10^{-36} \tau n_e 2\Delta\lambda_1/e \times V_p/w_i r_o^2 \lambda_1^2 T^{1/2} 4\pi L \equiv R$ and the total S/N ratio is

$$\frac{S}{N} = \frac{\sqrt{2} V_b}{a} e^{1/2} \sqrt{\frac{w_i r_o^2 n_e L d\Omega T d\lambda n}{\sqrt{2\pi} h a}} \left(\frac{1}{1 + \sqrt{R}} \right) \quad (54)$$

5. Comparison of Optimized Wavelength and Shifted Peak Techniques

The difference of two signals determined from a shifted peak technique which presumes sharp cutoff filters at λ_1 , and where one detector senses all light above and the other senses all light below λ_1 is used. We get

$$I_{s1} - I_{s2} = \frac{P_i r_o^2 n_e L d \Omega e \bar{T} \eta G}{\sqrt{2\pi} h a} \left[\int_{\lambda_1}^{\infty} e^{-(c^2/2a^2)} [(\lambda_1 - \lambda_s/\lambda_1) - v_b/c]^2 d\lambda_s \right. \\ \left. - \int_{-\infty}^{\lambda_1} e^{-(c^2/2a^2)} [(\lambda_1 - \lambda_s/\lambda_1) - v_b/c]^2 d\lambda_s \right] \quad (55)$$

and if $v_b/a \ll 1$, then

$$I_{s1} - I_{s2} = \frac{P_i r_o^2 n_e L d \Omega e \bar{T} \eta G}{\sqrt{2\pi} h c} \frac{2v_b \lambda_1}{a} \quad (56)$$

Accordingly, the signal to noise ratio (shifted peak) is

$$\frac{S}{N} = \frac{v_b}{a} \sqrt{\frac{e}{w_i r_o^2 n_e L d \Omega \bar{T} \eta \lambda_1 / \pi h c}} \quad (57)$$

We can get a comparison of techniques as follows. First,

$$\frac{(S/N)_{\text{two halves}}}{(S/N)_{\text{opt } \lambda_s}} = \sqrt{\frac{e}{2\sqrt{\pi}} \frac{\Delta\lambda_{1/e}}{d\lambda} \frac{\bar{T}_{t.h.}}{\bar{T}_{\text{opt } \lambda_s}}} = \bar{R} \quad (58)$$

First, for

$$\frac{\Delta\lambda_{1/e}}{d\lambda} = 5 \quad (59)$$

and

$$\frac{\bar{T}_{t.h.}}{\bar{T}_{\text{opt } \lambda_s}} = \frac{1}{4} \quad (60)$$

we get $\bar{R} = 1.0$ showing no advantage in either technique. But, blue shift and wings on filters would make accurate analysis of shifted peak quite difficult. Second, with

$$\frac{(S/N)_{\text{two halves}}}{(S/N)_{\text{opt } \lambda_s}} = \frac{e}{\sqrt{2\pi}} \left(\frac{a}{c}\right)^{1/2} \left(\frac{\lambda_i}{d\lambda}\right)^{1/2} \left(\frac{\bar{T}_{\text{c.h.}}}{\bar{T}_{\text{opt } \lambda_s}}\right)^{1/2} \quad (61)$$

For $d\lambda = 10 \text{ \AA}$, $\bar{R} = 0.61 T_e^{1/4}$, where T_e (eV). For $T_e < 7.2 \text{ eV}$ the optimized wavelength technique has a better S/N ratio. This is appropriate for end loss and wall interaction studies.

6. Measurements of Density, Temperature and Pressure, and Inferred Plasma Loss Velocity on a Theta Pinch Experiment

The geometry of the experiment that was used to provide a definable convecting plasma is shown in Figure 33. Also, the diagnostics used and their locations are shown. The measurements of n_e and T_e in the end region from Thomson scattering are shown in Figure 34. The impact pressure measurements and inferred values of flow velocity are presented in Figure 35.

The reference velocity was determined from pressure probe and Thomson scatter data. The pressure in a flowing plasma is described as follows. Impact pressure has two terms; from random flux and flow momentum, $P_{\text{meas}} = 2n_e kT_e + m_i n_e V_f^2$, where V_f is flow velocity, here the electron convective velocity. From the pressure expression, n_e and T_e information are needed at the same point in order to evaluate the flow velocity as

$$V_f = \sqrt{\frac{P_{\text{meas}}}{m_i n_e} - \frac{2kT_e}{m_i}} \quad (62)$$

with P_{meas} from impact pressure probe and n_e , T_e from Thomson scatter.

7. Thomson Scatter Techniques for the Direct Indication of Flow Velocity

The laser and detector parameters are shown in Tables VII and VIII.

Figure 33 Experimental Geometry and Diagnostics for Flow from Theta Pinch

Figure 34 Density and Temperature History At $Z = 13.5 \text{ cm}$

Figure 35 Pressure and Reference Velocity History At $Z = 13.5$ cm

Table VII. Laser (Apollo Model 35, Ruby 6943 Å) Characteristics

Energy	3 J
Pulse length	25 ns
Beam diameter	5/8 in
Scattering diameter	1.5 mm
Beam divergence	3.0 mrad

Table VIII. Detector Characteristics

Type	RCA C70024K
Quantum efficiency	6% @6943 Å
Tube amplification	2×10^5
Number of photons gathered	1.3×10^4
Number of photoelectrons generated	781
Calculated S/N ratio of difference signal	7

A schematic of the scattering system is shown in Figure 36.

8. Scattering Physics and Data Reduction for Laser Velocity Technique

The Salpeter approximation for laser scattering is given as

$$S_e(k, \omega) = \frac{2\sqrt{\pi} \exp(-X_e^2)}{ka\{[1 + \alpha^2 R\omega(X_e)]^2 + [\alpha^2 I\omega(X_e)]^2\}} \quad (63)$$

where

$$\alpha = \frac{2\lambda_1 \sin\theta/2}{2\pi \lambda_D} \quad (64)$$

We ignore $S_i(k, \omega)$ since for $\Delta\lambda = 6.4\text{Å}$, $X_1^2 = 199.5/T_1$.

With n_e , T_e determined, we can calculate $\alpha \approx 0.6$; this condition requires careful evaluation. Since $X_e < 1$, thus

Figure 36 Thomson Scatter Layout and Optics Diagram for Electron Velocity Determination

$$R\omega(X_e) = 1 - 2X_e^2[1 - 2X_e^2/3 + 4X_e^4/15 - \dots] \quad (65)$$

$$I\omega(X_e) = \pi^{1/2} X_e \exp(-X_e^2) \quad (66)$$

For the experimental plasma parameters (n_e , T_e) we can reduce $S_e(k, \omega)$ to

$$S_e(k, \omega) = \frac{2\sqrt{\pi}}{ka} \frac{\exp(-X_e^2)}{(1 + 2\alpha^2)} \quad \text{where} \quad X_e^2 = \frac{1}{a^2} \left[\frac{c\Delta\lambda}{\sqrt{2}\lambda_i} + \frac{v}{\sqrt{2}} \right]^2 \quad (67)$$

The difference signal for this case is then

$$\frac{I_1 - I_2}{I_2} = \left[\exp\left(\frac{\Delta\lambda}{\lambda_i} \frac{\sqrt{2} c v}{a^2}\right) - 1 \right] \quad \text{where} \quad v_b = \frac{v_f}{2} \quad (68)$$

has been used. Thus with $D = I_1 - I_2/I_2$, we get $v_b = n(D+1) \frac{a^2}{\sqrt{2} c \Delta\lambda}$. (69)

For this experiment, some of the more important parameters are given in Table IX. A comparison of the indications of flow velocity directly from Thomson scattering and of flow velocity inferred from the reference diagnostics is presented in Figure 37.

