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**RADIAL SPACE POTENTIAL MEASUREMENTS IN THE
CENTRAL CELL OF THE TANDEM MIRROR EXPERIMENT
WITH A HEAVY-ION-BEAM PROBE**

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APRIL 11, 1983

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TABLE OF CONTENTS

	Page
List of Tables	vii
List of Figures	viii
Abstract	xiv
Acknowledgements	xv
I. Introduction	1
II. Review of Heavy Ion Beam Probing	
A. Introduction	6
B. Heavy Ion Beam Probe Physics	
1. Introduction	6
2. Secondary Ion Production	9
3. Space Potential Measurements	12
4. Electron Temperature Measurements	15
C. Fluctuation Measurements	16
III. Design of the TMX Heavy Ion Beam Probe	
A. Introduction	19
B. Beam Trajectory Simulations	
1. Sweep and Detector Locations	20
2. Vacuum Magnetic Field Detection Grid	23
3. Detection Grid with Finite Beta	27
4. Detection Grid with Finite Beta and Potential	31
5. Sample Volumes	33
6. Calibration Trajectories	38
C. Primary Beam Monitors	
1. Introduction	38
2. Straight-Through Detector and Measured Beam Profile	39

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TABLE OF CONTENTS

	Page
3. The Primary Beam Detector	41
D. Secondary Current Level	46
E. Energy Analyzer	51
F. Beam Line	55
G. Control and Data Acquisition System	
1. Introduction	57
2. High Voltage Power Supplies	60
3. Analyzer	62
4. Ion Gun Filament	65
5. Operation	67
IV. System Calibration and Sensitivity	
A. Introduction	70
B. High Voltage Measurements	71
C. Energy Analyzer Calibration	
1. Introduction	74
2. Closed Loop Angular Calibration	76
3. Open Loop Angular Calibration	89
4. Theoretical Analyzer Response	91
5. Axial Analyzer Gain	98
D. Space Potential and Ion Current Measurement	
Sensitivity	
1. Description	104
2. Plasma Generated Noise	108
3. Gun Modulation Experiment	109
E. Conclusion	117

TABLE OF CONTENTS

	Page
V. TMX Space Potential Measurements	
A. Introduction	120
B. Measurement Profiles	122
C. Timing.	126
D. Temporal Profile of the Central Cell	
Space Potential	
1. Gas Box Fueling	128
2. Puffer Valve Fueling	136
E. Radial Profile of the Central Cell	
Space Potential	
1. Gas Box Fueling	139
2. Puffer Valve Fueling	152
F. Radial Electric Field	157
VI. Correlation and Scaling of Measurements	
A. Introduction	161
B. Comparison of the Theoretical and	
Experimental Central Cell Space Potential	162
C. Central Cell Well Depth	
1. Introduction	170
2. Puffer Fueling	172
D. Radial Profile of the Space Potential	
and Electron Temperature	179
E. Space Potential Scaling with Fueling Rate	
1. Measurements and Comparison with	
Electron Temperature	186
2. Theoretical Potential and Electron	
Temperature Scaling with Fueling Rate	189
3. Potential Well Scaling with Fueling	194

TABLE OF CONTENTS

	Page
VII. Fluctuation Measurements	
A. Introduction	198
B. Beam Attenuation	199
C. The 12 KHz Mode	
1. Structure	202
2. Correlation with $E \times B$ Drift	210
D. The 5 KHz Mode	212
VIII. Conclusions and Suggestions for Future Work	
A. Conclusions - Physics	218
B. Conclusions - Heavy Ion Beam Probe Development.	219
C. Suggestions for Future Work	220
List of References	222
Appendix I. Data Processing	
A. Introduction	226
B. Noise Reduction	228
C. Off-Line Processing	
1. Introduction	230
2. Derivation of the Off-Line Processing Equations	230
3. Sensitivity and Dynamic Range	237
D. Data Processing Examples	
1. Temporal Profile	239
2. Radial Profile	242
Appendix II. Photographs of the System	249
Appendix References	259

LIST OF TABLES

	Page
Table III.D.1 Beam Injection Voltages and Signal Levels for Probing the Plasma with the Alkali Ions	48
Table III.G.1 High Voltage Power Supplies	61
Table IV.B.1 High Voltage Measurement Accuracy	73
Table IV.C.1 Measured Analyzer Parameters	92
Table IV.D.1 Machine Conditions for Sept. 26, 1980 Shots 39, 48, Aug. 19, 1980 shot 88 and Sept 24, 1980 Shot 35	131
Table V.E.1 Machine Parameters for Sept. 26, 1980 shot 88 and Aug. 29, 1980 shot 105	142
Table V.E.2 Parabolic Fits to the Space Potential Profile for Sept 26, 1980 shot 88	149
Table V.E.3 Machine Conditions for Sept. 24, 1980	153
Table V.E.4 Space Potential and Standard Deviations for the Shot-to-Shot Radial Scan of the Plasma on Sept 24, 1980	155
Table VII.C.1 Calculated $E \times B$ Rotational Frequency and Measured Fluctuation Frequency for Sept. 26, 1980 Shot 43	211

LIST OF FIGURES

	Page
Figure II.B.1 Heavy Ion Beam Probe Schematic	8
Figure II.B.2 Effective Electron Impact Ionization Cross Section for Thallium	13
Figure III.B.1 Location of the Sweep Point and Energy Analyzer	22
Figure III.B.2 Energy/Angle Detection Grid with Vacuum Magnetic Field	24
Figure III.B.3 r, z, θ_a, θ_z , During Constant Energy and Constant Injection Angle Scans of the Plasma	25
Figure III.B.4 Secondary Trajectory when Probing Near the Plasma Center and Typical Primary Trajectory which Enters the Analyzer	28
Figure III.B.5 Energy/Angle Detection Grid with $\beta = 0.5$	30
Figure III.B.6 Energy/Angle Detection Grid with $\phi = 1$ kV	32
Figure III.B.7 Energy/Angle Detection Grid with $\beta = 0.5$ and $\phi = 1$ kV	34
Figure III.B.8 Plasma Sample Volume	36
Figure III.B.9 Sample Volumes with Vacuum Magnetic Field, $\beta = 0.5$ and $\phi = 0$, $\beta = 0$ and $\phi = 1$ kV, $\beta = 0.5$ and $\phi = 1$ kV.	37
Figure III.C.1 Straight-Through Detector	40
Figure III.C.2 Primary Beam Detector	43
Figure III.C.3 Primary Beam Detector Signals	45
Figure III.E.1 Electrostatic Energy Analyzer	52
Figure III.G.1 Control and Data Acquisition System	58
Figure III.G.2 Sum/Difference Amplifier	64
Figure III.G.3 Filament Controller	66

Figure IV.B.1	High Voltage Monitoring Circuit	72
Figure IV.C.1	Primary Beam Calibration Trajectory	75
Figure IV.C.2	Closed Loop Feedback Network	77
Figure IV.C.3	Typical Closed Loop Calibration Shot	80
Figure IV.C.4	Unstable Operation of the Feedback Loop	83
Figure IV.C.5	Measured Angular Response of the Analyzer	85
Figure IV.C.6	Measured Angular Response of the Analyzer for Various Entrance Slit Widths	90
Figure IV.C.7	Theoretical Analyzer Angular Response	94
Figure IV.C.8	Theoretical and Experimental Agreement after Translation and Magnitude Shift of the Theoretical Curve	95
Figure IV.C.9	Beam Scrapeoff in the Analyzer	97
Figure IV.C.10	Effect of Axial Analyzer Gain when Processing a Shot with Axial Sweep	100
Figure IV.C.11	Primary Beam Measurement with Axial Sweep	103
Figure IV.C.12	Axial Analyzer Gain	105
Figure IV.D.1	Detector and Beam Noise Levels	107
Figure IV.D.2	Ion Gun Energy Modulation Circuit	110
Figure IV.D.3	Split Plate Currents with 10 Volt Sinusoidal Gun Energy Modulation	111
Figure IV.D.4	Measured Minus Injected Beam Energy for Primary Beam in the Analyzer and 10 Volt Sinusoidal Energy Modulation	114
Figure IV.D.5	Sum Current for Primary Beam in the Analyzer with 10 Volt Sinusoidal Energy Modulation	115
Figure IV.D.6	Split Plate Currents with 1 kHz Square Wave Energy Modulation	118

Figure IV.D.7	Measured Minus Injected Beam Energy for Primary Beam in the Analyzer and 1 kHz Square Wave Energy Modulation	119
Figure V.B.1	Location of the Heavy Ion Beam Probe on the TMX Central Cell	123
Figure V.B.2	Radial Scan Coordinates for Constant Beam Energy and Constant Injection Angle	125
Figure V.C.1	Typical Machine Timing	127
Figure V.D.1	Temporal Profile of the Space Potential During Gas Box Fueling	129
Figure V.D.2	Temporal Profile of the Secondary Current Level During Gas Box Fueling	130
Figure V.D.3	Space Potential and Secondary Current Level with Increased Gas Feed	134
Figure V.D.4	Space Potential and Secondary Current Level Off-Axis	135
Figure V.D.5	Temporal Profile of the Space Potential During Puffer Fueling	137
Figure V.D.6	Temporal Profile of the Secondary Current Level During Puffer Fueling	138
Figure V.E.1	Single Shot Radial Scans of the Space Potential and Secondary Current Level	140
Figure V.E.2	Space Potential and Secondary Current Level During a Radial Scan from 18-20 ms	143
Figure V.E.3	Radial Sweep Waveform and Space Potential as a Function of Radius from the 18-20 ms Scan	145
Figure V.E.4	Parabolic Fit to the Radial Potential Profile	147
Figure V.E.5	Radial Potential Profile Near the Beginning of the Equilibrium Interval and Radial Potential Profile with 40 keV Neutral Beam Injection	148

Figure V.E.6	Radial Potential Profile Early in the Shot, Before Gas Box Turn-on, and Near the end of the Shot After the Neutral Beams in the West End-plug have been Turned off	151
Figure V.E.7	Radial Potential Profile During Puffer Valve Fueling (16 ms)	154
Figure V.E.8	Radial Potential Profile During Puffer Valve Fueling (26 ms)	156
Figure V.E.9	Comparison of the Plasma Density and Space Potential Profiles During Gas Box and Puffer Fueling	158
Figure VI.B.1	Cylindrical Flux Tube Model for the Plug and Central Cell Regions	164
Figure VI.B.2	Central Cell Axial Loss Current, Density, and Confinement Product	167
Figure VI.B.3	Measured Electron Temperatures and the Measured and Expected Central Cell Space Potentials	169
Figure VI.C.1	Measured Space Potentials and the Resulting Experimental Well Depth	173
Figure VI.C.2	Measured and Expected Potential Well Depths	178
Figure VI.D.1	Radial Profile of the Space Potential and Electron Temperature During Puffer Fueling	180
Figure VI.D.2	Radial Profiles of the East End-Plug and Central Cell Density	182
Figure VI.D.3	Radial Profiles of the Central Cell Potential, ϕ_e , the Expected Well Magnitude, $T_{ep}\ln(n_p/n_c)$, and their Sum, the Expected End-Plug Potential	184
Figure VI.D.4	Radial Profiles of the Measured End-Plug Potential, ϕ_p , the Calculated End-Plug Potential, $\phi_e + T_{ep}\ln(n_p/n_c)$, the Measured End-Plug Electron Temperature, T_{ep} , and Ratios of the Calculated and Measured End-Plug Potentials to the Electron Temperature	185
Figure VI.E.1	The Central Cell Potential and Electron Temperature as a Function of Central Cell Fueling	188

Figure VI.E.2	End-Loss Current (Referenced to the Central Cell Midplane) as a Function of Central Cell Fueling	191
Figure VI.E.3	Central Cell Density as a Function of Central Cell Fueling	193
Figure VI.E.4	Central Cell and End-Plug Potentials and the End-Plug to Central Cell Density Ratio as a Function of Central Cell Fueling	195
Figure VII.B.1	Space Potential Profile Obtained by Monitoring Tertiary ($1^+ \rightarrow 3^+$) Transitions	201
Figure VII.C.1	Temporal Profile of Typical Space Potential and Secondary Current Oscillations	203
Figure VII.C.2	Auto Power Spectrum of the Secondary Current Level and Space Potential and their Phase Relationship and Coherency	205
Figure VII.C.3	Time Dependent Auto Power Spectrum of the Secondary Current Level	207
Figure VII.C.4	Time Dependent Auto Power Spectrum of the Space Potential	208
Figure VII.C.5	Contour Plots of Constant Phase and Coherency Between the Space Potential and Secondary Current Level	209
Figure VII.D.1	Typical Space Potential and Secondary Ion Current Oscillations Off-Axis	213
Figure VII.D.2	Auto Power Spectrum of Off-Axis Oscillations	214
Figure VII.D.3	Time Dependent Auto Power Spectrum of the Off-Axis Measurements	216
Figure VII.D.4	Time Dependent Auto Power Spectrum of the Oscillations On-Axis During High Gas Feed	217
Figure AI.1	Location of the Analyzer Split Plates	227
Figure AI.2	Definition of Analyzer Parameters	231
Figure AI.3	Derivation of the Change in Split Plate Current as a Function of Beam Position in the X Direction	233

Figure AI.4	Beam Width as a Function of Analyzer Entrance Slit Width	236
Figure AI.5	Split Plate Currents During a Typical Shot with Gas Box Fueling	240
Figure AI.6	Split Plate Currents After the Low Frequency Noise is Removed	241
Figure AI.7	Typical Split Plate Currents During Radial Scans	243
Figure AI.8	Expanded Time Scale During a Radial Scan to Obtain the Noise Subtraction Interval	244
Figure AI.9	Split Plate Currents after Removal of the Low Frequency Noise	245
Figure AI.10	Sweep Voltage and the Calculated Analyzer Gain and χ During the Radial Scans	246
Figure AI.11	Radial Location of the Measurement Point and the Secondary Beam Angle at the Analyzer as a Function of the Injected Beam Angle	248
Figure AII.1	The Beam Line	250
Figure AII.2	The Analyzer Tank	251
Figure AII.3	The Energy Analyzer	252
Figure AII.4	Plan View of the Analyzer with the Ground Plate and Guard Ring Assembly Removed	253
Figure AII.5	4-Channel Current-to-Voltage Converter Assembly	254
Figure AII.6	The 3-Element Ion Gun	255
Figure AII.7	The Primary Beam Detector	256
Figure AII.8	The Operator's Station	257
Figure AII.9	The Tandem Mirror Experiment	258

ABSTRACT

Spatial and temporal profiles of the space potential in the central cell midplane of TMX have been obtained with a heavy-ion-beam probe. The absolute accuracy of measurements is ± 25 Volts (with respect to the machine vacuum walls) with a resolution of ~ 2 Volts. During moderate fueling with the gas boxes ($i_{\text{gas}} = 1200$ Atom-Amperes D_2), the plasma potential is parabolic to at least 25 cm radius, with $\phi_e \approx \phi_{\text{max}} [1 - (r/32)^2]$ and $300 < \phi_{\text{max}} < 450$ Volts. With puffer-valve fueling, the space potential is relatively flat to at least 27 cm radius, with $250 < \phi_e < 350$ Volts.

The magnitude of the central-cell potential on-axis is consistent with the measured electron temperature (from Thomson scattering) and simple tandem-mirror theory, with $\phi_e/T_{ec} \approx 6$. The axial potential well depth, ϕ_c , obtained by comparing the heavy-ion-beam probe measurements in the central cell with end-loss-analyzer measurements of the plug potential, indicate (at moderate fueling levels) a confining potential consistent with the Boltzmann relation $T_e \ln(n_p/n_c)$ on-axis.

During gas-box fueling, measurements indicate oscillations in the space potential and $nf(T_e)$ close to the fundamental $E \times B$ rotational frequency of the central-cell plasma. These oscillations are typically ~ 12 kHz with a 1-kG central-cell magnetic field. An off-axis oscillation is also observed at ~ 5 kHz, particularly during high-gas feed. Fluctuations are of low amplitude during puffer-valve fueling of the central cell.

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Several sections of this report compare beam probe data with measured TMX parameters and tandem mirror theory. TMX Experimentalists Dr. David Grubb and Dr. Thomas Casper receive credit for end-plug potential measurements with the end-loss analyzer. Electron temperature measurements in both the central cell and east plug were done by Dr. Ronald Goodman. Finally, Dr. Edward Powers has provided spectral analysis of beam probe fluctuation measurements with the advanced computer analysis techniques he and co-workers are developing at the University of Texas, Austin.

Although a diagnostic on a major fusion experiment involves a large number of support personnel, three technicians and three designers stand out as having made especially important contributions to this project. Physics

technician Tarry Schmidt was responsible for the vacuum system, ion source replacement, and general mechanical troubleshooting. More importantly, Tarry became a skilled operator of the system, which requires an understanding of beam probe operation and its interaction with TMX machine conditions. Next, I would like to thank electrical technician Tim Letendre for important contributions to the complex beam probe electronics. Tim provided initial debugging of a number of CAMAC modules, repaired failed circuitry, and got a custom auxiliary crate controller on-line. Finally, Tom Stack also operated the system, provided high voltage expertise, and helped to keep the beam probe operational.

Designer Ronald Lipps made an important contribution to the project through printed circuit designs for the non-commercial CAMAC modules and the layout of the high performance detector amplifiers. Designer Mike Balun handled wire-wrap circuitry in the control system. Mechanical layout of the beam line and various detectors was provided by Cecil Wells.

Several engineers have also made important contributions to the diagnostic. An advanced electrostatic energy analyzer was designed by Jack Lewis. The analyzer was tested and documented by Mike Reed. Particle orbit simulations were done by Kourosh Saadatmand for a wide range of plasma conditions and by Tim Cutler and Rick Foster with the full three-dimensional TMX magnetic field model. CAMAC software and a compiler for the auxiliary crate controller were developed by Paul Futscher. Finally, Jay Wiedwald was an important contributor to the design of the computer-based control system.

Last, but not least, I would like to express my sincere appreciation to Carolyn Mohrman for typing the many memos presenting beam probe data and results and this report.

CHAPTER 1

Introduction

Plasma confinement with the tandem mirror concept has recently emerged as an important candidate for a thermonuclear fusion reactor. With the world's dwindling supply of fossil fuels such reactors could be one of the most important developments of this century, providing a virtually unlimited source of safe, economical energy fueled only by easily obtainable deuterium and tritium. Lawrence Livermore National Laboratory's Tandem Mirror Experiment (TMX) is one of the first large-scale tandem mirror devices, designed to test fundamental plasma confinement and scaling.¹ TMX became operational in July 1979 and experiments were performed through October 1980, when it was shut down for major upgrading.

As the basic operation of a tandem mirror device depends on electrostatic plasma confinement, emphasis was placed on space potential diagnostics. Fundamental to this effort was the Heavy Ion Beam Probe located on the TMX central cell. The beam probe has provided the first potential measurements in a high temperature tandem mirror plasma, and in fact the first potential measurements in any hot mirror confined plasma. The diagnostic was designed and operated by Rensselaer Polytechnic Institute for LLNL*.

Initial design of the beam probe began in 1977 and continued through 1978. Most of the hardware was installed early in 1979. The first measurements were obtained in August of that year, shortly after the first plasmas were formed. Operation continued until the TMX shutdown.

This thesis describes heavy ion beam probe measurements of the TMX central cell space potential (ϕ_c), correlates the data with other measured parameters, and compares the results with simple tandem mirror theory. Fundamental to tandem mirror operation is the establishment of a potential well which provides axial confinement of central cell ions. The well depth in TMX is estimated, from beam probe measurements of the central cell potential and plug potential measurements (ϕ_p) from gridded end loss analyzers. The well depth is found to be consistent with the Boltzmann relation $e\phi_c = kT_e \ln(n_p/n_c)$, where T_e is the measured electron temperature, n_p and n_c the plug and central cell densities, and ϕ_c the well depth. An important parameter, related to confinement in mirror produced plasmas, is the ambipolar potential to electron temperature ratio, ϕ_e/T_e . This relationship is investigated and found to be in good agreement with classical predictions.

Radial profiles of the central cell potential have been obtained, allowing a determination of the radial electric field. The resulting azimuthal drift from $E_r \times B_z$ is calculated. Potential and $n_e f(T_e)$ fluctuations are presented, with the frequency of one of the observed modes agreeing well with the plasma rotational frequency for $m = 1$.

The dependence of the central cell space potential on machine parameters is investigated. A study is made of gas box and puffer valve

fueling techniques, and the scaling with fueling rate. The data is analyzed to determine the influence of radial profiles and total gas feed on electrostatic confinement.

Chapter II presents a general review of the heavy ion beam probe technique. The measurement sensitivity and accuracy are discussed.