A comparison of these results can now be made. First, agreement of velocity indication is good. Second, it should be noted that the range of laser scattered data is indicative of velocity values which vary more than an order of magnitude. At low velocities, the reference diagnostic is not accurate. At high velocities, there is best agreement which is directly due to large signals. Third, for more accurate results, a differential amplifier could be used for the shot at 3.0 μ s. The velocity measured represents only a 10 percent difference in the signals.

Table IX. Significant Parameters of the Velocity Measuring Experiment

Time (μ s)	Scattering Parameter (units)	Temperature (eV)	Electron Thermal Velocity (cm/s)
2.0	0.411	1.4	7.01×10^7
3.0	0.545	0.87	5.53×10^7
4.0	0.605	0.43	3.89×10^7

Figure 37 Comparison of Velocity from Thomson Scatter with Reference Velocity

IX. DEVELOPMENT OF A Nd-GLASS LASER SYSTEM FOR LOW DENSITY DIAGNOSTICS (Jacoby, Peterson)

1. Introduction

The evaluation of a laser system with Nd glass rods which operate at $1.06 \mu\text{m}$ for possible application to low density plasma diagnostics was first outlined² and then presented in report form³². Since that exploratory work, there has been increasing interest in the development of such a system which could diagnose local electron densities between 10^{10} and 10^{13} cm^{-3} . Accordingly, this effort has progressed to the present stage, where a modest alteration to the Apollo Model 35 Ruby Laser will allow accommodation of Nd-glass rods with 20-40 J output; this work will be accomplished during the present year. The primary diagnostic system would continue to utilize photomultiplier detectors by doubling the frequency of the laser beam. A substantial upgrade of the laser and doubling system to energies of 80-100 J is being proposed for the future to meet the proof-of-principle needs of some large experiments, such as TMX upgrade.

The present reporting will focus on the identification of the low density limit of glass systems that can be built at this time. This identification results from an effort which was recently carried out to clarify the basis for further experimental work on this technique. It will be noted that procedure for reducing line width data to indicate temperatures for the $\sim 25 \text{ \AA}$ glass line width are different from those for narrow ruby lines, but appropriate procedures have been outlined earlier.²

2. Technical Introduction

Pulsed plasma experiments where electron densities range from 10^{16} down to 10^{10} cm^{-3} are being conducted and planned as part of fusion (CTR) research programs³³. Standard Thomson scattering diagnostics³⁴ using ruby laser sources are well known to be effective down to electron densities of 10^{13} cm^{-3} using state-of-the-art techniques³⁵. However, no such diagnostic has been demonstrated to determine local n_e and T_e for plasmas with lower densities. Where synchronous detectors cannot be used for n_e ,

there are two possible alternatives for improving the resolution of standard Thomson scattering techniques for diagnosing the plasma: (1) use of a ruby laser with higher quantum efficiency detectors and improved optics, or (2) use of an alternative laser source, with the inherent possibility of improving power and detector capability. The first of these will be explored to establish the limits of a ruby system; the second alternative provides the basis for the present work. The alternative of using a doubled frequency Nd-glass system has been suggested in the literature³⁶, and one use of such a system for plasma at 10^{13} cm^{-3} has been identified³⁷, but details allowing confirmation have not been reported. This work describes techniques which would utilize existing Nd-glass technology to extend the diagnostic capability to 10^{10} cm^{-3} , and presents a new method of data analysis which is required to retain temperature resolution.

3. Description of Thomson Scattering System Performance

The state-of-the art of Thomson scattering diagnosis of plasmas can be identified in two recent works^{35,38}. In the first of these³⁵, a system using a 4 J ruby laser, an f/9 collection system and GaAr photomultiplier (PM) detectors (RCA C31034) with 15 percent quantum efficiency was used to diagnose a plasma with $n_e = 3.5 \times 10^{13} \text{ cm}^{-3}$, $T_e = 149 \text{ eV}$. It was proposed that, using an f/5 collection system and a 10 J ruby laser, the resolution could be extended to about 10^{12} cm^{-3} , however, such an extension has not been carried out. In the second work³⁸, an avalanche photodiode (APD) detector with a 65 percent quantum efficiency was used in a Thomson scattering system to diagnose plasmas with nominal 10 eV and 10^{16} cm^{-3} properties; it was proposed that the resolution could be extended down to electron densities of 10^{14} cm^{-3} . In both of the above systems, electronic noise in the detection system limits the signal-to-noise (S/N) ratio; stray light is bothersome, but is not the ultimate impediment to resolution, based on recent advances³⁹.

In order to diagnose low density ($<10^{13} \text{ cm}^{-3}$) plasmas both source and detection system should be optimized. Since any detection system requires a minimum number of scattered photons for minimum accuracy, a

laser source capable of high pulsed energy and power is explored here. Ruby laser systems generally deliver a maximum energy of 10 J. The lowest visible electron density ($n_e = 10^{12} \text{ cm}^{-3}$)³⁵ at a specified S/N is proportional to ν_i/W_i where ν_i is the laser frequency and W_i is the incident energy. Nd-glass lasers are capable of generating 150 J pulses with relative ease, however, the line width can vary from 2.5 to 5.0 nm depending on rod selection. These higher energy pulses will allow improved n_e resolution, but this line width does not allow the normal procedure of determining T_e from Doppler broadening to be used. Two Nd-glass systems which hold the possibility of considerable gains in low density Thomson scattering resolution will now be described; the numbers used for various parameters are state-of-the-art, and improve on those noted above^{35,38}. However, because of the intense efforts in laser fusion research⁴⁰, improvements in all aspects of (doubled) Nd-glass technology can be expected in the future.

The first system to be categorized will presume the use of a PM detection system with a Nd-glass source at 1.06 μm which is to be frequency doubled before incidence on the plasma. Specifically, assuming a 100 J laser energy and 50 percent energy conversion efficiency in KDP crystals, a diagnostic pulse with 50 J and 2.5 nm width is reasonable⁴⁰⁻⁴². An RCA 4526 photomultiplier with quantum efficiency η of 20 percent at 530 nm is presumed. Noise characteristics are dominated by photon statistics and taking³⁴ $S/N = 3$, $N_{pe} \approx 10$, so

$$n_e(\text{min}) = \frac{N_{pe} h \nu_i C_h}{W_i r_o^2 d\Omega L T} = 1.4 \times 10^{11} \text{ cm}^{-3} \quad (70)$$

where N_{pe} is the number of photoelectrons detected, h is Planck's constant $r_o^2 = 7.95 \times 10^{-26} \text{ cm}^{-2}$, C_h is the number (10) of channels in the detection system, $d\Omega = 2 \times 10^{-2}$, $L = 1 \text{ cm}$ is the scattering length, $T = 0.033$ is the transmission factor for the system, and $\eta = 0.20$. It should be noted that the order of magnitude improvement in density resolution is achieved by a combination of energy increase and detector efficiency over that of the system cited in Reference 35. The anticipated real gain in resolution with Nd-glass systems is attributed to increased laser energy, as there

is little difference between photomultiplier efficiencies at doubled glass and ruby wavelengths.