A description of the TMX beam probe is provided in Chapter III. Included are the operating regimes, bandwidth, resolution, and expected current levels. Detailed grid maps indicating plasma access are presented, along with finite size beam simulations used to estimate spatial resolution. The effect of plasma beta and potential on the particle trajectories is noted and discussed in relation to actual TMX parameters.

Chapter IV describes the extensive calibration of the heavy ion beam probe. The measured and theoretical response of the energy analyzer is presented. The accuracy and resolution of high voltage power supply monitors is discussed. Direct measurements of the beam probe's sensitivity and frequency response obtained by modulating the injected beam energy are presented.

Space potential measurements are presented in Chapter V and compared with tandem mirror theory in Chapter VI. Analytic fits (polynomial, least squares, etc.) to "typical" TMX data are given and deviations from such functions discussed. Data from machine parameter scans is presented and analyzed. The plasma motion from $\vec{E} \times \vec{B}$ effects is calculated.

Fluctuations in the plasma space potential and $nF(T_e)$ current are presented in Chapter VII. Several coherent modes are observed in the TMX central cell, with amplitudes sensitive to machine conditions (degree of cleanup, etc.) and fueling techniques (gas box, puffer). The temporal dependence of the modes is presented, and compared with the azimuthal $E \times B$ drift expected from the overall space potential and magnetic field profile. Spatial resolution is discussed, since effects such as primary (injected) beam intensity modulation can distort the normally localized beam probe measurement.

Finally, conclusions and suggestions for future work are presented in Chapter VIII. Much additional analysis of acquired data is possible, for both beam probe development and understanding the physics of TMX. Examples include more sophisticated noise reduction, such as software phase sensitive detection, and further analysis of fluctuation data. In addition, a beam probe has been discussed for the TMX upgrade, which has a higher central cell magnetic field (3 kG compared to 1 kG typical TMX operation) and higher electron temperature (300 eV). Substantial modifications of the present system are required.

Processing of the TMX data is described in Appendix I. Potential measurements are made off-line, after noise reduction techniques are applied to the raw data. Previous beam probes have operated closed-loop, where a complex feedback network maintains an exact ion trajectory through the electrostatic energy analyzer. The correction voltage applied to the

analyzer top plate is a direct measure of the plasma potential, hence an "on-line" measurement. In off-line measurements the top plate voltage is held fixed, and the beam position within the analyzer monitored.

Calculations, performed after the data has been acquired (typically by computer), yield the space potential and other parameters. This technique has several advantages, including better frequency response, complete stability, improved noise reduction, simplicity, and the inherent advantage of storing only raw data. Several factors must be carefully considered, however, including analyzer linearity and dynamic range. A substantial effort has been made to verify and establish the performance of off-line processing through both plasma and calibration tests. Such tests include modulating the injected beam energy, sweeping the analyzer top plate voltage, and varying the analyzer entrance slit width.

CHAPTER II

Review of Heavy Ion Beam Probing

A. Introduction

Particle beam probing of a plasma can take many forms. Attenuation of an ion or neutral beam directed through the plasma yields an integrated line density.¹ Zeeman splitting of the light emitted from the excitation of a neutral beam has been used for measuring plasma current density.² Another technique, heavy ion beam probing, is based on collisional ionization of the particles in a probing beam by plasma electrons, yielding a new particle flux which carries information from the plasma. A direct, localized, measurement of plasma space potential is obtained, as well as information on the plasma electron temperature and density.^{3,4}

Heavy ion beam probing is a well established technique, having been applied to several large experiments^{5,6} as well as smaller plasma facilities designed specifically for beam probe development.^{7,8} The technique was originally developed by R. L. Hickok and F. C. Jobes while working at the Mobil Oil Company Research Facility in Princeton, New Jersey.

B. Heavy Ion Beam Probe Physics

1. Introduction

Heavy ion beam probing is based on detecting the ionization products of a particle beam as it passes through the plasma. The injected

(primary) beam is usually singly charged, but a neutral beam may be advantageous in complex or very intense magnetic fields.⁹ When the primary beam (assumed singly charged in subsequent discussions) is within the plasma, electron impact ionization of some of the particles will increase their charge state an integral amount

The magnetic field confining the plasma separates the higher charge reaction products (secondaries) from the primary beam, as shown in Figure II.B.1. A suitably placed detector will generally intercept particles of only one of the possible charge states, created at a unique volume element within the plasma. This "observation point" may be scanned through the plasma by changing the beam energy or injection angle. Variable power supplies allow mapping the plasma in two dimensions (x and y) with a fixed detector location.

Subject to the confining magnetic field and machine access, beam injection conditions are established so that the probing ions reach the desired sample volume, and allow secondaries to escape. Heavy alkali metals (Cs, Rb, Tl, etc.) are used for the probing beam, as their high atomic weight minimizes the necessary injection energy. In addition these ions may be extracted from thermionic sources.

The secondary particle flux carries considerable information from the plasma. Most importantly, the energy of escaping secondary ions is increased above their injected energy by the plasma space potential. This increase, equal to the space potential at the ionization point times

Figure II.B.1. Heavy Ion Beam Probe Schematic.

the change in charge, allows a direct, spatially resolved measurement of this parameter.³ In addition, the production rate of secondary ions is proportional to the local plasma electron density and related to the plasma temperature, through the cross section for electron impact ionization.

2. Secondary Ion Production

The number of ionizations per unit volume per second when an ion beam, of density n_b , interacts with plasma electrons, of density n_e , is given by

$$\Gamma = n_b n_e \langle \sigma(v_r) v_r \rangle \quad (2)$$

where σ is the cross section for electron impact ionization and v_r is the relative speed between ions and electrons

$$v_r = |\bar{v}_b - \bar{v}_e| \quad (3)$$

If the beam has a cross sectional area A the number of ionization events occurring along a length l of the injected beam per second is

$$N = n_b n_e A l \langle \sigma(v_r) v_r \rangle \quad (4)$$

assuming the parameters are relatively constant over this distance. This represents a secondary current of

$$i_s = q_s e n_b n_e A l \langle \sigma(v_r) v_r \rangle \quad (5)$$

from the increment l along the primary beam path, where the factor q_s is the integral charge of the secondary ions. Substituting the primary beam current

$$i_p = q_p n_b e v_b A \quad (6)$$

yields

$$i_s = \frac{i_p q_s n_e l}{q_p} \left[\frac{\langle \sigma(v_r) v_r \rangle}{v_b} \right] \quad (7)$$

The quantity in brackets is defined as the effective cross section, yielding

$$i_s = i_p q_s n_e l \sigma_{eff} / q_p \quad (8)$$

The sample length parameter, l , is given by the distance along the primary beam where secondary ions are detected. This length is determined by the magnetic field geometry and the size of the detector's entrance slit.

Absolute cross sections for electron impact ionization have been determined experimentally from carefully controlled cross beam measurements. Significant work in this area has been done by B. Peart and K. Dolder, Culham, and by R. Feeney and his associates at Georgia Tech.¹⁰⁻¹³ Data exist for most of the alkalis, with some measurements out to the fifth ionization state. Some theoretical data also exist, primarily by M. Gryzinski,¹⁴ but present analysis tends to underestimate measured cross sections by factors of two or three.¹³ Possible explanations for the disagreement include several quantum mechanical processes (such as auto-ionization) not considered in the theoretical analysis but which tend to increase the actual cross section.¹⁵ Theoretical curves, however, are very useful in extending measured cross section data to higher energies than experimentally obtained. Agreement

between theory and experiment tends to be much better at higher energies, and the theoretical curves can be normalized to measured values.

Cross sections for electron impact ionization of alkali elements tend to peak at about 100 eV (equivalent electron velocity) and are the order of 10^{-16} cm². Cross sections for heavier species tend to be larger, for example rubidium and sodium are about a factor of 10 apart. Higher order ionizations tend to be down a factor of 3 or 4 from the next lowest transition¹³ ($1^+ \rightarrow 3^+$ vs $1^+ \rightarrow 2^+$, for example). Absolute (worst case) errors in cross section measurements are about $\pm 13\%$ for recent measurements.¹³

The effective electron impact ionization cross section is obtained by averaging

$$\sigma(v_r)v_r \quad (9)$$

over the velocity distribution of plasma electrons, usually assuming a monoenergetic beam of reacting ions. An integration is performed over velocity space

$$\langle \sigma(v_r)v_r \rangle = \int f(v_e) \sigma(v_r)v_r d^3v \quad (10)$$

where $f(v_e)$ is the electron distribution function. Assuming a Maxwellian electron distribution and making use of experimental cross section data, Bieniosek has numerically integrated the above relation for single ionization ($1^+ \rightarrow 2^+$) of most of the alkali metals.¹⁶ Results have been generated for several beam velocities (v_b), typically 10, 20, and 40 kilovolts, and are plotted as a function of the temperature of the

interacting electrons. The effective cross section for thallium, used in the TMX beam probe, is shown in Figure II.B.2.

For 10-keV beam energies and a 100-eV electron temperature effective cross sections range from $2 \times 10^{-16} \text{ cm}^2$ for sodium to $100 \times 10^{-16} \text{ cm}^2$ for thallium (thallium, although not an alkali, has an electronic structure yielding alkali-like properties). For typical beam probe operation ($i_p = 10 \text{ } \mu\text{a}$, $q = 2$, $n_e = 5 \times 10^{12} \text{ cm}^{-3}$, $l = 0.5 \text{ cm}$) equation (8) yields

$$5 \text{ na} < i_s < 250 \text{ na} \quad (11)$$

for the range of probing ions discussed. Although several factors have not been considered, such as primary beam attenuation, the calculation is representative of secondary current levels obtained in beam probe systems to date.

3. Space Potential Measurements

As the injected particles travel through the plasma their kinetic energy is modified by any electric fields. From Coulomb's law the process is path independent, and given only by the particle's charge times the change in potential. For ions undergoing additional ionization ($q_0 \rightarrow q$) within the plasma, however, a net energy change can occur between locations with the same potential. This happens because the particles of kinetic energy decreases by $q_0 e \Delta \phi$ when traveling to the point of ionization, but increases by $q e \Delta \phi$ when returning. The net change

$$(q - q_0) e \Delta \phi \quad (12)$$

Figure 17.B.2. Effective electron impact ionization cross section for thallium.

allows a direct measurement of the plasma space potential at the point of ionization by comparing the injected beam energy with the energy of escaping secondary ions

$$E_s = E_0 + (q - q_0)e\phi \quad (13)$$

In practice, the beam injection energy is carefully monitored and the secondary energy measured with a parallel plate electrostatic analyzer. Note that a convenient calibration exists, since if $q = q_0$ (monitor particles not undergoing additional ionization) the secondary and injected energies are the same.

For a finite size beam and detector the measurement actually made consists of a weighted average over a region of space, called the sample volume. The shape of the sample volume is determined primarily by the magnetic field geometry and the location of the detector referenced to the beam injection. Rectangular sample volumes, minimizing the spatial extent of measurements, are desired but generally only approximated under all conditions. The size of the sample volume is a function of the injected beam and detector size, and the magnetics. Sample volumes for the TMX beam probe are described in Chapter III. For this system sample volumes are close to rectangular under certain conditions (low plasma beta, for example) with a typical size $\sim 1 \text{ cm}^3$.

Sensitivity of the potential measurement is determined by the detector resolution, injected beam stability, and noise levels. Sensitivity in the volt range is obtainable, as described in Section IV.D for the TMX beam probe. Absolute accuracy (space potential with respect

to machine walls) is generally the order of tens of volts, and is also described in Chapter IV for the TMX system.

4. Electron Temperature Measurements

In principal the beam probe provides a localized measurement of the plasma electron temperature and density. From equation (8) the secondary current level is a linear function of the local plasma density and a function of temperature through the impact ionization cross section

$$i_s \propto n_e f(T_e) \quad (14)$$

These parameters can be separated by probing the same sample volume with different ion species, or alternatively with different charge states (e.g., $1^+ \rightarrow 2^+$ and $1^+ \rightarrow 3^+$). The techniques are based on the change in effective cross section $f(T_e)$, for the different conditions; two independent equations of form (14) exist for the unknowns.⁴

In practice, however, the measurement is difficult since many factors, such as sample volumes, injected beam current, cross sections, detected current, and beam attenuation must be accurately known. Considerable information, however, can often be inferred from the temporal and/or radial profile of the secondary current level. This is especially true if one of the parameters is constant or known from other diagnostics, such as interferometry or Thomson scattering. In addition, these diagnostics can serve as calibration sources: for instance radial or temporal temperature profiles obtained after normalization to Thomson scattering at a single point.

Higher order charge state measurements can also provide a rough upper and lower bound on the electron temperature, due to the sharp cross section falloff below the state's ionization potential.

Measurements of secondary, tertiary, and quaternary transitions ($1^+ \rightarrow 2^+$, $1^+ \rightarrow 3^+$, $1^+ \rightarrow 4^+$) of thallium clearly show the temperature evolution during a TMX discharge (Chapter VII).

C. Fluctuation Measurements

Low frequency fluctuations, generated by MHD activity, acoustic waves, $E \times B$ drifts, or other processes are an important factor determining plasma transport and stability. Fluctuation induced transport can be inward or outward, depending on the phase between electric field and density oscillations.¹⁷ Although electrostatic probes have provided considerable experimental data of space potential fluctuations near the plasma edge,¹⁸ a heavy ion beam probe is capable of providing the essential interior measurements. In addition, the $n(T_e)$ dependence of the secondary current level allows, under some conditions, a direct comparison of the phase between density and potential.

Present state of the art beam probe electronics provide a 1 MHz analog bandwidth with a secondary current sensitivity of 1 na (bandwidth can be traded for increased sensitivity). Fundamental limitations, however, are much higher as a secondary current level of 1 na still represents 10^4 particles/microsecond. Beam probe sensitivity is ~ 2 volts for potential fluctuations (Chapter IV).

Obtaining mode information, such as the spatial wave number (k) or the propagation direction, requires simultaneous measurements from at least two spatial locations. This is possible with a beam probe if two detectors are employed, or a single detector with multiple entrance apertures. Alternatively, it is theoretically possible to chop the observation point between the two spatial locations, at a rate sufficient to sample temporal variations

$$f_s \geq \frac{\omega}{\pi} \quad (15)$$

where f_s represents the chop frequency and ω the wave frequency. For optimum sensitivity the separation between spatial locations should be the order of a half wavelength

$$d \leq \frac{\pi}{k} \quad (16)$$

where the wave is of the form $e^{i(kx - \omega t)}$. Since the detector locations should be along the direction of wave propagation, and several modes of different wavelengths may exist, the spatial chop technique may be advantageous over multiple detectors since the sample locations are programmable.

In the absence of multiple spatial measurements considerable information is still available; fluctuations, in fact, are one of the most powerful beam probe measurements. Included are the frequency, amplitude, and temporal fluctuation profiles, as well as the phase between the

potential and $n_e f(T_e)$. Measurements may also include radial profiles, yielding radial envelopes and frequency dependence.

The beam probe capability for fluctuation measurements has been established, with MHD oscillations observed on the ST Tokamak and a flute instability studied on the RPI arc facility.⁷ Development is continuing, however, especially in the areas of increased bandwidth and advanced data processing. In particular, off-line processing has provided a 1 MHz bandwidth on the TMX system, an order of magnitude above closed loop (feedback) systems previously employed.¹⁹ In addition, Ed Powers and his associates at the University of Texas, Austin have applied advanced time dependent spectral analysis techniques to TMX data. Preliminary results of this work are described in Chapter VII.

CHAPTER III

Design of the TMX Heavy Ion Beam Probe

A. Introduction

The TMX heavy ion beam probe, although based on conventional beam probing techniques, incorporates new design features significantly improving its performance compared to previous systems. Unique aspects of the TMX plasma also had to be addressed, such as the high beta and space potential expected. Finally, the large physical size of the TMX and certain access restrictions influenced many aspects of the design.

Improvements in reliability, data acquisition, and operation were obtained through a microcomputer based digital control system. System checkout, pre-shot setup, and post-shot data handling are all controlled by simple commands from a terminal. The computer displays raw data between shots, and can also process the data if sufficient time is available (no local processing is possible, however, during normal shot intervals of approximately 3 minutes). Data are stored on floppy disc for later processing or transfer to a larger computer facility.

The secondary ion energy analyzer is of advanced design, incorporating internal front-end electronics and an internal guard-ring HV divider. This significantly reduces noise susceptibility and improves the signal bandwidth. The front-end amplifiers themselves are of improved design, with 1 MHz bandwidth and an equivalent input noise of 1 na.

Off-line computer processing of the analyzer signals was facilitated by the sophisticated data acquisition system. This allows a signal bandwidth limited only by the first stage electronics and digitizing rate. A hundred-fold bandwidth increase over conventional closed loop operation is obtained. In addition, open loop operation is completely stable, avoiding the oscillation problems inherent in the closed loop system.

Significant plasma pressure strongly modifies the vacuum trajectory of a probing beam. Beta values of 50% or more were expected in the central cell of TMX, with radial profiles unknown. The net effect on the beam probe is a movement of the sample volume within the plasma; measurements are still made, but at an unknown location and at reduced accuracy, since secondary ion angles into the energy analyzer are also unknown. To quantify these problems, possible beta profiles were included in the computer simulations of beam trajectories. In addition, a position sensitive detector was designed to monitor the location of the primary beam after it traversed and left the plasma. With this information, and plasma density and temperature profiles from other diagnostics, it was hoped that a self-consistent evaluation of the beta could be formed.

B. Beam Trajectory Simulations

1. Sweep and Detector Locations

Selection of the effective sweep point of the injected beam and the location of the secondary ion detector is a critical design decision, since they determine the system's basic spatial resolution.

The decision is often subjective, balancing performance over the expected range of plasma parameters, accessible plasma, noise immunity, and calibration. In addition, these locations strongly influence the overall complexity of the beam probe. Once specified, along with fixed constraints such as the magnetic field intensity, the required beam momentum, sweep range, and beam path lengths follow.

Optimization of the sweep and detector locations, subject to physical constraints imposed by the vacuum system, field coils, etc., are obtained through iterations of computer simulations of the primary and secondary ion orbits. The fairly straightforward solenoidal geometry of the TMX central cell allowed initial calculations to be performed with good accuracy on a Nova minicomputer, using a square well approximation to the magnetic field.¹ Perturbations from finite beta and large space potentials were also modeled with this system, using square well or gaussian dependencies. For verification of the results, and accurate data reduction, orbit calculations were also run using a full 3-D code on a larger DEC-10 computer system. These simulations provided very accurate grid maps and information on the axial displacement of the beam, from radial components of the field.

The location of the sweep and detector was optimized only with the central cell vacuum magnetic field, due to large uncertainties in the magnitude and distribution of plasma beta and potential. These locations, also subject to port restrictions, are shown in Figure III.B.1. Ion injection is from the bottom of TMX, 1.65 meters from the machine centerline. The analyzer is located above the machine, 2.1 meters from

Figure III.B.1. Location of the sweep point and energy analyzer.

the axis. The analyzer does not directly view the plasma (ultraviolet light from the plasma can be a strong source of noise if it enters the analyzer). The symmetric location of the four diagnostic ports around the TMX central cell did not allow optimum placement of the beam line and detector.¹ As a result the spatial resolution of the beam probe is slightly reduced from the maximum obtainable.

2. Vacuum Magnetic Field Detection Grid

The resulting energy/angle detection grid with the vacuum magnetic field only is shown in Figure III.B.2. Solid curves indicate the locus of spatial points entering the detector at a particular injection energy, dotted curves are for fixed injection angles. About 3/4 of the plasma is accessible with a 16 degree sweep and a 4.6 kV range of injected energy (the energy may be scaled as B^2/m for fields other than 1 kG or ions other than thallium). The grids are close to rectangular, an indication that the sample volume will also be close to the desired rectangular shape.

Results from the full 3-D simulations along the constant energy ($E_{inj} = 11.726$ kV) and constant angle ($\theta_1 = 5^\circ$) trajectories which pass through the plasma center are shown in Figure III.B.3. Both of these trajectories yield a fairly good radial scan of the plasma, with only a small change in azimuthal angle, as shown in Figure V.B.2 (exact radial scans can of course be obtained along any azimuth by programming the injected beam energy and angle simultaneously; this may pose certain difficulties, however, as described in Section V.8). The spatial

Ion: Thallium (Potassium)

Energy: 9.5 - 14.1 keV
(12.4 - 18.4 keV)

Angle: 121 - 137 deg.

Magnetic field: 1 kG (0.5 kG)

Plasma:

Beta: 0

Potential: 0

Source:

x: 70.0 cm

y: -140.0 cm

Detector:

x: 125.0 cm

y: 171.0 cm

Figure III.B.2. Energy/angle detection grid with vacuum magnetic field.