An alternative system which would function with undoubled Nd-glass at 1.06 μ m and APD detectors can also be evaluated. Recent advances in detectors for Nd-glass have been reported⁴³ which indicate 54 percent quantum efficiencies; 45 percent is chosen as conservative here. Extrapolating from DeSilva's results³⁸, based on efficiency and signal-to-noise ratio, Johnson noise is found to be dominant. With an APD amplifier input impedance of 17 k Ω , and a specified S/N = 3, an incident power of 4.3×10^{-10} W is needed. From Sheffield³⁴, the minimum acceptable scattered signal can be related to the minimum number density that can be diagnosed,

$$n_e(\text{min}) = \frac{P_s C_h}{P_i r_o^2 d\Omega L T} = 4.1 \times 10^{10} \text{ cm}^{-3} \quad (71)$$

where $P_{i,s}$ refers to laser incident or scattered power, respectively. While either of the above systems using Nd-glass indicates a substantial improvement in electron density resolution over ruby systems, the detailed development and technology will require an extended research effort because of cost and the development time required.

4. Definition of Applications of the Diagnostic

The physics problems which are being studied under this grant include plasma-wall interactions. Simply stated, wherever plasma is in contact with a wall there is considerable energy loss due to conduction which is influenced by convection. This problem exists where field lines intersect insulating boundaries, such as: (1) end regions of mirror machines and compact toroid confinement configurations, (2) divertors, particularly as they are being studied for Tokamak devices, and (3) the side walls of any toroidal configuration where plasma diffuses across field lines and is in wall contact. All of these situations will have plasmas with densities lower than that in the magnetically confined regions, i.e. between 10^{10} and 10^{13} cm^{-3} . No diagnostic is presently available that can provide local resolution of density in that range and temperature at compati-

ble values. In fact, considerable effort is being expended to develop a line integrated FIR laser interferometer which would operate between 5×10^{11} and 10^{14} cm^{-3} on PDX for application to TFTR.⁴⁴

More specifically, efforts on the present contract have been oriented toward applications which are important to major experiments in the national fusion laboratories. Those efforts have led to direct interactions with researchers at Lawrence Livermore Laboratory who are studying mirror confinement on TMX. The TMX upgrade will need a system which will diagnose center cell plasmas with density of about $5 \times 10^{12} \text{ cm}^{-3}$. The doubled Nd-glass system will meet the needs, but a demonstration of the system at 100 J input rather than the 20 J previously planned is needed. It is to satisfy these stated needs for the major plasma experiments that the higher energy diagnostic system has been pursued.

X. ZERO DIMENSIONAL MODELING OF FIELD-REVERSED THETA PINCH MACHINES (Klevans)*

A zero-dimensional (0-D) time dependent computer model is developed to describe post-implosion behavior of field-reversed theta pinch machines⁴⁵⁻⁴⁷. The model consists of six equations, representing the rate of change of plasma particle number, electron internal energy, and ion internal energy; radial pressure balance; axial tension balance; and the change of the flux inside the major radius R , where $B(R) = 0$. It is assumed that the length L is much larger than either R or the minor radius a , so that particle and heat losses are taken to be predominately radial. However, axial losses (through the X point, for example) can be included by use of phenomenological coefficients in the particle and heat loss confinement times.

A rigid rotor model⁴⁶ is chosen to describe the radial behavior of the density and B field:

$$n = n_m \operatorname{sech}^2 K[(r^2/R^2) - 1] \quad (70)$$

$$B = B_\infty \tanh K[(r^2/R^2) - 1] \quad (71)$$

where n_m and R , shown in Figure 38, and K are time dependent parameters, and B_∞ is a specified function of time.

Figure 38 $n(r)$ versus r

The electron and ion temperatures are assumed to be uniform inside the separatrix. By setting $B(r_s) = -B(0)$, where r_s is the separatrix radius, one finds that $r_s = \sqrt{2}R$. The minor radius is defined by Linford⁴⁶ through the relation

$$\frac{n_m 2\pi R(2a)}{m} = \int_0^\infty n 2\pi r dr \text{ which yields } R/a = 4K/(1 + \tanh K) \quad (72)$$

*Part of this work was performed while the author was a visitor at Los Alamos Scientific Laboratory.

Assuming axial uniformity of n and B within the separatrix, the equations for

$$N = 2\pi \int_0^R dr r n(r) \equiv 2\pi \bar{n}(\pi R^2) = 2\pi r_s^2 n_m (\tanh K)/K \quad (73)$$

$$W_e = 2\pi(3/2)T_e \int_0^R dr r n(r) = 2\pi r_s^2 1.5 T_e n_m (\tanh K)/K \quad (74)$$

$$W_i = 2\pi(3/2)T_i \int_0^R dr r n(r) = 2\pi r_s^2 1.5 T_i n_m (\tanh K)/K \quad (75)$$

can be reduced to

$$\frac{1}{n_m} \frac{dn_m}{dt} = -\frac{1}{\tau_\perp} - \frac{2}{R} \frac{dR}{dt} - \frac{1}{\ell} \frac{d\ell}{dt} - \left(\frac{2K}{\sinh 2K} - 1 \right) \frac{1}{K} \frac{dK}{dt} \quad (76)$$

$$\frac{1}{T_e} \frac{dT_e}{dt} = \left(\frac{T_i - T_e}{T_e} \right) \left(\frac{1}{\tau_{eq}} \right) - \frac{1}{\tau_{th}^e} - \frac{4}{3} \frac{1}{R} \frac{dR}{dt} - \frac{2}{3} \frac{1}{\ell} \frac{d\ell}{dt} + \frac{\dot{H}_\Omega}{W_e} \quad (77)$$

$$\frac{1}{T_i} \frac{dT_i}{dt} = - \left(\frac{T_i - T_e}{T_i} \right) \left(\frac{1}{\tau_{eq}} \right) - \frac{1}{\tau_{th}^i} - \frac{4}{3} \frac{1}{R} \frac{dR}{dt} - \frac{2}{3} \frac{1}{\ell} \frac{d\ell}{dt} \quad (78)$$

where $\tau_\perp$ is the particle confinement time; τ_{th}^e and τ_{th}^i are the electron and ion thermal conduction times; $\overline{(1/\tau_{eq})}$ is the average of the inverse of the electron-ion equilibration time, defined by

$$\overline{(1/\tau_{eq})} = \frac{2}{N} \int_0^R dr r n(r) / \tau_{eq}(r) = \left[\frac{8\sqrt{2}\pi m_e^{1/2} e^4 A^2 \ln A}{3m_i} \right] \frac{n_m}{T_e^{3/2}} \left(1 - \frac{\tanh^2 K}{3} \right) \quad (79)$$

where the Spitzer expression for $\tau_{eq}(r)$ was used; and $\dot{H}_\Omega$ is the Ohmic heating rate given by

$$\dot{H}_\Omega = 2\pi \int_0^R dr r n_\perp \phi_\perp^2 j_\theta^2 \quad (80)$$

with $n_\perp \phi_\perp$, the classical cross field electrical resistivity (associated with flux annihilation), and j_θ , the diamagnetic current density, given by

$$j_\theta = -\frac{c}{4\pi} (\partial B_z / \partial r) = -(rcKB_\infty / 2\pi R^2) \operatorname{sech}^2 K \{ (r^2/R^2) - 1 \} \quad (81)$$