Figure III.B.3. (a) Radial location of the sample volume, (b) azimuthal beam angle at the detector, (c) axial beam displacement at the detector, (d) axial beam angle at the detector, for a diameter scan of the plasma at constant beam energy ($V_{\text{gun}} = 11.726$ kV at 1 kG central cell magnetic field).

Figure III.8.3. (e) Radial location of the sample volume, and (f) azimuthal beam angle at the detector for a radial scan of the plasma at constant beam injection angle ($\theta_i = 5$ deg; V_{inj} indicated for 1 kG magnetic field).

linearity of these grid lines is a consequence of the large distances to the sweep and detector locations compared to the plasma radii ($r_{\text{swp}}/r_{\text{plasma}} \sim 5$). A perspective of this is given in Figure III.B.4(a), where the actual primary and secondary trajectories are shown when probing near the plasma center.

Fixed energy scans allow measurements to be obtained beyond the 30 cm nominal plasma radius in the $-x$ direction, as shown in Figure V.B.2. Injected beam scrapeoff on a vacuum valve limits the $+x$ scan to 21 cm radius, however, a consequence of the port structure. The radial scan obtained at a fixed injection angle is not restricted (this scan could be extended to $+y$ values not shown in Figure V.B.2 if desired).

As evident from (f) of Figure III.B.3, the constant injection angle scan results in only a small, ~ 1 degree, change in the secondary ion entrance angle into the analyzer. This is a preferred scan, as the analyzer may be adjusted so that this angle corresponds to the most constant region of its angular response. Conversely, detailed knowledge of the angular response of the analyzer is not required for a good relative measurement along this radii. During a constant energy scan, shown in (a-d) of Figure III.B.3, the beam entrance angle changes ~ 10 degrees across the plasma diameter. This large a change must be carefully included in data processing, as described in Section IV.C.

3. Detection Grid with Finite Beta

As TMX was expected to operate with a high central cell plasma beta ($\beta \leq 0.5$) ion orbits are significantly perturbed from the vacuum conditions. Since the distribution of beta was not known during the beam

Figure III.8.4. (a) Typical primary and secondary trajectories when probing near the plasma center, and (b) a primary trajectory entering the energy analyzer.

probe design a simplified model was used to estimate its effect on the grid map shape, injection parameters, and sample volumes. A square wall radial approximation was used, with flux conservation within the TMX vacuum tank.

The resulting grid map for $\beta = 0.5$ is shown in Figure III.B.5. Injection parameters for the 500 gauss vacuum magnetic field are shown, since if plasma parameters are not a strong function of vacuum field (which may not be the case) maximum beta should occur at the minimum central cell field level (of course the data is directly scalable to other field intensities if beta remains constant; the shape of the grid map remains the same). Beta has been held constant out to the nominal plasma radius of 30 cm (250-gauss net field), followed by a 4% increase in the vacuum field to the wall, providing flux conservation.

The nearly straight constant energy grid lines in the no beta case (Figure III.B.2) have become significantly curved. Resolution is lost in the right-half plane (positive x), but actually increased in the left, where close to rectangular grids are formed. The required energy range to scan the plasma changes. A beam energy of 11.6 kV is required to probe the plasma center in the 50% beta case; this compares to 15.4 kV with vacuum field (the grid line passing through the plasma center in Figure III.B.2 scales to 15.4 kV with potassium ion injection and a 500 gauss field).

Ion: Potassium

Energy: 10.6 - 12.6 keV

Angle: 123 - 137 deg.

Magnetic field: 0.5 kG

Plasma:

Beta: 0.5

Potential: 0

Source:

x: 70.0 cm

y: -140.0 cm

Detector:

x: 125.0 cm

y: 171.0 cm

Figure 11.8.5. Energy/angle detection grid with $\beta = 0.5$.

4. Detection Grid with Finite Beta and Potential

At the minimum TMX central cell field level of 500 gauss beam probe operation is restricted to potassium or rubidium ion injection, with an energy range of 5 to 18 kilovolts (the lighter alkalis, lithium and sodium, do not have sufficient electron-impact ionization cross sections). Since a kilovolt space potential was anticipated in TMX, 5 to 20% of the injected beam energy, it was expected that ion trajectories could be strongly modified by the plasma electric fields.

To determine the importance of this effect a model for the plasma potential was included in the computer orbit simulations. The potential was assumed flat to 25 cm radius, followed by gaussian falloff with a 5 cm half-width. The resulting detection grid for a 1 kV potential and vacuum magnetic field (no beta, is shown in Figure III.B.6. A comparison of this grid map with the zero potential, zero beta case (Figure III.B.2) indicates that the grids have become slightly less rectangular, although the degradation is not large. The energy required to scan the plasma is similar, although sample volumes are displaced as much as 15 cm, especially in the left half of the plasma.

Unlike finite beta perturbations, space potential influence on the trajectories is reduced at higher beam energies. When TMX is operated at 1 and 2 kG central cell field strengths, appropriate selection of K, Rb, Cs, or Tl ions allow injection from 10 to 100 kV. The beam probe was designed for up to 60 kV ion injection.

Ion: Potassium

Energy: 11.4 - 18.4 keV

Angle: 121 - 135 deg.

Magnetic field: 0.5 kG

Plasma:

Beta: 0

Potential: 1 kV

Source:

x: 70.0 cm

y: -10.0 cm

Detector:

x: 125.0 cm

y: 171.0 cm

Figure III.B.6. Energy/angle detection grid with $\phi = 1$ kV.

A grid map including both beta (0.5) and potential (1 kV) is shown in Figure III.B.7. The resulting detection grid is very different from either the beta only or the potential only simulations. The sample volume is increased over the entire plasma cross section as compared to the other cases. The required energy to scan the plasma is intermediate between the individual cases, but increases from right to left on the grid map, opposite to the other simulations including that with vacuum field only. This is clearly a difficult operating regime for the beam probe, both because of the poor resulting sample volumes and the difficulty in knowing the sample volume location without detailed knowledge of the beta and potential profiles.

5. Sample Volumes

Although energy/angle detection grids give a good indication of the sample volume shape, absolute determination requires finite beam and detector simulations. These simulations have been performed using the 2-D solenoidal field model implemented on the Nova minicomputer¹. Sample volumes have been calculated with vacuum field, 50% beta, and 1 kV potential conditions previously discussed.

A finite size parallel beam was approximated in the simulations with two beams originating at the effective sweep point, separated by one degree. With ~165 cm path length to the plasma center the beams are nearly parallel in the plasma with a separation of approximately 3 cm. The sample volume is obtained by locating secondaries

Ion: Potassium

Energy: 12.1 - 13.2 keV

Angle: 122 - 134 deg.

Magnetic field: 0.5 kG

Plasma:

Beta: 0.5

Potential: 1 kV

Source:

x: 70.0 cm

y: -140.0 cm

Detector:

x: 125.0 cm

y: 171.0 cm

Figure III.B.7. Energy/angle detection grid with $\beta = 0.5$ and $\phi = 1$ kV.

along each beam which hit the end-points of a finite size detector straddling the nominal detector location. This defines the sample volume in that plane, as shown in Figure III.B.8. A 3-cm detector was used in the simulations, orientated perpendicular to the incoming secondaries. The nearly solenoidal magnetic field in the central cell of TMX yields no significant axial (z) dependence to the sample volume shape. The sample volume is limited by the beam and detector extent in z.

The resulting sample volumes are shown in Figure III.B.9. The best overall spatial resolution is obtained with vacuum magnetic field only, shown in (a) of the figure. The sample volumes are close to rectangular at both small and large radii, in agreement with the grid map, Figure III.B.2. For the sample volume near the plasma center, the sample volume length l varies from ~ 4.02 cm on the right to ~ 4.29 cm on the left. With the 3 cm detector used in the simulations this represents a magnification of about 1.4. All actual measurements were taken with a 0.5 cm detector entrance slit width. With the magnification this results in a sample volume length of 0.7 cm along with beam path. The beam diameter (FWHM) is approximately 3 cm (Section III.C), yielding a sample volume cross section of 2.1 cm^2 in the x-y plane. The axial dimension of one of the split plate detectors is 3.2 cm, about the same as the beam diameter. With typical beam blow up, however, the effective sample volume extent in z is probably only ~ 2 cm, yielding an overall sample volume of $\sim 4 \text{ cm}^3$ under vacuum conditions.

Sample volumes with the beta and potential models included in the simulations are shown in Figure III.B.9(b,d). The sample volumes

Figure III.8.8. Definition of the plasma sample volume.

Figure III.B.9. Plasma sample volumes for several values of plasma beta and space potential.

generally become less rectangular under these conditions, again very similar to the shape of the grid maps. Spatial resolution is especially poor with both beta and potential compared to the other cases, as expected. About twice the linear distance is covered in the plasma for the equivalent sample volume. The beta only simulation yielded the best, nearly rectangular, sample volume in the lower left of the plasma.

6. Calibration Trajectories

An important requirement of the system geometry is the ability to have the primary beam orbit directly into the analyzer for in-situ system calibration. For the energy/angle range shown in Figure IV.C.1 this is accomplished with the TMX beam probe. Vacuum magnetic field is required, with the energy for thallium ion injection with a 1-kG field intensity shown. The actual beam trajectory for the calibration orbit is shown in Figure III.B.4(b), for an injected angle, θ_1 , of -7.5 degrees.

C. Primary Beam Monitors

1. Introduction

Injected beam intensity, profile, and purity are monitored by three detectors along the primary beam path. One of the detectors is located within the beam line, and two are in the main central cell tank.

Beam output from the ion gun may be verified with a cross-hair detector located in the beam line, without opening valves to the main vacuum vessel. The detector is movable from outside of the vacuum system,

and swings out of the beam path when not in use. The detector is located past the beam deflection plates, and may also be used to verify their operation.

A "straight-through" detector monitors the beam profile in the main central cell tank, at a distance from the ion gun comparable to the plasma. This detector is used when focusing the ion beam, and also verifies that all valves and the getter shutter in the beam line are open. In addition, the straight-through detector serves to calibrate the sweep system.

A third detector, the "primary beam detector" is accessible to the primary beam only with central cell magnetic field. This detector was designed to indicate the primary beam position during a shot, to follow plasma beta buildup and decay. It also serves to check the ion source purity, central cell field intensity, and out-of-plane (axial) beam deflection.

2. Straight-Through Detector and Measured Beam Profile

The beam profile is monitored with a "straight-through" detector mounted on one of the TMX diagnostic ports, as shown in Figure III.C.1. The detector is located in a line-of-sight path to the gun, at a distance of 3.2 meters. A 3 x 3 grid of ten gauge wire makes up the detector, as shown in Figure III.C.1(a). The wires are arranged in a rectangular grid, with a spacing of 4.5 cm. One set of wires is orientated parallel to the machine axis (z direction), and monitors the beam profile in the x-y plane. The remaining wires monitor the axial beam profile. Each wire feeds a current-to-voltage converter (i/v) which is monitored on an oscilloscope.

(a)

Straight through detector

(b)

$V_G = 11.94 \text{ kV}$
 $i_{\text{beam}} = 4.9 \mu\text{A}$
 Thallium

Figure III.C.1. Straight-through detector (a) schematic and (b) beam profile.

A large plate located directly behind the grid serves as a total current monitor. The plate is biased 50 volts positive, to collect secondary electron emission. I/V gains of 10^5 volts/amp and 10^6 volts/amp are used for the back plate and grid wires, respectively.

A typical beam profile shown in Figure III.C.1(b) is obtained by linearly sweeping the beam across the grid wires. Thallium ion injection is being monitored at a beam energy of 11.94 keV. The injected beam current is $4.9 \mu\text{A}$ (an RPI-type thermionic source² is being operated with a filament current of 6.9 amperes at a voltage of 2.2 volts). The width of the beam at half intensity (FWHM) is about 4.5 cm.

The straight-through detector is located somewhat further from the ion gun than the plasma. Assuming a linear defocusing of the beam from a small source at the gun, the beam FWHM at the plasma center is approximately 3 cm.

Better focusing of the ion beam is obtained at higher operating voltages and with lighter ions, although thallium injection at about 12 kV was used for most beam probe operation on TMX. Beam current is also a function of voltage and ion species ($i_b \propto V^{3/2}/\sqrt{m}$ for space charge limited flow from a Pierce structure with extraction voltage V and ion mass m), with source-emitter age also a factor. Maximum thallium beam currents obtained were $\sim 15 \mu\text{A}$, with typical operation in the 5 to $10 \mu\text{A}$ range.

3. The Primary Beam Detector

To monitor the primary beam with magnetic field the beam probe design included a linear position sensitive detector, the "primary beam

detector". This detector is mounted on the top rectangular diagnostic port in the TMX central cell, as shown in Figure III.B.1. The primary beam detector monitors the x coordinate beam position after it has traversed the main tank, and was designed to operate with or without plasma. Without plasma it serves in calibration and determining impurity levels in the primary beam. With plasma the detector is designed to monitor the plasma beta, by indicating the primary beam position after it exits the plasma.

The primary beam detector consists of 60 rectangular copper bars connected by 1 k Ω resistors, as shown in Figure III.C.2. The bars are spaced 1 cm apart, yielding a 60 cm position sensing range. The bars are shielded from the plasma by three screens, one of which is grounded and two of which may be independently biased. In addition, 15 wires are mounted perpendicular to the copper bars, to monitor the axial (z) position of the beam. Two wires are also mounted parallel to the copper bars for calibration purposes.

The output from the copper bar at each end of the detector is monitored through a current-to-voltage converter. The resistive string forms a current divider for the incident beam, with

$$x = \left[\frac{i_1}{i_1 + i_2} \right] l \quad (1)$$

where i_1 and i_2 are the currents from each end of the detector, l is the detector length (60 cm), and x is the beam position referenced to the end of the detector where i_2 is measured.

Figure III.C.2. Primary beam detector.

Measurements obtained with the primary beam detector with vacuum magnetic field (no plasma) are shown in Figure III.C.3. In each oscillogram, the beam is deflected into the detector by the buildup and decay of the central cell magnetic field. The field intensity never reaches a steady state value, however, due to the time constant of the 5/8" thick aluminum vacuum wall compared with the on time of the 18 coils making up the TMX magnet set. The current in one of the coils, the east inner cell, is shown in the lowest trace of each photo to give an indication of the magnet on time.

The top oscillogram, Figure III.C.3.(a), shows the primary beam deflected into the primary beam detector with constant injection conditions. The magnetic field sweeps the beam onto the north end of the detector, at which time the north copper bar signal deflects sharply downward, indicating the presence of beam current. As the beam deflects further along the detector, the north signal decreases while the south level comes up. A peak is reached about 1 division before the center of the photo, at which time most of the signal has switched to the south, indicating that the beam is close to that end of the detector. The field then decays and the beam returns to the north. Also shown in this oscillogram are three of the north-south wires, which monitor the axial (z) position of the beam. The beam is seen to be centered on the detector, with little beam current spilling to the wires located to the east and west.

Oscillogram (b) of Figure III.C.3 also shows the primary beam as it is deflected across the primary beam detector, except an additional

Figure III.C.3. Primary beam detector signals (a) magnet sweep only, (b) axial sweep applied, and (c) radial sweep applied.

axial (z) sweep has been applied. The axial beam position is clearly indicated by the array of north-south wires as it traverses the detector. The south end of the copper bars is also shown, which indicates current as long as the beam is not swept entirely out of the detector. Note that during an appreciable part of the sweep the beam is out of the detector to the east. The beam is only partially swept out of the detector to the west, as indicated by the slight drop in copper bar current (also by the west-most wire which shows only a single peak per sweep cycle).

The detector output when θ modulation (Figure III.B.1) is applied to the beam is shown in (c) of Figure III.C.3. The copper bar signals follow the beam position, with positive sweep bringing the beam closer to the south end of the detector. Theta sweep does not affect the signal on the center north-south wire, indicating good alignment of the theta sweep plates. The trace labeled "EW North" is the wire mounted parallel to the copper bars near the center of the detector, used to check the calibration and accuracy of the copper bar signals.

D. Secondary Current Level

The TMX plasma may be probed with several ion species, yielding varying levels of secondary current. Selection of appropriate ions is determined by the central cell magnetic field, since it is necessary to keep the beam injection energy within the 5 to 60 kV operating range of the ion gun. Except at the highest field intensity, a choice of injected species is available.

To calculate the expected signal levels the plasma density and temperature must be known. If attenuation of the beam is significant, the

radial profiles of these quantities must also be known, even to estimate signal levels on-axis. For the TMX central cell plasma, an electron temperature of 50 eV and an electron density of $4 \times 10^{12} \text{ cm}^{-3}$ is assumed. Square well profiles are also assumed, with the parameters flat to a radius of 20 cm and zero elsewhere.

The alkali ions which may be used to probe the TMX central cell are shown in Table III.D.1, for the three nominal field intensities. For each species, the range of injected energy required to probe the plasma is listed. Vacuum magnetic field is assumed ($\beta = 0, \Phi = 0$), with the beam energies scaled from Figure III.B.2. Cross sections and signal levels are given for the nominal injection voltage, V_0 , which is the voltage required to probe the plasma center.

The effective cross sections for electron impact ionization, σ_{eff} , are a function of the plasma electron temperature and ion beam velocity, as described in Section II.B.2. Bieniosek has calculated $1^+ \rightarrow 2^+$ effective cross sections for beam energies of 10, 25, and 40 keV, from the experimentally measured absolute cross sections.³ The cross sections given in Table III.D.1 are from the Bieniosek results, scaled to the required beam energy from the closest available data (the cross sections scale as $1/\sqrt{\text{energy}}$).

The secondary current, i_s , generated in the sample volume is calculated from eqn (II.8)

$$i_s/i_p = n_e l \sigma_{\text{eff}} q_s/q_p \quad (2)$$

Nominal Injection Voltage (V_0)									
C. Cell Field (gauss)	Ion	$V_{\min}$ (kV)	V_0 (kV)	$V_{\max}$ (kV)	σ_{eff} ($\times 10^{-16} \text{ cm}^2$)	i_s/i_p (na/ μa)	i_p/i_{po} ($r=0$)	i_{po} (μa)	$i_s/8$ (na)
500	Na	21.1	26.2	31.3	1.1	0.6	99%	70	5
	K	12.4	15.4	18.4	11.5	6.4	91%	25	18
	Rb	5.7	7.1	8.4	44.0	24.6	70%	5	11
1000	Rb	22.7	28.2	33.7	22.2	12.4	84%	40	52
	Cs	14.6	18.1	21.7	41.1	23.0	72%	16	33
	Tl	9.5	11.8	14.1	63	35.3	60%	7	19
2000	Tl	38.0	47.1	56.3	32	17.9	77%	60	103

Table III.D.1
Beam Injection Voltages and Signal Levels for Probing the Central Cell Plasma.
 V_0 is the acceleration voltage required to probe the center of the TMX plasma.

The sample length along the beam, l , is 0.7 cm as derived in Section III.B.5. Singly charged primaries and doubly charged secondaries are assumed ($q_s/q_p = 2$). A wide range in the level of secondary current per microamp of primary current delivered to the sample volume (i_p) is evident in the table.

The beam current actually delivered to the sample volume, i_p , is reduced from the injected current, i_{po} , by beam attenuation. The beam intensity is given by

$$i_p = i_{po} e^{-\int n_e \sigma dl} \quad (3)$$

with the integration performed along the beam trajectory. With the square-well density profile assumed here, the current delivered to the sample volume at the plasma center is equal to

$$i_p/i_{po} = e^{-n_e \sigma L} \quad (4)$$

with L equal to 20 cm. The cross sections used in calculating the above are the effective cross sections listed in the table. This neglects beam attenuation from tertiary and higher order ionization reactions, and all other processes affecting the beam. It also neglects attenuation of the secondary beam as it exits the plasma. With these omissions the beam attenuation may be considerably higher than listed, although the cross sections are not accurately known for most of the higher order reactions.

In the cases where beam attenuation is significant (e.g., Tl injection at 1 kG) the actual secondary current will probably be smaller than the value listed in the right column.

The injected beam currents, i_{p0} , listed in the table are the approximate outputs of the ion gun under normal operation (close to space charge limited flow).

The final column in Table III.D.1 lists the actual secondary current level expected on each detector plate. The injected beam current, i_{p0} , multiplied by the beam attenuation gives the primary current delivered to the plasma sample volume. This is then multiplied by the secondary production rate, i_s/i_p , to obtain the level of secondaries produced. The total secondary current, i_s , is divided by eight and listed in the table. A factor of two division is for beam defocusing, and a factor of four is introduced so that the expected current level on each of the four detector plates is listed.