Particle confinement is governed by $\tau_{\perp} = N/[2\pi r_s \ell (nu)_{r_s}]$. Assuming diffusive loss at the separatrix,

$$(nu)_{r_s} = -(D_{\perp} \frac{\partial n}{\partial r})_{r_s} = -\{[(c^2 n_{\perp}^p n(r_s)(T_e + T_i))/B^2(r_s)](\partial n/\partial r)_{r_s}\} \quad (82)$$

where $n_{\perp}^p$ is the resistivity governing particle loss. Several expressions for $n_{\perp}^p$ have been tested, including classical resistivity and the lower hybrid drift resistivity.⁴⁸ The form expression resulted in particle losses which were too small and did not agree with experiment. Consequently, we have chosen⁴⁸

$$n_{\perp}^p = \frac{2\sqrt{2}\pi^{3/2} m_e}{5\Omega_i} \left(\frac{m_e}{m_i}\right)^{1/2} \frac{(T_i/T_e)^{5/4}}{1 + (T_i/T_e)} \frac{\Omega_i^2}{\omega_i^2} (\epsilon_n a_i)^2 \left[1 - \frac{1}{\sqrt{10}} \left(\frac{T_i}{T_e}\right)^{1/4}\right] \quad (83)$$

where Ω_i is the ion cyclotron frequency and ω_i is the ion plasma frequency. The quantity $\epsilon_n = (\partial \ln n / \partial r)_{r_s}$ is the inverse gradient length, and a_i is the ion gyro-radius. When ϵ_n is evaluated at the separatrix using a rigid rotor profile, the value is sufficiently small that particle loss times are larger than those observed experimentally. Hamasaki⁴⁹ has found from 1-D modeling that the density drops very rapidly outside the separatrix, so ϵ_n should be larger than the value obtained from the rigid rotor profile. These uncertainties have led us to take the quantity $\epsilon_n a_i$ as a parameter which can be varied. Typically we have found that $\epsilon_n a_i = 1.7$ yields good agreement with experimental data.

The treatment of thermal conduction is uncertain because the temperature is constant inside the separatrix and is unknown outside the separatrix. If it is assumed that hot ions which cross the separatrix flow out the ends without collision then there is no ion thermal conduction loss across the separatrix. Classical cross field ion thermal conduction with an ion gyroradius temperature gradient length has also been studied. Although the differences in results are not great, dropping ion thermal conduction gives better agreement with experiment.

For electron thermal conduction we use

$$\tau_{th}^e = W_e / (q_r^e)_{r_s} 2\pi r_s \ell \text{ where } (q_r^e)_{r_s} = -K_{\perp}^e (\partial T_e / \partial r)_{r_s} = +K_{\perp}^e (T_e / \delta) \quad (84)$$

where δ is the thermal sheath length and $K_{\perp}^e$, the electron thermal conductivity, is given by

$$K_{\perp}^e = 4.66 \frac{n(r_s)^2 c^2 T_e n_i^p}{B(r_s)^2} = 4.66 \frac{n(r_s) T_e D_{\perp}(r_s)}{T_e + T_i}.$$

One might expect that δ would be approximately the ion gyroradius since the plasma sheath would be expected to be on the order of the ion gyroradius. Parameter studies have shown that better agreement is achieved if the value $\delta = a_i/2$ is used. This choice has produced satisfactory agreement with electron temperature behavior.

The unknowns in this theory are n_m , K , R , l , T_e and T_i . Consequently three more equations are needed. The first is obtained from pressure balance:

$$(1/n_m)(dn_m/dt) = -[1/(T_e + T_i)](dT_e/dt + dT_i/dt) + (2/B_{\infty})(dB_{\infty}/dt) \quad (85)$$

The next equation represents magnetic flux change inside R :

$$d\phi/dt = (d/dt) \int_0^R dr r B = \int_0^R dr r (\partial B / \partial t) \quad (86)$$

Using Ampere's Law and Ohm's Law to compute $\partial B / \partial t$, the integral on the right can be evaluated. The integral in the middle is evaluated using equation (71). After differentiation, equation (86) can be reduced to the expression

$$\frac{2}{R} \frac{dR}{dt} = -\frac{1}{\tau_{\phi}} - \left(\frac{K \tanh K}{\log \cosh K} - 1 \right) \frac{1}{K} \frac{dK}{dt} - \frac{1}{B_{\infty}} \frac{dB_{\infty}}{dt} \quad (87)$$

where $\tau_{\phi} = (\pi R^2 \log \cosh K) / (n_i^p c^2 K^2)$ is the decay time for the flux.

The final expression is obtained from axial tension balance (see Figure 39).

$$\int_0^{r_w} dr r [B^2(r, z_0) / 8\pi - p(r, z_0)] = \int_0^{r_w} dr r [B^2(r, 0) / 8\pi - p(r, 0)] \quad (88)$$

where r_w is a conducting wall, and $l/2 \ll z_0 <$ chamber half length.

Figure 39 B Line Behavior

We neglect particle pressure at z_0 , and take $B(r, z_0) = B(z_0)$. Also we neglect particle pressure beyond the separatrix at $z = 0$, and set $B(r, 0) = B_\infty$ for $r_s < r < r_w$. Using flux conservation, $B(z_0)\pi r_w^2 = B_\infty\pi(r_w^2 - r_s^2)$. Then equation (88) can be evaluated, resulting in the expression $(R^2/r_w^2) = 1 - (\tanh K)/K$. Note that setting $r_s^2 = 2R^2 = r_w^2$ results in a maximum value for K of 1.91. Converting the last expression into a differential equation we obtain

$$(2/R)(dR/dt) = [K \tanh^2 K / (K - \tanh K) - 1](1/K)(dK/dt) \quad (89)$$

The set of six equations can be reduced to obtain an equation for l :

$$\frac{1}{l} \frac{dl}{dt} = -\frac{3}{5} \left[\frac{1}{\tau_e} + \left(\frac{T_e}{T_e + T_i} \right) \frac{1}{\tau_{th}} + \left(\frac{T_i}{T_e + T_i} \right) \frac{1}{\tau_{th}} \right] + \frac{3}{5} \frac{\dot{H}_\Omega}{W_e} + \frac{\alpha}{\tau_\phi} - \left(\frac{6}{5} - \alpha \right) \frac{1}{B_\infty} \frac{dB_\infty}{dt} \quad (90)$$

where α is a function of K and is approximately 0.5 for the LASL experiments.

It is seen that l can expand or contract depending on the relative size of the heating and loss terms, and the behavior of the B field.

The set of equations (76), (77), (78), (85), (87) and (89) has been solved simultaneously on the computer. Comparison with a recent FRX-B set of experiments⁴⁷ conducted at 17 mTorr fill pressure of D_2 are shown in Figures 40 to 42. Initial values correspond to $t = 10 \mu s$ in the experiment. Initial conditions are the following: $B_0 = 6.8$ kG, $T_i = 185$ eV; $T_e = 120$ eV; $n_0 = 3.6 \times 10^{15} \text{ cm}^{-3}$; $K = 1.1$; $R = 4$ cm; $l = 50$ cm and $N = 1.3 \times 10^{19}$. The magnetic field behavior is given

Figure 40 Comparison of Experimental and O-D Predictions of Electron and Ion Temperatures for FRX-B

Figure 41 Comparison of Experimental and O-D Predictions of Ion Inventory for FRX-B

Figure 42 Comparison of Experimental and O-D Predictions of the Maximum Density for PRX-B

approximately by $B = B_0 [1 - (t/96 \text{ } \mu\text{s})]$. Figure 40 shows temperature behavior. Good agreement is achieved for both ion and electron temperature behavior. Figures 41 and 42 show the decay of N and n_m , both with exponential decay. These results are within the large error bars of the experimental values. Quantities not shown include length L , which decreased from 50 cm to 46 cm in 20 μs ; R , which decreased from 4.0 to 3.9 cm; and K , which decreased from 1.1 to 1.06. These results are consistent with experimental observation. Simulations have also been run for experiments conducted at 21 mTorr fill pressure. The agreement was within experimental error.

In conclusion, an O-D model has been constructed which predicts behavior consistent with behavior observed in FRX-B.

XI. PARTICLE AND ENERGY LOSS FROM A COLLISIONLESS PLASMA (Klevans and Gary)*

When the ion-ion mean free path in a plasma is longer than the length of a linear theta pinch device, the ions may be considered collisionless and classical fluid concepts are of questionable validity. In the Los Alamos Scylla IV-P experiment, an estimate based on collisional transport theory indicates that axial ion thermal conduction is an order of magnitude larger than convective thermal transport. However, Stover, et al.,¹⁸ and McKenna, et al.¹² both found that for computer models to reproduce Scylla IV-P temperature behavior, it was necessary to disregard axial ion thermal conduction.

An alternate way to treat axial ion heat flow is to use a flux limit of the form

$$Q_i = fn k_B T_i \left(\frac{2k_B T_i}{m_i} \right)^{1/2} \quad (91)$$

where n , T_i and m_i are the ion density, temperature and mass, k_B is the Boltzmann constant and f is a numerical coefficient which depends upon the existence of non-classical processes which limit the heat flow. There is no complete theory which predicts the value of f . An outward flowing half-Maxwellian distribution function gives $f = 0.2$ but, in the context of the electron thermal flux problem, a variety of other values have been used.⁵⁰⁻⁵²

In this work, the behavior of Q_i and f in a collisionless plasma column has been studied by computing these quantities through the use of a free-streaming distribution function. The results suggest that the neglect of ion thermal conduction in computer simulations of linear theta pinches with collisionless ions is justified.

The distribution function was obtained from Dreicer's free-streaming solution of the Vlasov equation which described one-dimensional flow out the ends of a collisionless plasma.⁵³ This solution was generalized to include a magnetic well, and thus mirror reflection. The inclusion of

*Part of this work was performed while the author was a visitor at Los Alamos Scientific Laboratory.

a mirror ratio $R > 1$ enables us to treat both self mirroring and applied mirrors.

When mirrors are present the distribution function consists of a trapped part and an untrapped part. In the results to be presented, these distribution functions have been normalized, and the axial dimension z , time t , and axial velocity v_z have been normalized as follows: $s = z/L$; $v = v_z/v_1$ where $v_1 = (2kT_1/m_1)^{1/2}$; and $\tau = v_1 t/L$ where L is the discharge chamber length. The normalized distribution functions for $R = 1.0$ and $R = 1.2$ are presented in Figure 43, a and b, at three different values of τ . It is seen that the system loses high energy ions first while retaining low energy ions. In particular, for $R = 1.2$, the structure of the distribution function changes markedly as τ increases.

The behavior of $\tilde{Q}(0.51, \tau)$, the ion thermal flux density at $s = 0.51$ normalized by $nkT_1 v_1$, is shown as a function of time in Figure 44. The value $s = 0.51$ was chosen in order to study heat flowing out of the end of the system. The important features of this figure are: (1) the maximum value of $\tilde{Q}$ decreases as R increases; (2) for $R = 1.0$, the maximum value of $\tilde{Q}$ is only 0.034, a value significantly smaller than that associated with a flowing Maxwellian; and (3) for $R = 1.2$, $\tilde{Q}$ becomes negative at $\tau > 0.9$.

To explain why $\tilde{Q}(0.51, \tau)$ becomes negative for $R = 1.2$, consider the distribution function for untrapped ions shown in Figure 43b. As τ increases, the faster particles are lost from the system while the g_u , the normalized distribution function of untrapped particles, for the slower ions remains unchanged due to replenishment from plasma at $s < 0.50$. In a frame moving with average flow velocity $\tilde{v}$, the untrapped ion velocity distribution becomes somewhat skewed, with a small "tail" pointing back toward $s = 0$. This can be seen in Figure 43b by using, for example, $\tilde{v} = 0.61$ at $s = 0.51$ and $\tau = 1.0$. Such a tail can strongly affect the thermal flux and, in this case, is sufficient to make it negative. This reasoning applies to $\tilde{Q}$ at $s < 0.50$ as well.

Figure 45 illustrates the ratio of thermal flux density, $\tilde{Q}$, to the kinetic energy flux density, $\tilde{q}$, at $s = 0.51$ as a function of time for $R = 1.0$ and $R = 1.2$. For $R = 1.0$, the ratio rises rapidly to 0.13, then

Figure 43 The reduced distribution functions $g_u(1/2, v, \tau)$ as functions of velocity at three different values of τ . The vertical arrows indicate the value of the average flow velocity $\bar{v}$ at $s = 1/2$ and the indicated values of τ . (a) At $R = 1.0$, the untrapped distribution.

Figure 43 The reduced distribution functions $g_j(1/2, v, \tau)$ as functions of velocity at three different values of τ . The vertical arrows indicate the value of the average flow velocity $\bar{v}$ at $s = 1/2$ and the indicated values of τ . (b) At $R = 1.2$, the trapped (dotted line) and untrapped (solid lines) distributions.

Figure 44 The ion thermal flux density at $s = 0.51$ as a function of time. The solid lines represent the case $R = 1.0$ and the dashed lines represent $R = 1.2$.

Figure 45 The ratio of the thermal flux to the kinetic energy flux at $s = 0.51$ as a function of time. The solid lines represent the case $R = 1.0$ and the dashed lines represent $R = 1.2$.

falls to very small values for $\tau > 1$. For $R = 1.2$, heat flow represents a maximum of only six percent of the energy flow. At $\tau > 0.9$ this ratio becomes negative because $\tilde{Q}$ is negative.

Thus, in this collisionless free flow model, the loss due to the ion thermal flux is generally much smaller than the total ion kinetic energy flux loss. This suggests that the neglect of the ion thermal conduction term in the numerical simulations of Scylla IV-P is justified.

This Page
Was Intentionally
Left Blank

impact pressure measurements outside the main confined plasma region. This data provided indirect evidence of the particle loss history; subsequent data recorded with interferometer scans across chords at various axial positions provided electron density data, and allowed a much more comprehensive picture of the loss history in FRX-A to be constructed. This work was organized for and reported at the Third APS Topical Conference on High Temperature Diagnostics in March, 1980. It is anticipated that further clarification of loss events will be pursued by analysis of this data; formal reporting will be through Los Alamos Scientific Laboratory.