Expected current levels range from a few nanoamps to over 100 nanoamps per plate. Optimum choice of the injected species can be made once the detector noise, electric field orbit perturbations, and other factors are known. Sodium operation will probably be limited, since the signal level expected on axis, 5 na, is only a factor of 5 above the front-end amplifier noise (although bandwidth may be traded for reduced noise).

E. Energy Analyzer

The energy of escaping secondary ions is measured with a specially designed parallel plate electrostatic energy analyzer. The analyzer contains a split plate detector, providing an energy resolution $E/\Delta E \sim 10^4$.

Proca and Green showed that for appropriate design of the analyzer, second order focusing could be obtained at a beam entrance angle of 30 degrees^{4,5}. These "30° analyzers" allow small deviations of the beam angle around 30° without affecting the measurement accuracy. To increase the overall angular acceptance range, analyzers used in beam probe systems typically modify these dimensions slightly to create an angular response with two first order foci. A family of such curves is given in Figure III.E.1 (the labeling of each curve corresponds to the larger of the two first order focusing angles and is referred to as the analyzer "design angle"). As shown in the figure, the analyzer gain can be held within a small error band for as much as 10 degrees of beam angle, where in the 30° case the gain dramatically changes after only a few degrees.

The TMX analyzer has been designed to allow changing its angular response through external adjustments. The analyzer design angle is a function of three mechanical dimensions,

$$\cot \theta_0 \left(1 + \frac{1}{\cos 2\theta_0} \right) = \frac{x_d}{y_{d1} + y_{d2}} \quad (5)$$

Figure III.E.1. (a) Angular sensitivity of (b) parallel plate electrostatic energy analyzer.

where θ_0 is the design angle and x_d , y_{d1} , and y_{d2} are as indicated in Figure III.E.1(b). External adjustment of the angular response is obtained by mounting the split plate assembly on a transport movable in the x direction. A rotating shaft through the vacuum wall provides access to the transport mechanism. An adjustment range of several centimeters is available, as described in Section IV.C.4.

The entrance slit width, w , is also adjustable from outside of the vacuum system. With off-line processing of the analyzer signals, the entrance slit width is an important parameter as it sets the analyzer's dynamic range; the change in potential which can be followed before the ion beam moves entirely off one of the split plates. The entrance slit width is also directly proportional to the total signal reaching the detector plates, and determines the length of the plasma sample volume along the beam path. Another important use of a variable entrance slit width is in determining noise sources, since the entrance aperture may be fully closed if desired. The entrance slit width is adjustable from 0 to 1.84 cm on the TMX analyzer.

Four split plates monitor the position of the beam in the TMX analyzer. This allows monitoring the beam position along the entrance opening (z), as well as the x beam displacement used in calculating the beam energy. The 4-way split plates are also useful under certain circumstances for noise reduction, as described in Appendix I.

The first stage current to voltage converters (i/v's) are located in the base of the TMX analyzer, as shown in Figure IV.C.2. This eliminates the noise problems which occur when the nanoampere signal levels from the split plates are fed through the vacuum wall to external amplifiers. In addition, the frequency response of the detector is enhanced, since the effective capacitance of the detector plates is minimized with very short lead lengths. Reduced input capacitance also substantially reduces the i/v noise.

The internal amplifiers consist of a 10^6 volt/amp i/v, followed by a voltage amplifier with a gain of 10^2 . The equivalent input noise of the front-end (30 pf load) is 1 na with a 3 db frequency response of 1 mHz. The maximum input signal is 100 na (10 volt output), yielding a 100:1 dynamic range. Filtering the output to reduce the amplifier noise, which is approximately white, allows increasing the dynamic range at reduced bandwidth. Alternatively, the second stage gain may be reduced to increase the dynamic range, since its maximum output is the limiting factor.

To minimize drift and remain within required operating temperatures the amplifiers are water cooled within the vacuum system. Each amplifier assembly (4 total) dissipates about seven watts. Active components are thermally bonded to an 1/8" thick copper plate, which also serves to electrostatically shield adjacent channels. Drift is further reduced by incorporating a dual FET in the first stage, with one of the FET's used for temperature compensation. An overall drift of ~ 10 mV/month (0.1% of full output) was achieved.

A uniform electric field is maintained between the top and ground plates of the analyzer with eight guard rings. The resistive divider which supplies their operating voltage is also located within the vacuum system. The resistors are mounted directly on the analyzer, using boron nitride insulators. Resistors located internally minimize noise pickup and the effective top plate capacitance. The vacuum compatible resistors (TRW uncoated CR8 series, $2.2\text{ M}\Omega$) are water cooled through the boron nitride. Each resistor dissipates 3.5 watts at the maximum analyzer design voltage of 25kV (for this power level water cooling must keep the resistors close to room temperature, 20°C . At typical analyzer operating voltages required on TMX the resistors dissipate less than 1.5 watts of power and derating curves specify operation to 200°C .).

F. Beam Line

The primary beam line consists of the components required to form and inject the heavy ion beam. The TMX beam line is made up of two main chambers, housing the ion gun and the deflection optics, as shown in Figure III.B.1. Pneumatically operated valves allow isolation of each tank from the rest of the system, and an interlocked shutter protects the beam line from gettering.

The injected beam is formed by a single lens ion gun incorporating a modified Pierce-type ion source.¹ The gun is located about two meters from the plasma, in an apertured chamber differentially pumped by an independent vacuum system. Ions are extracted from a thermionically heated zeolite which has been loaded with salts of the required ion.²

Two sets of electrostatic deflection plates steer the beam to the appropriate injection angle. Neglecting fringing fields, the deflection provided by two parallel plates with length L and separation d is given by

$$\tan \theta = \frac{qVL}{2dE} \quad (6)$$

where q is the beam charge/ion, E is the beam energy, and V is the voltage applied across the plates for a deflection θ .

The radial steering, θ_1 in Figure III.B.1, is provided by deflection plates with a length of 9" and separation of 1.5". These dimensions were selected to allow ± 10 degrees of deflection of an 80 keV beam with a maximum voltage of 5 kV across the plates. The plates are driven differentially, with opposite polarity voltages of equal magnitude. This maintains ground potential midway between the plates, minimizing fringing-field effects. Two Trek, Inc. 608A-2 power supplies provide ± 2.5 kV/ ± 5 ma with a slew rate of 30 V/ μ s. The deflection plates are parallel for the first 5.5" along the beam path, and then deflect outward at 10 degrees for the remaining 3.5". The plates measure 4" in the z direction.

A set of axial (z) deflection plates are also provided, to compensate for the radial component of the magnetic field which bends the beam out of the central cell midplane, and to correct any angular misalignment.

These plates are also used to chop the injected beam when desired. The axial plates are located before the main deflection plates, as shown in Figure III.B.1. They measure 5.5" in length by 4" long with a spacing of 1.0". Trek 604 power supplies feed the plates differentially at a maximum of ± 500 V/ ± 20 ma. Up to ± 5 degrees of axial deflection is obtained before mechanical blockage of the beam occurs.

G. Control and Data Acquisition System

1. Introduction

The heavy ion beam probe is controlled by a microcomputer through CAMAC based instrumentation. The computer, a Digital Equipment Corporation LSI-11, provides system checkout, pre-shot setup, post-shot data handling, status monitoring, and other functions. The LSI-11 will also provide data processing, although transfer of raw data to a large computer is generally desirable.

The layout of the control system is shown in Figure III.G.1. Three CAMAC crates are used, communicating through a serial highway. Two of the crates are located next to the machine and control the beam line and energy analyzer. The third crate is located in the diagnostic room and provides interface to the microcomputer. The serial highway is transformer coupled for ground isolation and operates at a data rate of 1 Mbit/sec. Both commercial and custom design CAMAC modules are used.

The microcomputer is interfaced to a dual floppy disc for data and program storage. Transfer of the raw data to a larger computer is accomplished by physically transferring diskettes. A DEC-10 interfaced to

Figure III.G.1. The control and data acquisition system.

the National MFE Computer Center was used for most of the processing of beam probe data.

User programming of the LSI-11 is in Fortran, with assembly language subroutines providing communication with the CAMAC system. Software is divided into three main programs; i) a control program for operation of the beam probe, ii) a routine for system calibration, and iii) a local (simplified) data processing package. Each program is menu orientated, with single key selection of a desired function. The program subroutines are organized in a multi-overlay structure since the computer is limited to 32K words of memory.

The computer and serial highway communication is used before and after each TMX shot, but is dormant during the actual discharge. Data transfer rates, ~1K words/sec between the LSI-11 and any peripheral are too slow for real time control.

During a shot, data is acquired and locally stored by fast digitizers and sweeping of power supplies or other components is handled by analog signal generators. Waveform recorder memories, containing both measurement data and sweep waveforms, are read into the computer after the shot. These data, along with the system status (power supply voltages and other conditions), are then transferred to the floppy disc. Five TMX shots are recorded on a single sided, single density diskette.

2. High Voltage Power Supplies

High voltage power supplies are required to drive the ion gun, energy analyzer, and sweep plates. To maximize bandwidths and personnel safety they are located in the machine area, within a few feet of their associated component. The ac power driving the supplies (110V/60Hz) is interlocked to an ionization gauge in the beam line, providing automatic shutdown if vacuum is lost. The supplies are programmed through 12-bit digital-to-analog converters (DAC's) located in the CAMAC crates.

The ion gun is driven by three Spellman RHR series power supplies, as indicated in Table III.G.1. Although the gun presents only a capacitive load (except for a few microamperes of beam current), fairly high current supplies are used to minimize possible plasma loading effects. Internal regulation and noise output of the supplies is better than 0.01%.

The output of the Pierce supply, which determines the energy of the injected beam, is accurately monitored with a precision resistive divider and a buffered 12-bit analog-to-digital converter. This circuitry and the measurement accuracy is described in Section IV.B. The remaining gun supplies, the extractor and shield, are not critical and rely on their 1% programming accuracy for the desired output.

The energy analyzer top plate may be driven by either of two high voltage supplies, a Trek 606 with up to 10 kV output, or a Spellman RHR series supply with a 30 kV maximum output. The Trek is used for all beam probe operation when the central cell magnetic field intensity is 1 kG or less. This supply has sufficient bandwidth for closed loop operation of

Power Supply	Output Voltage	Output Current	Supply Accuracy	Small Signal Bandwidth	Maximum Output Bandwidth	Output Step Size
<i>Ion Gun</i>						
Pierce	0-80 kV	0-3 ma	0.1%*		1 Hz	19.5 V
Extractor	0-50 kV	0-1 ma	1%		1 Hz	12.2 V
Shield	0-40 kV	0-1.5 ma	1%		1 Hz	9.8 V
<i>Analyzer</i>						
Trek	0-±10 kV	0-±1.6 ma	0.1%*	100 kHz**	160 Hz	4.9 V
Spellman	0-30 kV	0-5 ma	0.1%*		1 Hz	7.3 V
<i>Sweep</i>						
Theta	0-±2.5 kV	0-±5 ma	0.1%	5 kHz	1.9 kHz	1.2 V
z	0-±500 V	0-± 20 ma	1%	120 kHz	50 kHz	0.2 V

* With external monitor

** Gain-bandwidth product

Table III.G.1
High Voltage Power Supplies

the analyzer (used during calibration) and is more accurate and stable than the Spellman. The Spellman supply is used at higher field levels and if higher current is required should plasma loading of the analyzer be a problem.

The "theta" and "z" sweep supplies are lower voltage units with higher frequency response. Fast scans of the plasma during a shot may be obtained with the theta sweep, as its 2.5 MHz gain-bandwidth product and gain of 500 yields a 3 db frequency response of 5 kHz. A slew rate of 30 V/ μ s lowers the bandwidth to 1.9 kHz during full output, as shown in Table III.G.1. The axial sweep supply (z) is used for chopping the beam if desired, and requires even higher bandwidth. The 3 db frequency response of this supply is 120 kHz at a gain of 100. A slew rate of 10 V/ μ s provides a maximum signal bandwidth of 50 kHz.

Twelve bit analog-to-digital converters (Kinetic Systems 3112-MIA) providing 1 part of 4096 resolution drive each high voltage supply. The resulting step size of the power supply outputs are given in the rightmost column of Table III.G.1. Zener diode clamped RC filters are placed between the DAC outputs and all Spellman programming inputs, to prevent damage to the CAMAC modules which may otherwise occur if these supplies arc to ground.

3. Analyzer

The output of the analyzer amplifiers is filtered and analog processed prior to recording. The Sum/Difference Amplifier contains most of the circuitry for filtering and for feedback control of the analyzer

when enabled (schematics, parts listing, and other documentation is provided for this custom designed module in microfiche, with LLNL document number LEA 78-1193-01).

A block diagram of the Sum/Difference Amplifier is shown in Figure III.G.2. Each split plate signal is bandwidth limited by a 1 MHz 4-pole Butterworth low pass filter. Although the 3 db frequency response of the front-end amplifiers is 1 MHz, their noise output extends over a much larger bandwidth. Filtering eliminates the out of band noise, improving the signal to noise ratio when wide bandwidth recorders are used. Since the front-end electronics are located within the vacuum system, and not readily accessible, these stages also provide trim controls to compensate dc drift (offset) and small channel-to-channel gain variations. An adjustment range of 1% in gain and ± 1 volt of offset is provided. The split plate signals undergo additional bandlimiting before recording by the full-shot digitizers, since their sampling rate (100 kHz) is not sufficient for the full available analog bandwidth. Four pole Bessel filters are used, operating at 40 kHz bandwidth.

The split plate outputs are also fed through sum and differencing amplifiers to form the signals required for feedback control. Both up-down and axial (left-right) difference signals are formed, to allow feedback control of the analyzer top plate for closed loop potential measurements and feedback control of the beam position using the axial deflection plates. Feedback control of the analyzer was used in certain phases of calibration, as described in Section IV.C.2. Feedback control of the axial beam position was not needed, since the radial magnetic field

Figure III.G.2. Block diagram of the sum/difference amplifier.

(from the quadrupole magnets and field errors) did not produce significant change in the axial deflection of the beam across the plasma.

Circuitry within the Sum/Difference Amplifier is based on wide band, high slew rate operational amplifiers (Analog Devices 1321 or 1322). All outputs are capable of providing full ± 10 volt swings at 1 mHz.

4. Ion Gun Filament

The ion gun filament requires current drive at up to 8 amperes with an operating voltage of 2 to 5 volts. The filament floats at the gun potential, a maximum of 60 kV. High voltage isolation is obtained with transformer coupling to the filament. To minimize the gun capacitance to ground a small ferrite transformer is used, operating at a frequency of 2 kHz. Computer control is obtained by supplying the filament power with an audio amplifier fed by a custom designed CAMAC module. To minimize noise from the ion gun, which would be at an undesirable frequency within the system passband, a rectifier and filter is used after the isolation transformer to feed the filament dc.

A block diagram of the filament controller is shown in Figure III.G.3. Drive to the isolation transformer is provided by an Altec 1590A 200 watt audio amplifier (only ~50 watts is actually required). A three to one step-down transformer provides an impedance match to the 0.5 Ω filament. High voltage isolation is obtained by winding the transformer secondary with 100 kV wire (Dielectric Sciences Inc. 2024). The primary is wound with conventional magnet wire.

Figure III.G.3. Block diagram of the ion gun filament controller.

Control and monitoring of the filament is provided by the Filament Controller CAMAC module, which also contains the 2 kHz source oscillator. Filament current is monitored by measuring and scaling the current flowing in the primary, low voltage, transformer winding, with feedback control maintaining the desired value. The filament current is programmed through the CAMAC dataway, with a digital-to-analog converter interfacing to the analog circuitry. An analog-to-digital converter within the module allows the computer to monitor the actual filament current and voltage. The computer monitoring of the filament current is accurate to ~ 0.1 ampere.

The output of the isolation transformer is rectified and filtered in a conventional bridge configuration, and fed to the filament. Analog meters, viewed through a clear plexiglass window, indicate the current and voltage. They are located in the machine area not accessible during machine operation, however, and are used to check calibration of the controller module and during debugging.

5. Operation

The heavy ion beam probe is operated by simple commands executed from a video terminal. Assuming vacuum interlocks are normal and key operated safety switches have enabled line power to the HV power supplies, all further setup and operation is through the computer.

The first step is running the control program, file-named HIBP. A menu is displayed on the CRT, indicating the various system functions. Warm-up of the ion gun filament is generally the first task. Pressing an appropriate key displays a second menu, providing access to the various

filament functions. The desired filament current is entered, and the computer ramps the current to this value at 1 ampere/minute.

After filament warmup, the next step is verifying beam line operation and focusing the beam. The desired gun voltages are entered, and the computer energizes the power supplies if certain protection conditions are met. Requirements include maximum levels allowed and a maximum voltage permitted between the Pierce and extractor electrodes. The computer adjusts the gun energy to high accuracy by reading the precision monitor after a short settling time and calculating a new programming voltage based on the supply error. A message is printed if the gun cannot be properly adjusted after several iterations.

When proper gun operation is verified, by computer acceptance of the monitored electrode voltages and an indication of ion current on the straight-through detector, focusing of the ion beam may be done. Menu selection applies a triangular sweep to the beam, moving it back and forth across the focusing grid on the straight-through detector. An oscilloscope displays the beam profile. The ion gun extractor voltage may then be slewed up or down by holding down the U or D keys respectively on the terminal. When the desired beam profile is obtained a third key allows returning to the menu.

Final set-up before TMX shots commence include requesting analyzer top plate voltage (also monitored and precisely adjusted by the computer), arming the data recorders, and setting up the beam sweep. At any time the entire status of the beam probe may be displayed on the CRT by

pressing Q on the keyboard. Parameters displayed include all high voltage (requested and actual if monitored), and other parameters. A typical status printout is shown in Figure IV.C.3(b).

After a shot, the data recorders are read onto floppy disc by pressing another key and typing a file name when prompted (beam probe files are named day month . shot number, such as 19AUG.30). Any errors for the shot are printed, such as no trigger received or other problems. Before the data is stored, the computer requests comments on the shot. Comments are not limited in length, and are placed at the beginning of the data file. A blank line terminates the comment string and the computer begins storing the data for that shot. First the beam probe status is recorded on the floppy, followed by data from the waveform recorders. Five channels from the LeCroy 8210 full-shot recorders are stored (4-split plate signals and 1 sweep waveform, 20 k words total), followed by high frequency burst recorder data if enabled.

The computer also displays the raw data on a storage oscilloscope, configured as an x-y recorder. When data transfers are complete (~1 minute) the computer becomes available for modifying the beam probe setup. With a TMX shot repetition rate of about 3 minutes, several minutes are available for new set-up as directed by the experimental plan and data from the previous shot.

CHAPTER IV

System Calibration and Sensitivity

A. Introduction

Obtaining the plasma space potential with a heavy ion beam probe requires measuring very small changes, typically a fraction of a percent, in the energy of the injected ion beam. Careful attention must be given to system alignment, calibration, and verification of performance; this, in fact, occupies a substantial portion of the effort required to obtain meaningful plasma measurements. In addition to individual subsystem calibration, direct calibration by injecting the primary beam into the analyzer is employed, as it is difficult to accurately measure some of the critical parameters. In addition, direct, in-situ calibration allows frequent recalibration to verify accuracy, compensate component drifts, and establish system performance.

Sources of error in space potential measurements can be divided into four areas. Errors are associated with i) high voltage power supplies determining the injected beam energy and analyzer electric field, ii) the electrostatic energy analyzer which measures the detected ion energy, iii) particle trajectories, and iv) noise. Obtaining the exact response of the energy analyzer is the most critical and difficult aspect of calibration. Much of this chapter describes a complete analysis of the TMX analyzer.

B. High Voltage Measurements

The injected ion beam energy must be accurately known. It partially determines trajectories through the magnetic field and must be subtracted from the secondary ion energy to calculate the plasma potential. In addition, the energy analyzer top plate voltage must be known to calculate the secondary ion energy. Higher absolute accuracy is required here, as the top plate voltage is multiplied by the analyzer gain (typically ~ 3) when calculating the secondary ion energy.

The ion gun acceleration potential and analyzer top plate voltage are directly measured, with the monitoring circuit shown in Figure IV.B.1. A precision high voltage divider (Spellman HVD-100-1) provides a 10,000:1 voltage reduction with 0.1% accuracy. The divider output feeds a buffer/amplifier in order to provide the required input impedance ($> 10^9 \Omega$) to avoid loading the divider, which has 100 K Ω output impedance. The buffer also maps the maximum output voltage of the high voltage power supplies into the full-scale input of the a/d converter (LeCroy 2232A). The a/d provides 12 bit digitization and input to the CAMAC system.