Abstract*

(T. M. York, R. K. Linford, E. G. Sherwood)

A piezoelectric pressure transducer system was developed and used to diagnose the plasma loss from the ends of the coil of the FRX-A linear geometry compact torus. Radial and axial surveys of the end region allowed identification of the spatial distribution of plasma escaping from the torus as a function of time for several mirror configurations. Compatible interpretation of impact pressure data with side-on streak photography and magnetic probes provided a clear evaluation of global behavior of the torus plasma. Also, determination of the magnetic pressure history in the coil allowed qualitative identification of the transient loss mechanisms. With loss velocity estimated from thermal speeds, the history of particle flux from the coil and plasma contained by the fields were evaluated.

(*Work also supported by U.S. D.O.E. Contract W-7405-ENG-36)

3. Center Cell TMX Plasma Pressure Measurements (Lawrence Livermore Laboratory)

Following an initial visit to MFE Division, LLL in September 1979, a cooperative effort to accomplish pressure probing of the center cell plasma in TMX was initiated. Dr. T. Simonen assumed responsibility for the conduct of the effort; Dr. York was responsible for developing a measuring system and installing it in the machine. With short visits in December and March for planning and evaluation, a visit for initial

installation of a probe took place in January. The diagnostic was installed in TMX and a number of noise checks were initiated. The technical responsibility for the utilization of this diagnostic on TMX rests with Dr. Peter Poulson.

Plasma within the center cell is typically $n_e = 10^{13} \text{ cm}^{-3}$, $T_e \approx T_i = 100 \text{ eV}$ and lifetime is 20 ns. This plasma would have gas-kinetic pressure $p = 2n_e kT_e = 320 \text{ N/m}^2 = 3.2 \times 10^{-3} \text{ atm}$. This measurement presents two unique problems: (1) the lifetime is much longer than normally measured, and so heat transfer to the probe may be a problem, and (2) the signal levels are very low compared to normal applications, and so it will be necessary to use unique transducer designs and follower amplifiers to avoid degradation of the pressure signal in about 100 ft of cable.

Several probe systems were designed. Because of the signal lifetime, bar-type probes would not be useful, and tip-type probes were selected as best. One typical transducer unit was encased in an 8 mm o.d. quartz tube, with the sensing end having a 1 mm thick fused quartz wall. The coaxial design probe used a PZT transducer element of 1/8" dia and 0.040" thickness. The unit was calibrated in a shock tube to provide 0.41 V/atm or 4.1 V/atm with X10 amplifier at the end of 8' of coaxial cable needed to get the leads from the system. With the static pressure magnitudes noted above, output from this system would be 1.3 mV without an amplifier, or 13 mV with x 10 amplifier. These are small but measureable signal levels. Unfortunately, mechanical vibrations in the TMX system have been found to produce acceleration signals of about 1 mV. One subsequent improvement in sensitivity was brought about by redesign of follower-amplifier circuitry. The follower was miniaturized and installed at the probe, effecting an improvement in output by a factor of 1.4.

It is anticipated that the major difficulties with vibrator signals will be alleviated in a new design probe being fabricated. It will generate signals of 3.0 V/atm without amplifier and 30 V/atm with amplifier. It will have a built-in accelerometer, such that these signals can be used to compensate for extraneous vibration signals. The output signal anticipated will be 10 mV without amplifier or 100 mV with the x 10 amplifier. Installation of this system on TMX is planned for Summer 1980.

XIII. REVIEW OF FACULTY AND STUDENT PARTICIPATION

T. M. York Professor of Aerospace Engineering	June 1979 FT 2 weeks Sept. 1979-Feb., 1980 25% March 1979-May 1980 35%
E. H. Klevans Professor of Nuclear Engineering	June 1979 FT 2 weeks Aug. 1979 FT 2 weeks Sept. 1979-May 1980 25%
John Heidrich Graduate Assistant, Physics	June 1979-Sept. 1979 Grant-in-Aid June 1979-May 1980 Wage Payroll
Elmer Stover Graduate Assistant, Nuclear Engineering	June 1979-Sept. 1979 Grant-in-Aid
Barry Jacoby Graduate Assistant, Nuclear Engineering Research Engineer, Nuclear Engineering	June 1979-Sept. 1979 50% Sept. 1979-May 1980 100%
Franklin Mead Graduate Assistant, Aerospace Engineering	June 1979-May 1980 50%
John McCowan Graduate Assistant, Nuclear Engineering	June 1979-May 1980 50%
Art Peterson Graduate Assistant, Nuclear Engineering	June 1979-May 1980 50%
Akbar Parvesian Graduate Assistant, Nuclear Engineering	June 1979-Sept. 1979 50%

XIV. PROJECT REFERENCES

1. Reports

- a. T. M. York, "Scaling of End Loss Times in Linear Theta Pinches," ERDA C00-4020-1, Sci. Rept. 77-1, The Pennsylvania State University, January 1977.
- b. E. H. Klevans and R. Ankney, "Machine Parameters for Linear Theta Pinch Fusion Reactors," ERDA C00-4020-2, Sci. Rept. 77-2, The Pennsylvania State University, January 1977.
- c. T. M. York and E. H. Klevans, "A Study of Flow and Loss Processes at the Ends of a Linear Theta Pinch," Progress Report for the period June 1, 1976-May 31, 1977, ERDA C00-4020-3, Sci. Rept. 77-3, The Pennsylvania State University, February 1977.
- d. R. S. Freeman, "Studies of End Loss From a Theta Pinch Using a Twyman-Green Interferometer," ERDA C00-4020-4, Sci. Rept. 77-4, The Pennsylvania State University, November 1977.
- e. E. K. Stover, E. H. Klevans and T. M. York, "Computer Modeling of Linear Theta Pinch Machines," ERDA C00-4020-5, Sci. Rept. 77-5, The Pennsylvania State University, November 1977.
- f. T. M. York and E. H. Klevans, "A Study of Flow and Loss Processes at the Ends of a Linear Theta Pinch," Progress Report for the period June 1, 1977-May 31, 1978, DOE C00-4020-6, Sci. Rept. 78-1, The Pennsylvania State University, February 1978.
- g. B. A. Jacoby, T. M. York and R. A. Mollo, "A Doubled Nd-Glass Laser System for Incoherent Thomson Scattering from Low Density Plasmas," DOE C00-4020-7, Sci. Rept. 79-1, The Pennsylvania State University, February 1979.
- h. B. A. Jacoby and T. M. York, "Method of Measuring Directed Electron Velocities in Flowing Plasma Using the Incoherent Regions of Laser Scattering," DOE-C00-4020-8, Sci. Rept. 79-2, The Pennsylvania State University, February 1979.
- i. T. M. York and E. H. Klevans, "A Study of Flow and Ion Processes at the Ends of a Linear Theta Pinch," Progress Report for the period June 1, 1978-May 31, 1979, DOE C00-4020-9, The Pennsylvania State University, February 1979.
- j. V. P. Veglia, "The Design of Magnetic Mirrors for a Linear Theta Pinch," M.S. Thesis for Nuclear Engineering, The Pennsylvania State University, University Park, Pa., August 1979.

2. Publications

- a. E. H. Klevans and R. Ankney, "Machine Parameters for Linear Theta Pinch Reactors," Proceedings of the Second A.N.S. Topical Meeting on the Technology of Controlled Fusion, Richland, Wash., 1976, p. 978.
- b. E. K. Stover, E. H. Klevans and T. M. York, "Computer Modeling of Linear Theta Pinch Machines," Phys. Fluids 21, 2090, 1978.
- c. B. A. Jacoby, T. M. York and R. A. Mollo, "Evaluation of Nd-Glass Laser System for Incoherent Thomson Scattering Diagnostics of Low Density Plasmas," accepted for publication (1980) Applied Optics.
- d. B. A. Jacoby and T. M. York, "Optimized Method of Measuring Directed Electron Velocities Using the Incoherent Regions of Laser Scattering," accepted for publication (1980) Applied Optics.
- e. B. A. Jacoby and T. M. York, "High Voltage SCR Trigger Circuit Utilizing Disc Capacitors in a Max Array," accepted for publication (1980) Rev. Sci. Instr.
- f. E. H. Klevans, "Zero-Dimensional Modeling of Field-Reversed Theta Pinch Machines," Proc. of U.S.-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, New Jersey, December 1979.
- g. E. H. Klevans and S. P. Gary, "Particle and Energy Loss from a Collisionless Plasma" submitted for publication, Phys. Fl., May 1980.
- h. J. W. Robinson, "Self Crowbarring, Load Isolating Triggered Spark Gap," submitted for publication, Rev. Sci. Instr., May 1980.

3. Presentations

- a. E. H. Klevans with R. Ankney, "Machine Parameters for Linear Theta Pinch Fusion Reactors," paper presented at Second Topical Meeting on the Technology of Controlled Nuclear Fusion, September 21-23, 1976, Richland, Washington.
- b. T. M. York with E. H. Klevans, "Scaling of Particle and Energy End Loss in Linear Theta Pinches," presented at 18th Annual Meeting of the American Physical Society, Division of Plasma Physics, November 15-19, 1976, San Francisco, California.
- c. E. Stover, E. H. Klevans and T. M. York, "Computer Modeling of Linear Theta Pinch Machines," presented at IEEE International Conference on Plasma Science, May 23-25, 1977, Troy, New York.

3. Presentations (cont'd)

- d. T. M. York, R. Freeman and R. Mollo, "Evaluation and Scaling of Plasma Loss from a Very Short Theta Pinch," presented at IEEE International Conference on Plasma Science, May 23-25, 1977, Troy, New York.
- e. E. K. Stover, E. H. Klevans and T. M. York, "Simple Theta Pinch Implosion Dynamics Models," presented at Division of Plasma Physics Meeting of the American Physical Soc., November 7-11, 1977, Atlanta, Georgia.
- f. J. E. Heidrich, T. M. York, J. W. Robinson and E. H. Klevans, "Early Transient Flow at the End of a Linear Theta Pinch," presented at 19th Annual Meeting of the American Physical Society, Division of Plasma Physics, November 7-11, 1977, Atlanta, Georgia.
- g. B. A. Jacoby, T. M. York and R. A. Mollo, "A Doubled Nd-Glass Laser System for Low Density Incoherent Thomson Scattering," presented at Second Topical Conference on High-Temperature Plasma Diagnostics, March 1-3, 1978, Santa Fe, New Mexico.
- h. B. A. Jacoby and T. M. York, "Proposed Method of Measuring Directed Electron Velocities Using the Incoherent Regions of Laser Scattering," presented at Second Topical Conference on High-Temperature Plasma Diagnostics, March 1-3, 1978, Santa Fe, New Mexico.
- i. J. E. Heidrich, et al., "Transient Plasma Loss From a Linear Theta Pinch with Reversed Trapped Field," presented at Division of Plasma Physics Meeting, APS, October 31-November 3, 1978, Colorado Springs, Colorado.
- j. B. A. Jacoby, et al., "Comparison of Thomson Scattering and Spectroscopic Measurements of Plasma in the End Region of a Theta Pinch," presented at Division of Plasma Physics Meetings, APS, October 31-November 3, 1978, Colorado Springs, Colorado.
- k. E. K. Stover, E. H. Klevans and T. M. York, "One-Dimensional Modeling of Linear Theta Pinch Devices," presented at Division of Plasma Physics Meetings, APS, October 31-November 3, 1978, Colorado Springs, Colorado.
- l. B. A. Jacoby, T. M. York, J. W. Robinson, J. E. Heidrich and E. H. Klevans, "Particle and Thermal Loss Processes at the Ends of a Collisional Theta Pinch" presented at Division of Plasma Physics Meeting, APS, November 12-16, 1979, Boston, Mass.
- m. J. McCowan, E. Klevans and T. York, "Zero-Dimensional Modeling of Pinches with Rotation and with Forward Trapped Field" presented at Division of Plasma Physics Meeting, APS, November 12-16, 1979, Boston, Mass.

3. Presentations (cont'd)

- n. J. W. Robinson, J. Veglia, F. B. Mead, T. M. York and E. H. Klevans, "Magnetic Mirror System with a Self-Crowbarring, Load Isolated Spark Gap for Theta Pinch Loss Studies" presented at Division of Plasma Physics Meeting, APS, November 12-16, 1979, Boston, Mass.
- o. B. A. Jacoby, T. M. York and A. Peterson, "A Thomson Scattering Diagnostic System for Measurement of Convective Electron Velocities" presented at Third Topical Conference on High Temperature Plasma Diagnostics, March 17-19, 1980, APS, Los Angeles, Ca.
- p. T. M. York, R. B. Howell and K. F. McKenna, "Direct Measurement of Wall Plasma Pressure and Comparison with Magnetic Field Measurements in the ZT-S Toroidal Reversed Field Pinch" presented at Third Topical Conference on High Temperature Plasma Diagnostics, March 17-19, 1980, APS, Los Angeles, Ca.
- q. T. M. York, R. K. Linford and E. G. Sherwood, "Measurements of Plasma Pressure in the End Region of the FRX-A Compact Torus" presented at Third Topical Conference on High Temperature Plasma Diagnostics, March 17-19, 1980, APS, Los Angeles, Ca.

REFERENCES

1. York, T. M. and Klevans, E. H., Progress Report for the Period June 1976-May 1977, DOE Report C00-4020-3, February 1977.
2. York, T. M. and Klevans, E. H., Progress Report for the Period June 1977-May 1978, DOE Report C00-4020-6, February 1978.
3. York, T. M. and Klevans, E. H., Progress Report for the Period June 1978-May 1979, DOE Report C00-4020-9, February 1979.
4. Heidrich, J. E., "Experimental Study of Transient Loss of Plasma From a Theta Pinch Having Initially Reversed Magnetic Fields," Ph.D. Thesis, Department of Physics, The Pennsylvania State University, University Park, PA., June 1980.
5. Taylor, J. B. and Wesson, J. A., "End Losses From a Theta Pinch," Nuclear Fusion, Vol. 5, 1965, p. 159.
6. Wesson, J. A., "Plasma Flow in a Theta Pinch," in Plasma Physics and Controlled Nuclear Fusion Research, Vol. 1, Conference Proceedings, Culham, September 1965, p. 223.
7. Friedberg, J. P. and Weitzner, H., "Endloss from a Linear Theta Pinch," Nuclear Fusion, Vol. 15, 1975, p. 217.
8. Weitzner, H., "End Loss From a Theta Pinch," Phys. Fl., Vol. 20, 1977, p. 384.
9. Brackbill, J. N., Menzel, M. T. and Barnes, D. C., "Numerical Studies of the Linear Theta Pinch," Third Topical Conference on Pulsed High Beta Plasmas, Culham, Sept. 9-12, 1975.
10. Morse, R. L., "Adiabatic End Loss from a Theta Pinch," Phys. Fl., Vol. 11, 1968, p. 1558.
11. McKenna, K. F. and York, T. M., Phys. Fluids, 20, 1556 (1977).
12. McKenna, K. F., Bartsch, R. R., Comisso, R. J., Ekdahl, C. A., Quinn, W. E. and Siemon, R. E., Collisionless Flow and End-Loss from a High Energy Theta Pinch Plasma," to be published in Phys. Fluids.
13. Davidson, R. C. and Ogden, J. M., "Electromagnetic Ion Cyclotron Instability Driven by Ion Energy Anisotropy in High Beta Plasmas," Phys. Fluids, 18, 1045 (1975).
14. Jacoby, B. A., "Particle and Thermal Loss at the Ends of a Collisional Theta Pinch," Ph.D. Thesis, Nuclear Engineering Department, The Pennsylvania State University, University Park, Pa., November 1980.
15. Hobbs, G. D. and Wesson, J. A., Plasma Physics, Vol. 9, 1967, p. 85.