Only dc monitoring of high voltage is provided. The HV divider is uncompensated and has only a few hertz frequency response. The precision buffer is based on low-bandwidth instrumentation amplifiers and the a/d converter contains integral low pass filtering for noise reduction and anti-aliasing of its half-millisecond conversion time.

The monitoring accuracy is summarized in Table IV.B.1.

Figure IV.B.1. High voltage monitoring circuit.

<u>COMPONENT</u>	<u>ACCURACY</u>	<u>ABSOLUTE ERROR</u>	<u>TYPICAL ERROR*</u>
High Voltage Divider (Spellman HDV-100-1)	$\pm 0.1\%$	± 1.0 volt/kilovolt	Ion Gun: ± 11 volts Analyzer: ± 3.5 volts
Precision Buffer (LLL LEA 79-1114-01)	$\pm .001\%$ $\pm 25\mu\text{V}/^\circ\text{C}$	Insignificant	Insignificant†
A/D Converter (LeCroy 2232A)	± 1 count ± 30 ppm/°C	Ion Gun: $\pm \frac{60\text{kV}}{4096} = \pm 15$ volts Analyzer: $\pm \frac{30\text{kV}}{4096} = \pm 7$ volts	Ion Gun: ± 15 volts Analyzer: ± 7 volts

*11 keV beam energy

Table IV.8.1
High Voltage Measurement Accuracy

C. Energy Analyzer Calibration

1. Introduction

The energy of escaping secondary ions must be determined to about 1 part in 10^4 . The secondary ion flux, typically nanoamperes, is measured in the presence of plasma and externally generated noise sources. The required sensitivity and resolution is provided by a specially developed parallel plate electrostatic energy analyzer, as described in Section III.E.

Calibration is provided by directly injecting the primary beam into the analyzer with vacuum magnetic field on, as shown in Figures III.B.4(b). and IV.C.1. The magnetic field is pulsed, requiring discrete angular calibrations on a shot-to-shot basis. Data recorders and electronics used to acquire physics data are also used during calibration.

Beam entrance angle (θ) calibration is obtained operating the analyzer both open loop and closed loop. In closed loop operation *feedback circuitry automatically centers the ion beam on the split plate detector*. The analyzer gain, $G_A(\theta)$, is then simply the ratio of the gun to top plate voltage. Open loop calibration is obtained by monitoring the relative beam position on the plates (all plasma data is obtained open loop). The measured angular calibration is also compared with the theoretical response calculated from the analyzer mechanical parameters.

Axial (z) calibration is presented in Section IV.C.4. Although an ideal analyzer would not be sensitive to the axial beam position, small mechanical asymmetries in the entrance slit and split plate assembly yield significant axial corrections in the TMX analyzer.

θ_1 : beam injection angle referenced to zero
sweep plate voltage ($\theta_{INJ} = 130.45 - \theta_1$)

θ_A : analyzer entrance angle, theta

θ_Z : analyzer entrance angle, axial

All angles in degrees
thallium ion injection
1kG magnetic field

Figure IV.C.1. Beam injection energy and angle to inject primary beam into the energy analyzer. Circles are from computer trajectory simulations, triangle and square are experimental data.

The TMX analyzer contains a 4-way split plate assembly. As calibration is a lengthy process, most calibration data presented in this chapter is for the west split plate pair (the beam location on one split plate pair is sufficient to determine the ion energy). The east pair, although similar in response, has generally been used only for common mode noise reduction in data analyzed to date. Computer stored calibration data exists for both plate pairs, however, allowing phase sensitive detection or more advanced processing techniques during operation when the beam was chopped between the split plate pairs.

2. Closed Loop Angular Calibration

Closed loop operation of the TMX energy analyzer provides the most accurate "0" angular calibration. Ion current on the upper and lower split plates is dynamically balanced to better than 1 na by feedback control of the analyzer top plate voltage. Angular calibration is obtained by mechanically rotating the analyzer between magnetic field pulses. Since the split plates are automatically balanced to high accuracy during each field pulse only one or two shots at each angular position is required.

A block diagram of the feedback network is shown in Figure IV.C.2. The overall loop gain is 10^{11} volts/ampere, yielding a sensitivity of 100 top plate volts per nanoampere of split plate imbalance. A dc level, generated by the computer control system, allows setting the top plate voltage near the expected value. Single pole loop

Figure IV.C.2. Analyzer configuration during closed loop (feedback) operation.

stability is maintained by filtering the output stage, a Trek 606 high voltage power supply, to 35 Hz with its RC gain network (other stages operate with 1 MHz bandwidth). Since the response time is fairly slow ($\tau = RC = 4.4$ ms) the data recorders are slowed down from 40 ms total record time to 160 ms by decreasing their sample frequency (a magnetic field pulse lasts about 5 seconds with no appreciable change occurring during this record interval). The Spellman dc dividers continue to monitor the high voltage bias on the top plate before each field pulse and a fast monitor tap on the Trek power supply indicates dynamic changes during a shot. The fast monitor output is fed into one of the data recording channels. The dc divider is used to calibrate the fast monitor since its absolute accuracy is not sufficient for the HV measurements.

For accurate calibration the analyzer entrance slit must be uniformly illuminated with primary beam. With the ion gun fully defocused (a point is reached where only beam intensity changes with further changes in gun electrode voltages) a 5 gauss window exists for acceptable entrance slit illumination. Since the injected beam energy is not "slaved" to the magnetic field and the shot-to-shot field reproducibility is not within 5 gauss, the ion beam is slowly swept up and down (θ_1 , Figure III.B.1) about one degree during the shot.

As the beam is swept into the analyzer the feedback network "locks" onto the signal and nulls the difference current in about two

system time constants (~ 9 ms). A typical shot is shown in Figure IV.C.3(a). The split plate currents have been balanced to ~ 1 na by a change in top plate voltage of about 160 volts. Very little secondary current is needed for top plate voltage correction, due to the high loop gain, as evident from the temporal profile illustrated in Figure IV.C.3(b). The top plate voltage is close to equilibrium at 24 ms, with only about 5 na of split plate current.

Absolute calibration of the fast top plate voltage monitor is obtained by comparing its reading, prior to beam entering the analyzer, with the pre-shot voltage level from the high accuracy dc divider. In Figure IV.C.3(b), for example, the fast monitor indicates 3590 volts until beam begins to enter the analyzer at ~ 16.5 ms (Figure IV.C.3(a)). The actual analyzer top plate voltage, obtained just prior to the shot when the system is armed, is 3497 volts as indicated in the system status printout of Figure IV.C.3(b). The difference, which is stable throughout the run (118 volts with a 3 volt standard deviation averaged over 10 shots), is used as an offset correction to the temporally recorded top plate voltage.

In an analysis of electrostatic energy analyzer feedback networks, Reinovsky¹ showed that the feedback loop can become unstable for an ion current above some maximum level. The effect occurs because with higher input currents a given change in top plate voltage yields a larger change in difference current; essentially the loop gain is

Figure IV.C.3. (a) Split plate currents as the beam is swept into the energy analyzer with feedback operation.

FILE NAME--70CT.2

(c)

DATA FILE USED: 70CT.2
 07-OCT-80
 AUX. CRATE CONTROLLER IS NOT ONLINE
 LOCAL SYSTEM STATUS:
 PRI BEAM DET: GRID2= 0.0V GRID3= 0.0V BP= 0.0V
 REQ ANALY TOP PLATE=..... 3.500 KV
 ACTUAL ANALY TOP PLATE=..... 3.497 KV
 REQ GUN ENERGY =..... 5.222 KV
 ACTUAL GUN VOLTAGE=..... 5.227 KV
 EXTRACTOR VOLTAGE=..... 4.177 KV
 SHIELD VOLTAGE=..... 2.611 KV
 -----THETA SWEEP-----
 THETA OFFSET= -4.500 DEG (-71.79 VOLTS)
 THETA SWEEP=+- 1.500 DEG (23.95 +-VOLTS)
 -----Z SWEEP-----
 Z OFFSET= 0.800 DEG (11.07 VOLTS)
 Z SWEEP=+- 0.000 DEG (0.00 +-VOLTS)
 REQ FIL CUR= 5.10A ACTUAL FIL CUR= 5.26A
 ACTUAL FIL VOLTAGE= 4.14V

Figure IV.C.3. (b) The analyzer top plate voltage as the beam is swept into the analyzer and (c) status prior to this calibration shot.

proportional to the beam current. This instability is evident in Figure IV.C.4(a), where the loop breaks into an 18.3 kHz oscillation when the split plate current exceeds 20 na. Peak-to-peak oscillation in the split plate current is ~ 20 na ($\tilde{i}/i \approx 50\%$) and the top plate voltage oscillation level is ~ 20 volts peak-to-peak ($\tilde{V}/V \approx 0.5\%$), as shown in Figure IV.C.4(b). Note that the correct phase relations exist; an increasing top plate voltage increases the bottom split plate current and decreases the top.

Measurement of the analyzer gain is not affected by loop oscillation if average values are used. In general, however, the ion gun output was reduced if oscillation occurred to operate below the oscillation threshold. Detector oscillation can only occur if the analyzer is operated closed loop, and is one of the advantages of off-line, open loop operation used to obtain secondary (plasma) data. Other factors influencing the choice of open loop operation for physics data include the much reduced frequency response of closed loop networks and the problems associated with handling plasma generated noise under closed loop conditions. Calibration is essentially noise free, as no plasma is required, and high frequency response is not necessary.

The measured angular response of the TMX analyzer, obtained closed loop, is shown in Figure IV.C.5. At least two measurements were made at each of the angular positions used, indicating shot-to-shot scatter in the data. General trends are indicated by a curve hand fit to the points; the calculated analyzer response is compared to the measured response, and a best fit obtained, in Section IV.C.4.

Figure IV.C.4. (a) Unstable operation of the feedback loop.

Figure IV.C.4. (b) Expanded time scale showing phase relationships during unstable operation of the feedback loop.

Figure IV.C.5. Measured angular response of the energy analyzer.

Data point scatter can be explained from quantizing effects and the reproducibility of the TMX magnetic field. At any given angle the maximum scatter in measured analyzer gain is ~ 0.007 . Since the analyzer gain is given by the gun to top plate voltage, $G_A = V_D/V_A$, the required uncertainty in these values to explain the measured data scatter is

$$\frac{\partial G_A}{\partial V_D} = \frac{1}{V_A} \quad \frac{\partial G_A}{\partial V_A} = -\frac{V_D}{V_A^2} \quad (1)$$

$$\Delta V_D = V_A \Delta G_A \quad \Delta V_A = -\frac{G_A V_A^2}{V_D}$$

With the injection voltage required for primary beam orbit into the analyzer

$$\begin{aligned} \Delta V_D &= (3300 \text{ volts}) (.007) & \Delta V_A &= -\frac{(.007) (3300 \text{ volts})}{(5200 \text{ volts})} \\ \sim 23 \text{ volts} & & \sim 15 \text{ volts} & \end{aligned} \quad (2)$$

The measurement uncertainty in these voltages is discussed in Section IV.B and summarized in Table IV.B.1. These uncertainties are more than sufficient to explain measured data scatter.

In addition to high voltage uncertainty, the shot-to-shot reproducibility of the TMX magnetic field will cause scatter in the data. This causes the beam to enter the analyzer on a different phase of the beam sweep, with a slightly different trajectory and hence entrance angle. An estimate of the importance of this effect can be obtained from

Figure IV.C.1, where the beam entrance angle into the energy analyzer (θ_A) is indicated for several injected beam angles (θ_I) and injected voltages. For the closed loop calibration being described (October 7, 1980), the average magnetic field intensity was 1095 gauss with a standard deviation of 20 gauss. This is about a 1.8% average fluctuation.

Figure IV.C.1. indicates the injected voltage required at 1 kilogauss for beam orbit into the analyzer. This may be directly converted to a required magnetic field at some other fixed injection voltage, since for a constant trajectory the beam energy must be proportional to the square of the field strength ($V_{inj} \propto B^2$ for constant larmor radii). This implies about a 3.6% change in the nominal injection voltage of 4400 volts is required for a fixed orbit for a 1.8% field change. Figure IV.C.1. indicates that a 3.6% change in injected beam energy (~ 150 volts) yields about a 2 degree change in entrance angle. This causes horizontal scatter of data points in the measured analyzer gain, Figure IV.C.5.

Figure IV.C.5 also indicates the range of entrance angles occurring during single shot radial scans of the plasma. Here the injected beam energy is held fixed, and the injected angle swept with the electrostatic sweep plates. This type of scan yields the largest change in beam entrance angle into the analyzer; radial scans of the plasma made instead by varying the injected energy (see Section V.B) yield almost no entrance angle change, but cannot be done in a single shot due to the high voltage scan required.

During single shot radial scans the absolute analyzer gain changes about 0.01, or ~0.5%. With a typical analyzer top plate potential of 3900 volts (1 kG magnetic field, thallium ion injection) the correction to the indicated space potential, if the analyzer gain is assumed constant, is given by

$$(2) (3900 \text{ volts}) (0.01) = 78 \text{ volts} \quad (3)$$

The factor of 2 is from the doubling in the analyzer gain during secondary measurements.

Most of this change occurs in the last 15 cm during downward sweep of the injected beam. For the range $|r| \leq 15$ cm the analyzer gain changes only about 0.004, yielding a correction of

$$(2) (3900 \text{ volts}) (.004) = 31 \text{ volts} \quad (4)$$

to the space potential. Since the error obtained if entrance angle variations are not included in data processing is significant (~10% of the typical potential) angular corrections are included in the processing of TMX data.

In previous closed loop systems the space potential, uncorrected for entrance angle variations, was obtained directly from the error voltage generated to maintain beam centering within the analyzer. The gain dependence was termed a 'voltage correction function', and applied later to correct the measurement. Data from the TMX analyzer, however, is stored in raw form (the beam position within the analyzer, which is allowed to vary), and processed off-line to obtain the plasma

potential. With this technique it is convenient to directly make use of the analyzer gain curve during data processing, yielding the correct space potential directly.

3. Open Loop Angular Calibration

The response of the TMX analyzer has also been measured open loop. With this technique the top plate voltage is set at a dc level which remains fixed during the shot. The split plate currents are not balanced, since the required top plate voltage is not a priori known. The top plate voltage required for balancing is calculated from recorded split plate current levels, using formulas derived in Appendix I. The analyzer gain is then calculated as before, simply as the ratio of injected beam voltage to the analyzer top plate voltage required for centering the beam.

The results of open loop calibration are shown in Figure IV.C.6. The analyzer entrance slit width (w) is adjustable from outside of the vacuum system, and response curves for several openings are presented. Ideally the entrance slit width should not affect the analyzer angular response, but as shown in the figure strong sensitivity actually exists. The reason for this is that for large slit widths beam scrapeoff on the analyzer ground plate occurs. As described in Section IV.C.4, this effectively modifies the analyzer geometry (X_d and Y_{d1} , Figure III.E.1) as a function of beam entrance angle, which yields the large change in analyzer gain. The analyzer response is similar for the two smallest slit widths, 1 mm and 0.5 cm, but deviates strongly at the wider openings where scrapeoff occurs over more of the angular range. Note that

Figure IV.C.6. Measured angular response of the energy analyzer for several entrance slit widths.

the analyzer gain for all entrance slit widths is the same when the beam entrance angle is 32 degrees. This adds confidence in the measurement, as it is the angle where no scrapeoff should occur.

Beam scrapeoff is undesirable due to the large corrections which must be applied during data processing, so consequently all physics data acquired after the effect was discovered (March 1980) has been taken with a small entrance slit width, 0.5 cm. This opening yields an analyzer response close to the theoretical value (some scrapeoff still exists at entrance angles far from the design angle) and an adequate dynamic range to follow the potential buildup and decay in TMX plasmas.

Closed loop calibration, done with an entrance slit width of 0.5 cm, is in good agreement with open loop results. This provides a check of the off-line processing technique, as the open loop calculations are very similar to those used for processing plasma data. Larger scatter in the data points is obtained during open loop operation, however, a consequence of the extra steps involved, system linearity, and analyzer a/d step size.

4. Theoretical Analyzer Response

The response of the TMX energy analyzer has been calculated from directly measured mechanical dimensions. The theoretical response agrees quite closely with the measured response described in Sections IV.C.2 and IV.C.3. A "best fit" is obtained to the measured response by a slight slew of the theoretical curve, yielding an analytic expression

accurately describing the analyzer angular response. The expression is used in the processing of plasma data.

Mechanical asymmetries yield an axial dependence to the analyzer gain, as described in Section IV.C.5 and already noted in Section IV.C.1. Dimensions presented in this section are for a beam path which is centered on the west split plates, as has been the case for the measured analyzer response.

The measured analyzer dimensions used in calculating the angular response are given in Table IV.C.1. Standard deviations are from several measurements of the same parameter at different points within the analyzer.

Although X_d is externally adjustable from 24.965 cm to 27.165 cm, allowing optimization of the analyzer response, the value indicated was used for all calibration and data acquisition.

$d = 6.595 \pm 0.005 \text{ cm}$
$X_d = 26.286 \text{ cm}$
$Y_{d1} = 2.751 \text{ cm}$
$Y_{d2} = 2.130 \text{ cm}$

Table IV.C.1

Measured Analyzer Parameters

The coordinates of the beam, referenced to the entrance slit, after exiting the analyzer field region are given by

$$x_d = \frac{V_o}{V_A} \frac{q_{pri}}{q_{sec}} 2d \sin 2\theta + y_d \cot \theta \quad (5)$$

with parameters as defined in Figure III.E.1.

The analyzer gain is given by V_o/V_A ,

$$\begin{aligned} G_A = \frac{V_o}{V_A} &= \frac{x_d - (y_{d1} + y_{d2}) \cot \theta}{2d \sin 2\theta} \\ &= \frac{(26.286) - 4.881 \cot \theta}{13.190 \sin 2\theta} \end{aligned} \quad (6)$$

This function is plotted in Figure IV.C.7.

The measured analyzer response (Figure IV.C.5) and calculated response (Figure IV.C.7) agree to $\sim 0.8\%$ in absolute analyzer gain. Over the range of interest ($28^\circ < \theta < 36^\circ$), a "best fit" to the measured analyzer response can be obtained by translating the theoretical curve slightly

$$\begin{aligned} \theta &\rightarrow \theta - 1.5^\circ \\ G_A &\rightarrow 1.0083 G_A \end{aligned} \quad (7)$$

This yields an analytic expression for the analyzer response

$$G_A = \frac{26.286 - 4.881 \cot (\theta - 1.5^\circ)}{13.081 \sin 2 (\theta - 1.5^\circ)} \quad (8)$$

which closely approximates the measured data points. This curve is plotted over the measured response in Figure IV.C.8.

Figure IV.C.7. Theoretical angular response of the energy analyzer.

Figure IV.C.8. Theoretical and experimental agreement after translating and increasing the magnitude of the theoretical curve slightly. The horizontal bar indicates the operating range during single shot radial scans of the plasma.

Angular (abscissa) disagreement between the theoretical and experiment response requiring the 1.5 degree shift is due to errors in i) absolute angular positioning of the analyzer, ii) absolute beam injection angles, and iii) the actual magnetic field shape compared to the computer model used in orbit calculations. The theoretical curve is modified, rather than the experimental, since offset errors in angular positioning exist for both calibration and physics data, and will tend to cancel with the in situ calibration techniques employed. The calculated curve is only a convenience, providing an analytic formula for data reduction.

Absolute gain (ordinate) disagreement between theory and measurement is most likely from i) the difficulty is accurately measuring the analyzer dimensions, ii) changes in the entrance slit and split plate location during removal of the analyzer from TMX (these parameters are externally adjustable and have some play) and iii) absolute power supply errors. Again, the measured values are relevant and absolute errors will not affect the measurement accuracy substantially since they exist for both calibration and physics runs.

The measured and theoretical analyzer gains tend to deviate considerably for beam entrance angles sufficiently removed from the 32 degree design angle. This difference is due to ground plate beam scrapeoff, which is not included in the present calculations. With an entrance slit width of 0.5 cm the agreement is good within about 6 degrees of the design angle, as shown in Figure IV.C.8. As shown in Figure IV.C.9, for very large or very shallow beam entrance angles only a fraction of the beam entering the entrance slit makes it into the electric field region.

Figure IV.C.9. Beam scrapeoff in the analyzer. The analyzer gain is decreased for large entrance angles and increased for shallow angles by the scrapeoff.

Ground plate scrapeoff is modeled as a change in the Y_{d1} analyzer parameter, since the beam entrance point is effectively modified. For large beam entrance angles Y_{d1} is effectively larger, which from the basic analyzer equation yields a smaller analyzer gain. The reverse occurs for shallow entrance angles, which yields a larger analyzer gain. These effects are in agreement with the measured gain differences. The scrapeoff effect can be quantitatively included in the analyzer model by using piecewise continuous functions for Y_{d1} in the analyzer gain equation (6). However, since the measured and theoretical analyzer responses only differ substantially outside of the interval required for data reduction ($28 < \theta < 36$), equation (8) is sufficient for analyzing the TMX data.