16. Jones, W. B., et al., Phys. Fl., Vol. 13, 1970, p. 800.
17. Eberhagen, A. and Kelchacker, M., Proc. of 6th Int'l. Conf. Ionization Phenom. in Gases, Vol. 2, 1976, p. 573.
18. Stover, E. K., Klevans, E. H. and York, T. M., Phys. Fl., Vol. 21, 1978, p. 2090.
19. Rostoker, N. and Kolb, A. C., Phys. Rev., Vol. 124, 1961, p. 965.
20. Little, E. M., Quinn, W. E., Ribe, F. L. and Sawyer, G. A., Nucl. Fusion Suppl., Vol. II, 1962, p. 497.
21. Bodin, H. A. B., Green, T. S., Niblett, G. B., Peacock, N. J., Quinn, J. M. and Reynolds, J. A., Nucl. Fusion Suppl., Vol. II, 1962, p. 521.
22. Griem, H. R., Kolb, A. C., Lupton, W. H. and Phillips, D. T., Nucl. Fusion Suppl., Vol. II, 1962, p. 543.
23. Bodin, H. A. and Newton, A. A., Phys. Fl., Vol. 6, 1963, p. 1338.
24. Kvartskhava, I. F., Keryalidze, K. N., Zukakishvili, G. G. and Gvaladze, Yu. S., Nucl. Fusion, Vol. 3, 1963, p. 285.
25. Hintz, E. and Holb, A. C., Phys. Fl., Vol. 8, 1965, p. 1347.
26. Spitzer, L., Physics of Fully Ionized Gases (Wiley, New York, 1956).
27. Freeman, R. S., "Studies of End Loss From a Theta Pinch Using a Twyman-Green Interferometer," ERDA Rept. C00-4020-4, November 1977.
28. Veglia, J., "The Design of Magnetic Mirrors for a Linear Theta Pinch," M.S. Thesis, Nuclear Engineering Department, The Pennsylvania State University, University Park, Pa., August 1979.
29. Knoepfel, H., Pulsed High Magnetic Fields, North-Holland Publishing Co., Amsterdam (1970).
30. Jackson, J. D., Classical Electrodynamics, John Wiley & Sons, Inc. (1975).
31. Jacoby, B. A. and York, T. M., "Optimized Method of Measuring Directed Electron Velocities Using the Incoherent Regions of Laser Scattering," Applied Optics to be published.
32. Jacoby, B. A., York, T. M. and Mollo, R. A., "A Doubled Nd-Glass Laser System for Incoherent Thomson Scattering from Low Density Plasmas," Report C00-4020-8, U.S. D.O.E., February 1979.

33. Coensgen, F. H., Simonen, T. C. and Turner, W. C., "Tandem Mirror and Field Reversed Mirror Experiments," UCRL-82791, Lawrence Livermore Laboratory, August 1979, also Proc. of Workshop on Physics of Plasma Close to Thermonuclear Conditions, USDOE, CNR/EURATOM/CNEN, Varenna, Italy, August 1979.
34. Sheffield, J., Plasma Scattering of Electromagnetic Radiation, Academic Press Inc., New York, 1975.
35. Sethian, J. D. and Ekdahl, C. A., "Cornell Thomson Scattering System," Rev. Sci. Instrum., Vol. 49, 1978, pp. 729-735.
36. DeSilva, A. W. and Goldenbaum, G. C., Methods of Experimental Physics, Part 9A, Edited by H. R. Griem and R. H. Lovberg, Chap. 3, Academic Press, Inc., New York, 1971.
37. Voronev, G. S., Proceedings of the International School of Plasma Physics on Acquisition Systems, Edited by H. Eubank, Varenna, Italy, pp. 318-320, 1974.
38. DeSilva, A. W., "Spectral Analyzer for Thomson Scattering," Rev. Sci. Instrum., Vol. 50, 1979, pp. 1605-1608.
39. Siemon, R. E., "Polychrometer with Extreme Rejection of Stray Light," Applied Optics, Vol. 13, 1974, pp. 697-699.
40. Swain, J. E., Hunt, J. T., Kobierecki, M. W. and Marchi, F. T., "Frequency Doubling at 90 mm Aperture," Paper TuB7, Conf. on Laser and El.-Opt. Systems, Opt. Soc. Am., Feb. 1980.
41. Lyubavsky, Tu. and Oushinnikev, V., Solid State Laser Technology, MIR Publishers, Moscow, 1975.
42. Adlov, R. S. and Oregag, M., "Frequency Doubling Crystals: Unscrambling the Acronyms," Electro-Optical System Design, 1974, pp. 20-24.
43. McIntyre, R. J. and Webb, P. D., "Silicon Detectors for Fiber Applications in the 1-1.15 μ m Range," Paper WCC3, Conf. on Laser and El.-Optics Systems, Opt. Soc. Am., Feb. 1980.
44. Mansfield, D. K. and Johnson, L. C., "A TFTR FIR Laser Interferometer for Electron Density Measurements," Third APS Topical Conference on High Temperature Plasma Diagnostics, Los Angeles, Ca., March 1980.
45. Linford, R. K., Armstrong, W. T., Platts, D. A. and Sherwood, E. G., 7th IAEA Conference on Plasma Phys. and Controlled Fusion Research, Innsbruck, 1978.
46. Linford, R. K., Platts, D. A. and Sherwood, E. G., "LASL Controlled Thermonuclear Research Annual Report, Jan.-Dec. 1977.

47. Armstrong, W. T., et al., Bull. APS, 24, 1979, p. 1082.
48. Gary, S. P., "Wave-Particle Transport from Electrostatic Instabilities," 1979, submitted to Phys. Fluids.
49. Hamasaki, S. and Linford, R. K., Bull. APS, 24, 1979, p. 1081.
50. Malone, R. C., McCrory, R. L. and Morse, R. L., Phys. Rev. Lett., 34, 1975, p. 721.
51. Gray, D. R. Kilkenny, J. D. and White, M. S., Phys. Rev. Lett., 39, 1977, p. 1270.
52. Gary, S. P., Sgro, A. G. and DeSilva, A. W., Phys. Fluids, 21, 1978, p. 2103.
53. Dreicer, H., presented at the Third International Symposium of Plasma Heating in Toroidal Devices, Italy, 1976.