In addition to modifying the angular response of the analyzer, beam scrapeoff also changes the effective beam width, w . This parameter is necessary for off-line potential measurements and is used in calculating the plasma sample volume. A model for the beam width can be obtained graphically from diagrams like Figure IV.C.9, if required (again, beam entrance angles on the TMX system are within the non-scrapeoff region).

5. Axial Analyzer Gain

The TMX analyzer gain is a linear function of the axial (z) beam position. This is caused by small mechanical asymmetries in the analyzer geometry. The gain variation, which has been directly measured, is about 1.5% across the entrance slit. This is a substantial change,

which must be considered in data processing. The analyzer gain decreases from east to west, in a coordinate system where the analyzer is located north-south with the entrance slit to the north (Fig. AI.1).

For noise reduction much of the TMX data has been obtained by linearly chopping the injected beam along the axial direction, with a triangle waveform. This technique allows common mode noise reduction and the implementation of software phase sensitive detection without sacrificing any signal. With the axial gain dependence described, the processed space potential changes

$$\frac{1}{2} (11,000 \text{ volts}) (0.015) \sim 80 \text{ volts} \quad (9)$$

across the entrance slit if the analyzer gain is assumed constant (11kV beam energy, typical for thallium in a 1 kG field. The factor of 1/2 is for processing only the west split plate pair).

The results of processing a typical TMX shot are shown in Figure IV.C.10. Axial sweep of the beam has been adjusted to linearly sweep from one split plate pair to the other, with a slight overshoot in each direction. Data from processing only the west split plate pair is shown (thus the blank intervals). The z offset (~ 20 volts) required is from multipole magnetic field components, which produce axial beam steering, field errors, and beam probe misalignment. The potential linearly increases as the beam is swept across the split plates, followed by a linear decrease as the beam returns in the opposite direction (ignoring fast fluctuations, which originate within the plasma). The total change agrees quite well with the 80 volt calculated

Figure IV.C.10. Space potential, sweep voltage, and total secondary current level during a typical shot with axial beam chop.

value. Note that the peak sum current (where the beam is centered on the split plate pair) occurs midway along the potential ramp as expected. No constant current region exists since the beam diameter is approximately equal to the split plate width. The slight phase shift evident when comparing the sweep waveform to the processed data is from a 3kHz filter inserted before the waveform recorder and the beam transit time in the vacuum system ($\approx 50 \mu\text{s}$).

The analyzer sensitivity to two critical parameters, X_d and Y_d , is given by

$$\frac{V_o}{V_A} = G_A = \frac{1}{2d \sin 2\theta} \frac{q_{\text{sec}}}{q_{\text{pri}}} (X_d - Y_d \cot \theta) \quad (10)$$

$$\frac{\partial G_A}{\partial X_d} = \frac{1}{2d \sin 2\theta} \frac{q_{\text{sec}}}{q_{\text{pri}}}$$

$$\frac{\partial G_A}{\partial Y_d} = \frac{\cot \theta}{2d \sin 2\theta} \frac{q_{\text{sec}}}{q_{\text{pri}}}$$

The analyzer is more sensitive to changes in Y_d , by $\cot \theta \sim \cot(60^\circ) \sim 1.7$. For primary beam ($q_{\text{sec}} = q_{\text{pri}}$) and TMX analyzer dimensions

$$\frac{\partial G_A}{\partial X_d} = \frac{1}{(2)(6.6) \sin(60)} = 0.087 \quad (11)$$

$$\frac{\partial G_A}{\partial Y_d} = \frac{\cot(30)}{(2)(6.6) \sin(60)} = 0.15$$

The measured gain variation (1.5%) can be explained by either

$$\Delta X_d \sim 1.7 \text{ mm} \quad \text{or} \quad \Delta Y_d \sim 1 \text{ mm} \quad (12)$$

or some combination. Asymmetries of this magnitude have been directly measured in the TMX analyzer.

The axial gain of the TMX analyzer has been experimentally measured. The primary beam was injected directly into the energy analyzer (as done to obtain the angular response) and slow axial sweep applied. Beam is also rapidly swept up-down across the entrance slit. This was done since the TMX magnetic field is only repeatable to about 10 gauss and the HIBP gun was not slaved to the field. Without up-down sweep the beam would miss the analyzer for most of the shots. Typical data is shown in Figure IV.C.11.

The analyzer gain is defined as

$$q_b G_A(\theta) = \left. \frac{E_b}{V_A} \right|_{bal} \quad (13)$$

where a beam of energy E_b and charge q_b is balanced on the split plate detector. For primary beam in the analyzer

$$E_b = q_b V_G \quad (14)$$

where V_G is the ion gun acceleration voltage. This yields

$$G_A(\theta) = \left. \frac{V_G}{V_A} \right|_{bal} \quad (15)$$

Using this definition for the analyzer gain, the change in split plate current as a function of V_A and V_G is derived in Appendix I. The analyzer gain, from the signals in Figure IV.C.11 and eqn. 17 in App. I is shown

(a)

(b)

Figure IV.C.11. (a) Split plate currents with primary beam injected into the analyzer, and (b) the axial beam sweep. The fast modulation of the split plate current is from the radial beam sweep.

in Figure IV.C.12. Note that the analyzer gain changes .011 across the entrance slit, or .011/1.58 $\sim$.7%. Since this is only for the west split plates the gain change is about twice this amount, $\sim$ 1.5% for the entire axial extent of the analyzer.

D. Space Potential and Ion Current Measurement Sensitivity

1. Description

The beam probe's sensitivity to small changes in plasma potential, density, and electron temperature is determined primarily by i) internal and externally generated noise, ii) performance of the energy analyzer and recording electronics, and iii) the injected ion beam stability and energy distribution. Tradeoffs are generally available; for example, the space potential sensitivity can be increased by decreasing the analyzer's entrance slit width, at the expense of detected current level and dynamic range (the change in potential that can be followed) if operating open loop.

Performance of the analyzer electronics is dominated by the current to voltage converters detecting the split plate ions. This transimpedance amplifier, described in Chapter III, has a 1 MHz bandwidth and equivalent input noise of 1 nA. The noise spectra is approximately white, allowing linearly increasing sensitivity with reduced bandwidth operation (via external low pass filtering).

Split plate currents recorded for the full TMX shot are low pass filtered at 40 kHz with four pole active Bessel filters. This provides anti-aliasing with the 10 μ s sample period of full shot

Figure IV.C.12. (a) Total current measured on the west split plates and (b) the analyzer gain as a function of axial beam position.

digitizers, and an internal front end noise level of ~ 0.2 na. The i/v output is recorded with 10 bit resolution, which introduces quantizing noise of the order of the analog noise. The full scale i/v output is 100 na (± 100 na dynamic range) yielding a digitized step size of $100\text{na}/512 = 0.2$ na. An overall detection sensitivity of a fraction of a nanoampere is achieved. The overall internal noise level of the detection and recording electronics is shown in the upper trace of Figure IV.D.1. The 0.2 na digitizer step size is clearly evident (computer plotting routines connect the data points) and the noise level is below 0.2 na rms. Note that essentially no dc offset from drift exists.

Plasma generated noise and external noise pickup is added to the internal noise level. External noise pickup is insignificant, as the i/v's are located within the energy analyzer, very close to the detector plates. Plasma generated noise is significant for most operating conditions. Most plasma related noise is low frequency, however, and removed by computer processing of the split plate signals.

Noise on the injected ion beam directly affects the measurement sensitivity. The TMX beam line has been designed to reduce this noise to essentially zero. The high voltage power supplies produce an rf output at their 50 kHz power oscillator frequency, but the level is low ($0.02\% \pm 2$ volts RMS, ~ 4 volts for 10 kV injection energy) and above the detector cutoff frequency with the filtering used. The filament is driven with dc power, at a temperature of $\sim 1000^\circ\text{C}$, which is only 0.1 eV. The lower trace of Figure IV.D.1 shows the overall noise level with

Figure IV.D.1. Noise level of the detection electronics (upper trace) and the overall noise level with primary beam in the analyzer. The low frequency ($\sim 1/2$ cycle over the displayed interval) change in beam current evident in the lower trace is from the slowly changing magnetic field which is bending the beam into the analyzer.

primary beam in the analyzer. The beam is being swept into the analyzer with vacuum magnetic field and slow θ sweep.

Space potential resolution is a function of the split plate current resolution, secondary current level, and the entrance slit width. For most TMX beam probe operation an entrance slit width of 0.5 cm is used. The total detected secondary ion current during plasma equilibrium is typically 100 na. From Appendix I (describing off-line potential measurements), for an entrance slit width of 0.5 cm and a typical analyzer voltage of 3.9 kV, a 682 volt potential change is required to move the ion beam from completely on one split plate to completely on the other. With a sensitivity of ≈ 0.2 na the basic measurement resolution is given by

$$\left(\frac{0.2 \text{ na}}{100 \text{ na}} \right) 682 \text{ volts} = 1.36 \text{ volts} \quad (16)$$

2. Plasma Generated Noise

Measurement sensitivity and absolute accuracy are reduced in the presence of plasma generated noise. Noise suppression, making use of the 4-way split plate assembly, is applied during the processing of secondary ion data considerably improving the signal-to-noise ratio of the raw data. Some noise remains, however, particularly during puffer valve fueling where higher frequency noise is present.

External noise influence can be obtained from the derivations in the previous section. There it was shown that 0.2 na of internal noise yields a 1.36 volt uncertainty in the plasma potential for a 100 na signal level.

This calculation is based on the ability to determine the beam location on the split plates, and is also applicable to external noise sources. Therefore, for each nanoampere of secondary current uncertainty per 100 na total (1%) about 7 volts of uncertainty in plasma potential exists. This is based on an entrance slit opening of 0.5 cm and an analyzer top plate voltage of 4 kV. For a narrower slit width less space potential is required to move the ion beam from one split plate to the other, and the sensitivity to noise is improved (of course signal is also reduced with smaller entrance apertures, and noise may or may not be reduced proportionally).

3. Gun Modulation Experiment

The beam probe's sensitivity and resolution has been experimentally verified. This is accomplished by modulating the injected beam energy, as shown in Figure IV.D.2. A low voltage ac source is added to the gun dc high voltage, and injection conditions are established so that the primary beam orbits into the energy analyzer during vacuum magnetic field. As done for analyzer calibration, a slow up-down sweep is also applied to the injected beam, guaranteeing beam illumination of the entrance slit with shot-to-shot field variations.

Raw split plate currents for a 10 volt sine wave modulation are shown in Figure IV.D.3. A blowup of several cycles is also given, during a time interval when the entrance slit is most uniformly covered with beam. The 10 volt energy modulation is clearly visible on the recorded data, and the

Scope monitor output

Generator

Modulation waveform

Figure IV.D.2. Ion gun energy modulation circuit.

Figure IV.D.3. Split plate currents with 10 Volt sinusoidal energy modulation of the beam.

correct (out of phase) relationship between the upper (split plate 1) and lower (split plate 3) split plate currents exist.

Quantitative analysis is obtained from the off-line potential equations derived in Appendix I. From eqn.(17) in the Appendix,

$$V_{G2} - V_{G1} = \frac{[(i_L - i_U)_1 - (i_L - i_U)_2]}{i_L + i_U} V_A \xi(\theta, \beta, d, w) \quad (17)$$

where

$$\xi(\theta, \beta, d, w) = \frac{w \sin(\beta + \theta)}{4d \sin 2\theta \sin \theta} \quad (18)$$

For the analyzer conditions on 8-OCT-80

$$\xi = \frac{(0.5) \sin(60+32.5)}{(4)(6.595) \sin(65) \sin(32.5)} = 0.0389 \quad (19)$$

and

$$G_A = 1.572 \quad (20)$$

From the split plate current traces the beam energy modulation can be calculated

$$\Delta V_G = \frac{[(i_{U2} - i_{U1}) - (i_{L2} - i_{L1})]}{i_L + i_U} (3115 \text{ Volts})(0.0389) \quad (21)$$

$$\approx \frac{(46 - 40) \text{ nA} - (60 - 66) \text{ nA}}{(43 + 64) \text{ nA}} (121) \text{ Volts} \quad (22)$$

$$\approx 13.5 \text{ Volts} \quad (23)$$

where the change in split plate currents are obtained from the approximate envelopes shown in Figure IV.D.3. Agreement of the calculated change in beam energy, 13.5 Volts, is in reasonable agreement with the 10 Volt modulation.

Results from processing this data with the program used for obtaining the plasma space potential from secondary ion signals is shown in Figure IV.D.4. From 15 ms to 23 ms the beam is being swept into the analyzer, and not providing uniform illumination of the entrance slit due to beam profile effects. From 23 ms to about 33 ms the entrance slit is uniformly illuminated, and the processor provides meaningful output. The dc value (~ 18 Volts) is within measurement error bars. The sinusoidal modulation is slightly larger than the applied 10 Volts, as obtained with the hand calculations just described.

The sum current, also provided by the processing code, is shown in Figure IV.D.5. During equilibrium the total current is ~ 105 nA and the sinusoidal modulation fairly small. Ideally the sum current should show no trace of the gun modulation, since only the ion energy is being varied. An important effect, however, makes the experiment more complex. When the gun energy is modulated, the beam trajectory through the magnetic field is also modulated, as its larmor radii is proportional to the beam velocity. Since the beam profile is not flat, but typically some sort of gaussian, modulating the beam position necessarily modulates the current into the analyzer. It also effects the beam distribution on

Figure IV.D.4. Measured minus injected beam energy for primary beam in the analyzer and 10 Volt sinusoidal energy modulation.

Figure IV.D.5. Sum current with 10 Volt sinusoidal energy modulation of the beam.

the upper and lower split plates, since the current is changing across the entrance slit width. This may be the reason the measured potential modulation tends to be somewhat higher than the modulated beam energy, and why it tends to change during the shot.

An estimate of the beam position change with a small energy modulation can be obtained from the larmor radius

$$r_L = \frac{4.56\sqrt{Vm}}{B} \text{ cm} \quad (24)$$

where V is the particle's energy (kV), m the particle's mass (AMU), and B is the imposed magnetic field (kG). The change with voltage is given by

$$\frac{dr}{dV} = \frac{2.28}{B} \sqrt{\frac{m}{V}} \quad (25)$$

For thallium in a 1kG field

$$\frac{dr}{dV} = \frac{2.28}{1} \sqrt{\frac{204}{V}} = \frac{32.5}{\sqrt{V}} \quad (26)$$

$$dr = 32.5 \frac{dV}{\sqrt{V}}$$

With an injected beam energy at 4.85 kV and a 0.01 kV modulation

$$\Delta r = .15 \text{ cm} \quad (27)$$

For a beam traveling roughly one quarter of a larmor radii (Figure III.8.4(b)) this represents the approximate shift in beam position. This is about 5% of the beam size at the analyzer, which is about the percentage of secondary current modulation observed (Figure IV.D.5).

More precise verification of the off-line processing technique will have to be done with a line of sight gun/analyzer path, which requires no magnetic field. Test stand operation is required.

Square wave modulation of the injected ion energy has also been done. As evident from Figure IV.D.2 the voltage "rings" into the gun load (a consequence of capacitively loading the "non-ideal" power supply temporarily installed to modulate the gun energy), yielding an envelope with both low and high frequency components. The basic modulation frequency is 1 kHz and the ringing occurs at ~ 41 kHz. The recorded split plate data, Figure IV.D.6, clearly shows both components, although the ringing is attenuated by about a factor of 2. This is expected since the ring frequency is slightly above the 3 dB frequency of the analyzer filters. The system shows excellent transient response, which is due to the wide bandwidth i/v's and Bessel filtering. The processed space potential and total current level for this shot are shown in Figure IV.D.7.

E. Conclusion

The TMX beam probe has been extensively calibrated and accuracies verified through independent tests. Absolute measurements of the plasma potential with respect to the machine wall are made to ~ 25 volts in the absence of plasma generated noise. For typical operating conditions, an additional 7 volts of uncertainty exists for each percent of noise not removed during data processing. Sensitivity to potential change is ~ 2 volts, and secondary ion current can be determined to a fraction of a nanoampere, in the absence of plasma generated noise.

Figure IV.D.6. Split plate currents as measured with primary beam in the analyzer and 1 kHz square wave energy modulation of the beam.

Figure IV.D.7. Measured minus injected beam energy and the sum current for primary beam in the analyzer and 1 kHz square wave energy modulation of the beam.

CHAPTER V

TMX Space Potential Measurements

A. Introduction

The heavy ion beam probe is capable of a variety of profile measurements in the central cell of TMX. By holding the observation point fixed during the shot the detailed evolution of the plasma is obtained. The resulting continuous temporal profile provides information on plasma buildup, equilibrium, and decay. The effects of impurity injection, ICRH, or other pulsed experiments can be monitored with microsecond resolution. The observation point can be located on-axis or shifted to various radial positions between shots.

The radial distribution of plasma potential and secondary ion current level ($\propto n(T_e)$) can also be obtained during a single shot. Scan times of 100 μ s to 10 ms yield several to dozens of complete radial profiles during a TMX discharge. With shot-to-shot machine variations, profiles obtained in a single shot are considerably more accurate and of higher resolution than data from consecutive shots, even when conditions are held constant. The multiple scans obtained allow monitoring changes in the plasma occurring on time scales longer than the scan time.

Space potential measurements have been obtained for both gas box and puffer fueling of the central cell plasma. Data presented in this chapter is for typical operation of the experiment. Correlation with

scaling of parameters such as the gas feed rate, neutral beam current, etc., is presented in Chapter VI.

Axial sweep of the injected beam provides noise reduction, through chopped beam techniques, when required. Chopped beam operation is used primarily during puffer fueling of TMX, due to a higher noise level from the background gas. Axial sweep is also useful when verifying secondary ion signals, and when signal levels are low such as during higher order charge state measurements.

Puffer valve fueling of TMX has caused measurement difficulty, as previously mentioned. Puffer operation injects cold gas near the vacuum wall, substantially increasing the analyzer noise level. The noise source is most likely cold gas charge exchange with neutral beam particles, yielding energetic deuterons at about the same energy as the beam probe ions being detected. A small fraction of particles (~ 30 na from the 50 amp central cell neutral beam) has the right momentum to orbit to the analyzer in the weak magnetic field near the machine wall.

A substantial reduction in the analyzer noise level was obtained with the installation of two radial limiters for the ICRH heating experiment. The limiters straddle the central cell midplane, extending from a radius of 38 cm to the wall, probably blocking the path for the multiple scattering required. With the ICRH limiters the first beam probe data during puffer fueling was obtained, in August 1980. Data were still noisier than with gas box fueling and better off-line noise reduction processing is needed for comparable accuracy.

B. Measurement Profiles

The heavy ion beam probe is located on the midplane of the TMX central cell, as shown in Figure V.B.1. Although most of the plasma cross section is accessible (Section III.B), measurements presented in this thesis are along specific radii to be described in this section.

Radial profiles of the plasma cannot be obtained instantaneously with the heavy ion beam probe. The detection volume must be scanned through the plasma cross section, at a rate limited by system electronics and the number of data points (digital samples) desired per scan. Scans are generally made at both slow and fast rates, ranging from the full equilibrium plasma interval to the electronics limited rate. Slow scans give better statistics and the spatial distribution of fluctuations. Fast scans provide a plasma "snapshot" where less can change, and fluctuation phase information if frequencies are sufficiently low.

Two scan techniques are used to generate radial profiles. When temporal profiles are also desired or noise levels are high the radial location is changed on a shot-to-shot basis by incrementing the beam injected energy. The radial position may be located to an accuracy of about ± 1 cm. This type of scan minimizes the change in particle entrance angle into the energy analyzer at different radial positions. Corrections for the angular gain dependence of the analyzer (Chapter IV) are avoided, increasing the measurement accuracy and simplifying data processing. For single shot radial scans, however, this technique is not possible as slow, high voltage, power supplies do not allow changing the

Figure V.B.1. Location of the heavy ion beam probe on the TMX central cell.

injected beam energy during a shot. Instead, the injected beam angle is varied, by electrostatic sweep plates operating at lower voltage. Radial scans along a different azimuth are obtained, and a significant change (5 degrees for a 30 cm sweep) occurs in the analyzer entrance angle. The coordinates for these two methods of operation are summarized in Figure V.B.2.

Temporal profiles at non-zero radii are made by incrementing the beam injection energy above that required for probing the plasma center, resulting in the downward (-y) scan in Figure V.B.2. This has several beneficial effects; first the current extracted from the Pierce-type ion source increases (for space charge limited flow $i \propto V^{3/2}$ where V is the extraction voltage). In addition, better focusing of the gun at higher voltage levels increases the beam current density. Finally, with the sample volume moved closer to the gun the primary and secondary ions travel less distance through the plasma, minimizing signal loss by attenuation. Since this mode of operation is typically used during noisy conditions these effects are important, especially since signal levels are reduced at large radii with the lower plasma density and temperature.

Single shot radial scans, made at a constant injection energy, allow almost a full diameter scan of the plasma. As shown in Figure V.B.2, full radial sweep is possible in the negative x,y direction. Positive sweep, however, can only be made to about a radius of 20 cm. At this point injected beam is scraped off in the primary beam line prior to

Figure V.B.2. Radial scan coordinates for constant beam energy and constant injection angle.

entering the main tank (a consequence of the port structure on the main TMX vacuum tank).

Beam chopping, when required, is accomplished by axially sweeping the beam across the 4-way analyzer split plate assembly. With proper sweep amplitude a square wave chop will center the beam on alternate split plate pairs on the two phases of the waveform (a triangular waveform providing linear sweep between plates is also frequently used). By later combining the split plate pairs a continuous measurement is obtained, although at alternating spatial locations (in z) separated by a few centimeters. Chop frequencies from 100 Hz to 5 kHz have been used. A slow chop simplifies fluctuation measurements while a fast chop provides better noise immunity. In TMX, plasma parameters do not change along field lines at the central cell midplane. The result is a continuous beam probe measurement with high noise immunity.

C. Timing

A timing diagram typical of most TMX operation is shown in Figure V.C.1. A shot sequence occurs as follows: 3 ms after zero time a titanium-washer stream gun injects a target plasma into each end plug. The plug neutral beams, also switched on at 3 ms, make use of this target for ionization and plasma buildup. At 6 ms the gas boxes are fired, replacing particle losses and fueling the central cell. Stream guns are then switched off, as they are a source of plasma impurities. Plasma buildup continues, with an equilibrium reached at about 10 ms into the shot. Equilibrium is maintained until 21 ms, at which time the neutral beams in the west plug are turned off. The west plasma collapses and

central cell particles begin to flow preferentially from that end (some experiments require the longer equilibrium obtained if both plugs remain on until 28 ms, but early turnoff of one plug is an important source of diagnostic information). At 28 ms the east plug is also switched off, since the neutral beams are designed for 25 ms operation. The plasma then rapidly decays.

Figure V.C.1. Typical machine timing.

Operation with puffer fueling is similar, with one to four valves located on the central cell midplane supplying the gas feed. The plasma profile is quite different, however, with central cell density falling off much more slowly with radius (inverted (hollow) density profiles are obtained with sufficient gas feed). Such differences in the plasma are expected, as the puffer injects gas at large radii and gas box operation supplies gas directly into the mirror throat. Puffer and gas box operation are two important modes of TMX operation, since plasma processes such as transport and instabilities are sensitive to plasma profiles and vacuum conditions surrounding the plasma.

D. Temporal Profile of the Central Cell Space Potential

1. Gas Box Fueling

A typical temporal profile of the plasma space potential on-axis with gas box fueling is shown in Figure V.D.1. Machine parameters for this shot, number 39 on September 26, 1980, are representative of normal tandem mirror operation, and are summarized in Table V.D.1. Gas feed has been adjusted to supply ~1050 atom-amps of deuterium to the central cell. The total secondary current level (sum) for this shot is shown in Figure V.D.2. Data were processed off-line from raw split plate current signals as described in Appendix I.

The central cell plasma space potential is positive, reaching a level of about 400 volts during the equilibrium part of the shot. This value generally ranges from about 300 to 500 volts, depending on machine

Figure V.D.1. Temporal profile of the central cell space potential (gas box fueling).

Figure V.D.2. Temporal profile of the secondary current level during gas box fueling.

	Sept. 26, 1980 Shot 39	Sept. 26, 1980 Shot 48	Aug. 19, 1980 Shot 88	September 24, 1980 Shot 35
Gas Box Pressure	300 torr, $\Delta P = 2.8$	600 torr, $\Delta P = 6.2$	300 torr, $\Delta P = 3.5$	Out
Puffer	Out	Out	Out	40 lbs, 1 1/2 turns
Getters	In	Out	In	In
LN Liners	Cold	Cold	Cold	Cold
Vacuum				
East	1.5×10^{-8} torr			1.3×10^{-8} torr
Center	2.2×10^{-8} torr			3.2×10^{-8} torr
West	2.5×10^{-8} torr			3.1×10^{-8} torr
East Plug Electron Temperature (16 ms)	83 eV	70 eV	63 eV	69 eV
Central Cell Electron Temperature (16 ms)	64 eV	68 eV	Thomson Scattering Not Installed	
Neutral Beam Current (20 kV)				
East	168 amps	166 amps	133 amps	150 amps
West	168 amps	148 amps	87 amps	149 amps
Central Cell Density, n_c (16 ms)	3.5×10^{12} cm $^{-3}$	5.4×10^{12} cm $^{-3}$	4.2×10^{12} cm $^{-3}$	3.6×10^{12} cm $^{-3}$
Central Cell Radius	27 cm	30 cm	29 cm	34 cm
n_p/n_c (16 ms)				
East	5.5	4.3	4.7	7.3
West	7	7	10	6.2
n_c (16 ms)	8×10^9 cm $^{-3}$ sec	1×10^{10} cm $^{-3}$ sec	9×10^9 cm $^{-3}$ sec	1.4×10^{10} cm $^{-3}$ sec

Table V.D.1. Machine parameters for shots discussed in the text.

conditions such as neutral beam current, neutral beam energy, gas feed rates, etc. A second equilibrium occurs at the end of the shot when the west end plug neutral beams are switched off. This causes the plasma in the west plug to collapse, eliminating electrostatic confinement of the central cell plasma. The expected magnitude of the space potential during various phases of the discharge is presented in the next chapter.

Correlation between the plasma potential, secondary current level, and machine timing (Figure 1.0.1) is quite strong. Secondary current appears about 3.2 ms into the shot, just after the stream guns and neutral beams are turned on. A quasi-equilibrium (stream gun plasma) is reached at about 5 ms, lasting until ~6.5 ms. Then the gas boxes, turned on at 6 ms, begin supplying particles to the central cell allowing further plasma buildup. The potential peaks at 8 ms, at the time the stream guns are switched off (this peak is sometimes the highest potential attained during a shot - although not the case for this shot). Further buildup in the plasma potential then occurs, as well as a large increase in the secondary ion current fluctuation level. The main plasma equilibrium is reached about 10 ms into the shot. The space potential and secondary current level remain fairly constant until about 22 ms, one millisecond after the west plug is turned off. The potential then decays, with about a 1 ms time constant, to another steady state value of ~250 volts. The secondary current level, however, increases slightly due to the decrease in the plasma temperature (beam attenuation is the dominating factor influencing secondary ion production; a decrease in overall plasma

temperature or density allows more primary beam to be delivered to the sample volume, yielding an increased signal. This effect is discussed in Section III.D.). The new equilibrium is maintained until just after the 28 ms east plug turn-off. The potential then rapidly decays in less than one millisecond.

The space potential profile indicates a step at the very beginning and very end of the shot. These steps are not real, but a consequence of the 0.5 nA minimum processing current selected. The space potential is not calculated until the secondary current level on both plates exceeds this value, avoiding division overflows within the computer processing the raw data.

A shot with twice the gas feed of shot 39 is shown in Figure V.D.3. This data, part of a gas box scan, is discussed in detail in Section VI.E where a slightly decreasing space potential with increased gas flow is reported. Shot 48 from September 26, 1980, illustrates this result, with an equilibrium potential about 50 volts lower than the 300 torr case. Machine conditions for this shot are also given in Table V.D.1. Temporal profiles of the space potential are similar, although the drop in potential after one plug is turned off is smaller with the increased gas feed. The higher plasma density increases primary beam attenuation, yielding a lower secondary current level throughout the shot.

An off-axis shot where the potential was continuously monitored as a function of time is shown in Figure V.D.4. This shot, number 88 on August 19, 1980, was monitored at a radial position of 8 cm.

Figure V.D.3. Space potential and secondary current level with increased gas feed into the central cell.

Figure V.D.4. Space potential and secondary current level off-axis.
Measurements are at 8 cm radius.

Machine conditions are again summarized in Table V.D.1, which indicates less injected neutral beam current and a lower electron temperature than the shots previously described. The equilibrium potential, ~300 volts, is also lower, about at the minimum for typical TMX operation (radial profiles are described in Section V.E.). Neutral beams in both plugs are left on until 28 ms, extending the equilibrium interval to the end of the shot.

2. Puffer Valve Fueling

The temporal behavior of the central cell space potential during puffer fueling is similar to that obtained with the gas box. Shot 35, on September 24, 1980, is shown in Figures V.D.5 and V.D.6. The puffer was adjusted to supply ~2400 atom-amps of deuterium to the central cell. Machine conditions are summarized in Table V.D.1.

The injected ion beam was chopped for this run, by sweeping the beam between the east and west detectors. The very good signal to noise ratio obtained after processing the split plate signals is evident on the total secondary current waveform, which shows little signal between the chop intervals. Processing of only the west split plate pair is shown; adding the east would eliminate the blank intervals.

The magnitude of the space potential during equilibrium (10 - 21 ms) is ~400 volts, comparable to the value obtained during gas box operation. A blowup of the data at 16 ms, given in Figure IV.C.10, presents in more detail the linear sweep of the beam into the analyzer and

Figure V.D.5. Temporal profile of the space potential during puffer fueling.
The injected beam is chopped for this measurement.

Figure V.D.6. Temporal profile of the secondary current level during puffer fueling. The injected beam is chopped for this measurement.

the resulting potential measurement. Plasma fluctuations are low during puffer fueling, evident from comparing the secondary current level in the figure to that obtained during gas box operation, Figure V.D.2.

A systematic change in the potential during each chop interval is evident (Figure IV.C.10), which is an instrumentation effect and not plasma related. As shown in Section IV.C.5 this is a consequence of the axial gain dependence of the energy analyzer. At the beginning of the chop interval signal is acquired and the potential calculated. As the beam travels axially across the detector plates the uncorrected axial gain (assumed fixed in the processing) causes the calculated value of the potential to increase. A peak occurs when the triangular sweep reverses direction and begins sweeping the ion beam back across the detector plates.

Since the axial gain of the analyzer is linear (Figure IV.C.12), averaging the data points during a sweep yields the average potential during that interval. Although the detailed axial gain dependence could be included in data processing, yielding a continuous temporal profile, averaging is a simpler technique when only the slow plasma evolution is required.

E. Radial Profile of the Central Cell Space Potential

1. Gas Box Fueling

A TMX discharge where single shot radial scans were obtained with the beam probe is shown in Figure V.E.1. The space potential and total secondary ion current level are given for shot 88 on September 26, 1980. The injected beam sweep rate is set to radially scan

Figure V.C.1. Single shot radial scans of the space potential and secondary current level.

the plasma in about 2 ms, yielding 13 complete profiles per shot. Measurements are obtained along the constant injection energy coordinates shown in Figure V.B.2.

This shot is representative of profiles obtained when the central cell was fueled at a typical feed rate of ~ 1200 atom-amps by deuterium gas injection into the two gas boxes, located around the thin elliptical transition regions on the central cell side of the plug mirrors. Machine timing is similar to that depicted in Figure V.C.1 except the west neutral beams are not switched off at 21 ms, yielding an equilibrium interval extending to 28 ms. A summary of the remaining machine parameters is given in Table V.E.1.

The potential and secondary current level from 18 to 20 ms are expanded in Figure V.E.2. This is at about the midpoint of the equilibrium interval, when the plasma is fueled from the gas boxes and heated with neutral beam injection. The peak potential is slightly lower than the value obtained in shot 39, where the $r = 0$ temporal profile was monitored. This is primarily correlated with a drop in neutral beam current, as evident from Tables V.D.1 and V.E.1.

The very low noise level obtained after processing the analyzer signals (Appendix I) is evident on the sum current during intervals where the injected beam is swept out of the plasma ($t < 18.2$ ms and $t > 19.7$ ms). A minimum processing current of 0.4 na allows tracking the potential over almost all of the scan. The sharp cutoff at $t \approx 19.7$ ms is from the injected beam scrapeoff on a vacuum flange, as discussed in Section V.B.

	Sept. 26, 1980 Shot 88	Aug. 29, 1980 Shot 105
Gas Box Pressure ¹	300 torr, $\Delta p = 2.8$	300 torr, $\Delta p = 3.6$
Puffer	Out	Out
Getters	In/Out ²	In
Ln Liners	Cold	Cold
Vacuum		
East	1.7×10^{-8} torr	
Center	2.1×10^{-8} torr	
West	2.4×10^{-8} torr	
Neutral Beam Current (20 kV)		
East	150 amps	90 amps
West	150 amps	130 amps
Neutral beam Current (40kV)		
East	Out	30 amps
West	Out	20 amps
Central Cell Density (16 ms)	$3.9 \times 10^{12} \text{ cm}^{-3}$	
Central Cell Radius (16 ms)	25 cm ⁽³⁾	

1. Equivalent atom-amperes of $D_2 = 400 \Delta p (\text{torr})$.
2. Alternating shot-to-shot.
3. $1/e$ for gaussian fit.

Table V.E.1
 TMX machine parameters for shot 88 on Sept. 26, 1980
 and shot 105 on Aug 29, 1980.

Figure V.E.2. Space potential and secondary current level during a radial scan from 18-20 ms.

Fluctuations, described in detail in Chapter VII, are very pronounced on the secondary current signal at all radii, with a peak-to-peak amplitude approaching the "dc" level. Space potential fluctuations are also evident, although of smaller amplitude.

The injected beam angle is determined by the voltage applied to the θ deflection plates. This voltage, digitized and recorded along with the analyzer signals, allows a precise determination of the radial sample volume location within the plasma. The procedure, described in Appendix I, makes use of the sweep voltage, injected beam energy, and computer orbit simulations (the zero beta case is used). The sweep waveform for shot 88 on Sept. 26 is shown in Figure V.E.3(a).

Shot 88 is shown again in Figure V.E.3(b), with the abscissa labeled in radial position. The resulting waveform is quite similar to the temporally displayed profile (Figure V.E.2), since the beam injection angle is linearly swept in time and the plasma radius is small compared to the magnetic field ($r_{field}/r_{plasma} > 3$). Positive values of radial position indicate the positive x and y coordinates of Figure V.B.2.

The sharp dropoff in signal from beam scrapeoff occurs at about 24 cm radius, in good agreement with the computer orbit calculations shown in Figure V.B.2. Sufficient plasma to provide a detectable secondary ion current level ($n_e > 10^{11} \text{ cm}^{-3}$, $T_e > 5 \text{ eV}$) is the only requirement for the scan in the opposite direction, and measurements are obtained to about 28 cm radius. The plasma limiter is located at 38 cm, and other TMX diagnostics indicate the plasma is cold and tenuous beyond 30 cm, consistent with the loss of beam probe signal.

Figure V.E.3. (a) The voltage applied to the radial sweep plates (divided by 500) and (b) the space potential as a function of radius during the scan from 18–20 ms.

A parabolic fit to the measured profile is indicated in Figure V.E.4. The parabola

$$\phi_e = 320 \left[1 - \left(\frac{r-3.5\text{cm}}{32.3\text{cm}} \right)^2 \right] \text{ volts} \quad (1)$$

provides a very good fit for the entire scan. The off axis shift is an instrumentation effect not plasma related, as discussed shortly.

The space potential has dropped to ~50 volts when secondary ion signal is lost at about 27.5 cm (31 cm if the plasma is actually geometrically centered in the solenoid). Although measurements are not obtained at larger radii the potential must deviate from parabolic falloff to satisfy a grounded limiter located at 38 cm radius.

A profile near the beginning of the plasma equilibrium interval, from 12-14 ms, is expanded in Figure V.E.5(a). Excellent agreement is again obtained with a parabolic fit to the measured profile, with parameters quite similar to the scan from 18 to 20 ms. The centering parameter, however, is smaller for this scan ($r_{\text{cen}} = 0.3 \text{ cm}$).

Table V.E.2 summarizes fits for the remaining radial scans during this shot. The fit parameters remain relatively constant during the equilibrium (~10 - 28 ms) portion of the shot. The centering parameter, r_{cen} , is seen to systematically shift from close to zero to about 3 cm on successive scans. Since the shift is correlated with the scan direction (up or down sweep of the injected ion beam) an instrumentation problem is suggested rather than the centering of the plasma. Only the input waveform to the HV sweep supply is recorded, and a

Figure V.E.4. Parabolic fit to the radial potential profile.

Figure V.E.5. (a) Radial space potential profile near the beginning of the main equilibrium interval, and (b) radial profile with 40 keV neutral beam injection.

Scan	Time, ms	$\phi_{\max}, \text{V}$	$r_{\text{cen}}, \text{cm}$	r_0, cm
1*	6.2-8.2	295	5.3	25.0
2	8-10	330	-3.0	28.0
3	10-12	340	3.0	32.0
4	12-14	335	0.3	31.5
5	14-16	320	3.0	31.0
6	16-18	325	-1.0	30.0
7	18-20	320	3.5	32.3
8	20-22	320	-0.5	30.0
9	22-24	327	3.0	31.0
10	24-26	340	-1.0	30.0
11	26-28	325	3.0	30.0
12*	28-30	228	11.0	27.0

*Substantial change in the plasma occurred during these scans.

$$\phi = \phi_{\max} \left[1 - \frac{(r - r_{\text{cen}})^2}{r_0} \right]$$

Table V.E.2

Parabolic Fits for Shot 88, September 26, 1980.

small phase delay during the up or down ramp could cause the offset. In addition, the absolute accuracy of the radial position is difficult to determine within a centimeter or so, a consequence of determining the precise beam injection angle, the effective sweep point, magnetic field, and the computer orbit simulation accuracy.

The equilibrium plasma potential during another shot with gas box fueling, number 105 on Aug. 29, 1980, is shown in Figure V.E.5(b). Table V.E.1 summarizes the machine conditions. The peak potential, the order of 435 volts, is higher than that obtained in shot 88 and others previously described. During shot 105 40 KeV neutral beams were used in addition to the 20 KeV injectors supplying input power to the plasma. The total injected neutral beam current for this shot contains about 20% of the higher energy component, as summarized in Table V.E.1. As evident from Figure V.E.5(b) a parabola also fits the potential profile for this shot quite well, which is the case for all gas box data obtained during normal machine operation at 300 torr. Beyond 20 cm the potential tends to flatten out, as it must for sufficiently large radii.

The radial potential profile early in time, before the gas box is turned on and the plasma is being formed by titanium-washer stream guns, is shown in Figure V.E.6(a). The peak potential is lower than the equilibrium level, in agreement with the temporal profiles (Figure V.D.1). The plasma radius is also smaller during this interval. A parabolic fit is still fairly good, with an r_0 value of 23 cm. The smaller plasma most likely reflects the stream gun mapping along field

Figure V.E.6. Radial space potential profile (a) early in the shot before gas box turn-on, and (b) near the end of the shot after the neutral beams in one end-plug have been turned off.

lines, rather than the neutral beam footprint which determines the plasma size during equilibrium.

Shown in Figure V.E.6(b) is the radial potential profile near the end of the shot, from 25 to 27 ms. For this shot the west end plug is again turned off early, as shown in the timing diagram, Figure V.C.1. The peak potential is lower, in agreement with the temporal profiles shown previously, and the radial profile is broader than during the main equilibrium. A parabolic fit indicates an r_0 of 36 cm, close to the radial position of the limiter (38 cm) although actual measurements are only made to about 27 cm radius.

2. Puffer Valve Fueling

The analyzer noise level during puffer operation makes it necessary to determine radial profiles from shot to shot measurements. For the data reported here two puffer valves were in use, located on the top and bottom of the central cell midplane ($x = 0$, $y = \pm 100$ cm in Figure V.B.2). Deuterium gas feed was adjusted to approximately 1600 atom-amps by setting 40 lbs. pressure on a needle valve orifice adjusted to one turn open. Machine conditions and timing for this run are summarized in Table V.E.3.

The resulting potential profile, shown in Figure V.E.7, was obtained during a diagnostic scan in which machine operation was held constant. Data at 16 ms is shown, during the equilibrium discharge interval. To optimize signal levels the radial scan is made along the

Gas Box: Out	Electron Temperature (16 ms)
Puffer: 40 lbs, 1 turn (top & bot)	Plug: 77 ± 15 eV
≈ 1560 atom-amperes D_2	Center: 52 ± 13 eV
Getters: In all shots	Neutral Beam Current (20 kV)
Liners: Cold	East: 151 ± 13 Amps
Vacuum	West: 159 ± 27 Amps
East: $1 - 1.5 \times 10^{-8}$ torr	Neutral Beam Current (40 kV)
Center: $3 - 3.3 \times 10^{-8}$ torr	East: Out
West: $2.8 - 3.3 \times 10^{-8}$ torr	West: Out

TIMING

Table V.E.3

Machine conditions for September 24, 1980.

Figure V.E.7. Radial potential profile during puffer valve fueling. Data are for Sept. 24, 1980. A least squares fit is given to the measurements, which were obtained over 20 shots.

vertical path shown in Figure V.B.2. The potential profile at 26 ms, after the east plug neutral beams have been switched off, is shown in Figure V.E.8. Fewer measurements are available at 26 ms due to decreased S/N ratio.

At least two shots were taken at each of the five radial positions monitored. The average value of the potential and its shot-to-shot standard deviation are given in Table V.E.4. Scatter in the data increases for measurements at larger radii, and is a result of the HIBP absolute accuracy (± 25 volts), increased noise level (Section IV.D.2), and TMX reproducibility.

Radial Position	Number Shots	Average Potential	Standard Deviation
0 cm	9	353 volts	+ 15 volts
13 cm	2	324	+ 23
18 cm	3	288	+ 62
23 cm	4	311	+ 41
28 cm	2	296	+ 50

Table V.E.4
Radial scan data for September 24, 1980 puffer
operation. Data are at 16 ms.

Figure V.E.8. Radial potential profile during puffer valve fueling after the neutral beams in one end-plug are shut off. Data are for Sept. 24, 1980.

The radial potential profile is almost flat, in contrast to the parabolic profile obtained during gas box fueling of the central cell. At the largest radial position monitored, 28 cm, the space potential is still ~300 volts, implying a steep gradient and large electric field at the plasma boundary.

The two fueling methods are compared in figure 4.E.9, where the central cell density is also given¹. With puffer fueling the plasma density also remains relatively flat with radius, and actually peaks off axis beyond the largest radii where beam probe measurements are available. With gas box fueling the central cell density falls monotonically with increasing radius.

F. Radial Electric Field

The parabolic potential profiles measured in the central cell of TMX during gas box fueling indicate a linearly increasing radial electric field

$$E_r = 2 \phi_{\max} \left(\frac{r - r_{\text{cen}}}{r_0^2} \right) \quad (2)$$

With the fit parameters obtained for shot 88 on September 26,

$$E_r = 0.61 (r - 3.5 \text{ cm}) \text{ volts/cm} \quad (3)$$

Figure V.E.9. Comparison of the plasma density and space potential profiles during gas box and puffer valve fueling. Data are at 16 ms.

The electric field, zero at the plasma center, reaches a maximum value of ~20 volts/cm near the plasma boundary.

In a uniform solenoidal magnetic field with a linearly dependent radial electric field the plasma should rotate as a rigid body at the $E \times B$ drift frequency. For TMX parameters the frequency is

$$f_{E \times B} = 3.18 \times 10^4 \phi_{\max} / r_0^2 \quad (4)$$

For the parameters of shot 88,

$$f_{E \times B} = 9.8 \text{ kHz} \quad (5)$$

Observations of space potential and/or secondary current level fluctuations at the $E \times B$ frequency or harmonics of this frequency indicate azimuthal (m number) modes of the plasma

$$f = mf_{E \times B} \quad (6)$$

Spectral analysis of beam probe fluctuation data during gas box fueling indicate the existence of a strong, coherent mode at the fundamental ($m = 1$) frequency, as well as several other well defined oscillations. These data are discussed in Chapter VII.

The relatively flat potential profile measured during puffer fueling indicates the radial electric field over the interior of the

plasma is small. Near the plasma edge the potential averages 30 volts/cm, as a 300 volt potential drop must occur during the final 10 cm preceeding the limiter (this falloff is not actually measured). This is larger than the maximum value of about 20 volts/cm near the plasma edge measured during gas box fueling.

With the small radial electric field plasma motion from $E \times B$ drift is also small. A very low fluctuation level in the plasma interior is observed in HIBP data and data from other TMX diagnostics during puffer fueling.

CHAPTER VI

Correlation and Scaling of Measurements

A. Introduction

The tandem mirror concept is based on establishing an electrostatic potential distribution, $\phi(z)$, which axially confines ions in a solenoidal central cell plasma. Space potential profiles throughout TMX are therefore of fundamental interest. Measurements of the plasma potential and other parameters allow an investigation of the confining well depth, radial transport, and electron confinement. This work is concerned with measurements in the central cell.

The potential variation during a number of machine parameter scans has been investigated. Parameters such as the gas feed rate, neutral beam current, and neutral beam energy have been changed on a shot-to-shot basis. These scaling experiments cover a wide range of equilibrium and stability conditions of the tandem mirror.

In this chapter, the expected magnitude of the central cell space potential is derived from classical mirror theory, and compared with the beam probe measurements. The magnitude of the confining well depth as experimentally measured is compared with the expected value from the Boltzmann relation, and the radial profile of the potential is compared with the electron temperature profile. The potential variation during the gas box fueling scan is presented in detail. Scaling is obtained over an order of magnitude gas feed rate and the data is correlated with expected tandem mirror operation.

B. Comparison of the Theoretical and Experimental Central Cell Space Potential

The magnitude of the central cell potential is determined by the required balance of ion and electron loss rates. The space potential in an open-ended system is positive, as electrons are scattered into loss cone regions significantly faster than are the ions.

Calculations in this section are based on the classical confinement properties of a tandem mirror system. Non-ambipolar particle losses from rf fluctuations, resonant transport, or radial losses which act preferentially on the ions or electrons are not included. Experimental data is examined on-axis ($r = 0$) to minimize these effects.

The loss rate for electrons in a magnetic mirror trap with an ambipolar confining potential ϕ_e is given by Pastukhov.¹ For a tandem mirror configuration, with central cell and plug volumes V_c and V_p and densities n_c and n_p ,

$$\frac{d}{dt}(n_c V_c + 2n_p V_p) = \frac{2(n_c^2 V_c + 2n_p^2 V_p)}{g(R) (n \tau)_{ee}} \left(\frac{kT_e}{e\phi_e} \right) \exp \left(-\frac{e\phi_e}{kT_e} \right) \quad (1)$$

where R is the plug to central cell mirror ratio and $g(R) = [\sqrt{\pi}(2R+1)/4R] \ln(4R+2) \approx 4$. The electron temperature, T_e , is assumed uniform along flux lines through the plug and central cell, and τ_{ee} is the electron-electron 90° scattering time

$$n \tau_{ee} = 1.8 \times 10^4 T_e^{3/2} \text{ cm}^{-3} \text{ sec} \quad (2)$$

where T_e is in eV and $\ln \Delta$ is taken to be 15.

Equating the ion and electron loss rates,

$$\frac{2(n_c^2 v_c + 2 n_p^2 v_p)}{g(R) (n\tau)_{ee}} \left(\frac{kT_e}{e\phi_e} \right) \exp \left(-\frac{e\phi_e}{kT_e} \right) = \frac{j_c v_c}{qL_c} + \frac{2j_p v_p}{qL_p} \quad (3)$$

where j_c is the loss current from the central cell and j_p is similarly the loss current from a plug. To evaluate this expression on-axis consider a cylindrical flux tube along the machine center-line, as shown in Figure VI.B.1. From flux conservation,

$$\frac{r_c}{r_p} = \sqrt{\frac{B_p}{B_c}} \quad (4)$$

where r_c and r_p are the flux tube radii in the central cell and plug and B_c and B_p are the corresponding magnetic field strengths. For typical TMX operation ($B_c = 1$ kG, $B_p = 10$ kG, $L_{c,eff} = 315$ cm, $L_{p,eff} = 25$ cm)

$$\frac{v_c}{v_p} = \frac{\pi r_c^2 L_c}{\pi r_p^2 L_p} = \frac{B_p L_c}{B_c L_p} = 126 \quad (5)$$

Since $j_c > j_p$ (central cell gas feed ~ 1000 atom-amps compared to ~ 150 amps neutral beam current in the plugs)

$$\frac{2j_p v_p}{qL_p} \ll \frac{j_c v_c}{qL_c} \quad (6)$$

Figure VI.B.1. Cylindrical flux tube model in the end-plugs and central cell.

and can be neglected in (3). For typical plug and central densities, however, $n_p/n_c \sim 5$ yielding

$$\frac{2n_p^2 V_p}{n_c^2 V_c} \approx 0.4 \quad (7)$$

indicating that the plug term on the left hand side of (3) is significant. Therefore equation (3) can be simplified to

$$\frac{2.8}{g(R)(n\tau)_{ee}} \left(\frac{kT_e}{e\phi_e} \right) \exp \left(- \frac{e\phi_e}{kT_e} \right) = \frac{j_c}{qL_c n_c^2} \quad (8)$$

Substituting

$$(n\tau)_c = \frac{n_c^2 L_c e}{j_c} \quad (9)$$

and rearranging yields a transcendental equation for ϕ_e

$$e\phi_e = kT_e \ln \left[\frac{2.8 (n\tau)_c}{g(R)(n\tau)_{ee} e\phi_e / kT_e} \right] \quad (10)$$

This relation can be iteratively solved for the ratio $e\phi_e/kT_e$.

The large number of identical shots obtained during the September 24, 1980 run provides a good data base for experimental verification of equation (10). Machine conditions were held as uniform as possible for the entire run, allowing shot-to-shot scatter (from machine

reproducibility and diagnostic accuracy) to be averaged. In addition, detailed scans were obtained with the Thomson scattering and other diagnostics. Table V.E.3 summarizes the machine conditions and timing.

The central cell loss current, j_c , for this run is shown in (a) of Figure VI.B.2. Data were obtained by monitoring the axial loss of ions along the machine centerline, where radial losses are small. Measurements are indicated at 16 ms, during full tandem mirror operation, and at 26 ms after the neutral beams in the west end-plug were switched off, presumably eliminating electrostatic confinement of central cell ions ($n_p/n_c \approx 1$). The current was monitored with biased Faraday cups and swept end-loss-analyzers.^{2,12} Error bars indicate the standard deviation in shot-to-shot measurements.

The central cell density, n_c , is given in Figure VI.B.2(b). Data were obtained with calibrated Thomson scattering^{3,4} and by measurement of the attenuation of a diagnostic neutral beam directed through the plasma.^{5,6} These data and the total end loss current, $j_{c,east} + j_{c,west}$ allow a calculation of the central cell confinement product, $(n\tau)_c$, via equation (9). The result is shown in (c) of Figure VI.B.2. The total loss current was estimated by averaging the end-loss-analyzer and Faraday cup measurements, and adding the results for the east and west ends of the machine. Similarly, the Thomson scattering and beam attenuation density measurements were averaged, although they are in close agreement. The error bars indicated on the $(n\tau)_c$ calculation were obtained from the worst case error limits (i.e., the lower limit is

Figure VI.B.2. Central cell (a) axial loss current, (b) density, and (c) the resulting confinement product.

obtained from the lower particle density limit and the upper current density limit).

Thomson scattering measurements of the on-axis electron temperature in the east end-plug and in the central cell of TMX are shown in Figure VI.B.3(a). Although classical tandem mirror theory assumes a free mixing of end-plug and central cell electrons, forming a uniform temperature along field lines, during full tandem mirror operation of TMX (16ms) the central cell electron temperature is measured to be less than that of the plug.¹⁵ This difference is larger than that expected from electron-electron coulomb collision energy exchange between the plug and central cell and is presently not understood. Measurements at 26 ms, however, which occur after the east plug has been switched off eliminating electrostatic confinement of the central cell ($n_p = n_c$), indicate a uniform electron temperature of about 25 eV throughout the unheated plasma.

From the $(n\tau)_c$ values shown in Figure VI.B.2, the electron temperature measurements in Figure VI.B.3(a), and equation (10) the expected magnitude of the central cell space potential is calculated. The result is shown in Figure VI.B.3(b), for both $T_e = T_{ec}$ and $T_e = T_{ep}$. Error bars indicate only the uncertainty in temperature measurements.

Also shown in this figure is the experimental value of the potential measured from the heavy ion beam probe. During steady-state tandem mirror operation (16 ms) the measured potential is close to the calculated value using the plug electron temperature.

Figure VI.B 3. (a) Measured electron temperatures, and (b) measured and calculated central cell space potentials on-axis.

Good agreement between theory and experiment is also obtained at 26 ms, after the east end-plug is turned off. At this time the electron temperature in the unfueled east plug and central cell equilibrate to about the same value. Using these temperatures in the Pastukhov relation a space potential slightly lower than the measured value is calculated.

C. Central Cell Well Depth

1. Introduction

The enhanced confinement of a tandem mirror over conventional single cell mirror devices is based on electrostatically "plugging" the velocity space loss cones of a solenoidal central cell plasma. A potential well for ions is established, by maintaining plasmas of higher density at each end of the solenoid in minimum $-|B|$ "end-plugs". For Maxwellian electrons, electrostatic and pressure force balance requires

$$e\phi_c = kT_e \ln\left(\frac{n_p}{n_c}\right) \quad (11)$$

along field lines⁷, where ϕ_c is the difference in electric potential between the two regions. Central cell ions with energies less than $q\phi_c$ are confined axially in the potential well. For an ion temperature T_c and $\phi_c \geq 2T_c$, ion confinement time is increased above the 90° ion-ion scattering time τ_{ii} by⁸

$$\tau_c = \tau_{ii} g(R) \left(\frac{\phi_c}{T_c} \right) \exp \left(\frac{\phi_c}{T_c} \right) \quad (12)$$

The potential well depth in TMX has been experimentally determined by separately measuring the plug potential, ϕ_p , and the central cell potential, ϕ_e , with respect to machine ground

$$\phi_c = \phi_p - \phi_e \quad (13)$$

The plug potential is obtained by measuring the minimum energy of ions escaping axially from the machine⁹. Since all ions escaping in this direction pass through the plug they leave with a minimum energy $e\phi_p$.

Retarding grid electrostatic end-loss-analyzers located in the far region of each end-plug measure this energy, by rapid sweep of the repeller voltage. The characteristics of the analyzers and their calibration has been provided by Molvik¹⁰. The effects of ion-cyclotron fluctuations in the plug on the measurements has been analyzed by Poulsen.¹¹

Measurements of the central cell potential, ϕ_e , with the heavy ion beam probe were presented in the previous chapter. End-loss-analyzer data has been analyzed by Casper, Grubb, and Correll, particularly for the runs on September 24, 1980, (puffer)¹², and September 26, 1980, (gas box)¹³. Electron temperature and density measurements were also obtained during these runs.

2. Puffer Fueling

The on-axis space potentials obtained on September 24, 1980 are shown in Figure VI.C.1. Measurements are given at 16 ms, during full tandem mirror operation, and at 26 ms, five milliseconds after the neutral beams in one plug were turned off (early turn-off of both the east and west plugs were done). The run consisted of a total of 54 shots of constant machine conditions and 20 background shots used for diagnostic calibration.

The average neutral beam current for this run was 151 ± 13 atom-amperes in the east end-plug and 159 ± 27 atom-amperes in the west, where the $\pm$ range indicates the shot-to-shot standard deviation over the run. The average neutral beam energy was 11.6 keV and 11.0 keV in the east and west plugs, respectively. Deuterium gas feed was adjusted to ~1560 atom-amperes from two puffer valves located on the top and bottom of the central cell midplane. The LN liners were cold and the walls were gettered between each shot, providing base pressures of 1×10^{-8} , 3×10^{-8} , and 3×10^{-8} torr in the east plug, central cell, and west plug respectively. The central cell magnetic field was 1 kG.

Beam probe measurements of the central cell potential graphed in Figure VI.C.1 were obtained from nine shots, in which the sample volume was located at $r = 0$. The sample volume was set off-axis for the remaining shots, to obtain a shot-to-shot radial scan of the plasma. Error bars indicate the standard deviation of shot-to-shot scatter in the data.

Figure VI.C.1. (a) Measured on-axis space potentials and (b) the resulting potential well depths.

Plug potential measurements from both east and west end-loss-analyzers are also shown in Figure VI.C.1⁵. Data at 16 ms is averaged over all usable shots on the east and those shots on the west end where the movable end-loss analyzer was located at $r = 3.4$ cm. (End loss current from a Faraday cup array and from the movable end-loss-analyzer indicated that the plasma fan on the west end wall is displaced from the machine axis. The maximum value of the west end-plug potential is shown in the figure, and was actually obtained at a radius of 3.4 cm referenced to the plug midplane geometrical axis. This corresponds to a 10.8 cm radius in the central cell). The 26 ms data is an average of shots 1 - 59, when the west end-plug was switched off early at 21 ms. For the remaining shots (60 - 74) the east plug was turned off early, allowing Thomson scattering measurements under early turn-off conditions.

Measurements at 16 ms, during full tandem mirror operation, indicate a confining potential well of

$$\phi_c = 480 - 328 \quad (14)$$

$$= 152 \text{ volts (west)}$$

$$\phi_c = 540 - 328 \quad (15)$$

$$= 212 \text{ volts (east)}$$

A definite well is indicated, as error bars from the plug and central cell diagnostics do not overlap, with

$$54 < \phi_c < 250 \text{ volts} \quad (16)$$

as shown in Figure VI.C.1(b). Measurements made at 26 ms, after the west end plug has been switched off, indicate that within the error bars no well exists on the west end of the machine. In the east plug, however, which remains fueled until 28 ms, the potential difference remains.

The expected potential well depth may be calculated from the Boltzmann eqn. (11) and measured values of the plasma density and electron temperature. Table VI.C.1 indicates these parameters for the September 24 run, obtained from Thomson scattering³ and neutral beam attenuation measurements.¹⁴ The range indicated with $\pm$ signs is again the shot-to-shot statistical fluctuations in the data.

The potential well expected on the east end of the machine, where the electron temperature in the plug is directly measured, is given at 16 ms by

$$\begin{aligned} \phi_{c,east} &= T_e \ln(n_p/n_c) \\ &= 76.8 \ln(1.3 \times 10^{13} / 2.7 \times 10^{12}) \\ &= 121 \text{ volts} \end{aligned} \quad (17)$$

where the plug and central cell densities have been obtained from the beam attenuation measurements. The plug electron temperature has been used in the calculation, although the Boltzmann relation requires a uniform temperature along the field lines which does not actually exist (Table VI.C.1). For the west end of the machine

<u>Parameter</u>	<u>16 ms</u>	<u>26 ms</u>
<u>Electron Temperature (eV)</u>		
Thomson scattering		
East	$T_{ep} = 76.8 \pm 14.5$	$T_{ep} = 20.9 \pm 10.4^*$ $= 49 \pm 17^+$
Center	$T_{ec} = 52.3 \pm 12.5$	$T_{ec} = 28 \pm 5.5$
<u>Plasma Density ($\times 10^{12} \text{ cm}^{-3}$)</u>		
Thomson scattering		
East	$n_p = 9.5 \pm 1.4$	$n_p = 1.9 \pm .8^*$ $= 12 \pm 1.7^+$
Center	$n_c = 2.5 \pm .4$	$n_c = 3.0 \pm .7$
Beam Attenuation Detectors		
East	$n_p = 13 \pm 1.0$	
Center	$n_c = 2.7$	
West	$n_p = 17 \pm 2$	

*Shots 60-70 when the east end-plug was unfueled at 26 ms.

+Shots 71-73 when the east end-plug was fueled at 26 ms.

Table VI.C.1

On-axis plasma density and temperature for Sept. 24, 1980

$$\begin{aligned}\phi_{C,west} &= 76.8 \ln(1.7 \times 10^{13} / 2.7 \times 10^{12}) \\ &= 141 \text{ volts}\end{aligned}\tag{18}$$

where the temperature in the east end-plug has been used, since it is not measured in the west.

The expected potential well at 26 ms, after one of the end-plugs has been turned off, should also be given by the Boltzmann eqn. (11). At the east end of the machine, where the Thomson scattering is located, and with early turnoff in the east plug,

$$\begin{aligned}\phi_{C,east} &= 20.9 \ln(1.9 \times 10^{12} / 3.0 \times 10^{12}) \\ &= -9.6 \text{ volts}\end{aligned}\tag{19}$$

The expected well is essentially lost, a consequence of the almost equal plug and central cell densities. From Table VI.C.1 note that the electron temperatures in the plug and central cell are about the same at 26 ms, and the Boltzmann relation should accurately predict the difference in potential between the two regions.

The measured and expected potential wells are compared in Figure VI.C.2. Good agreement is obtained at both 16 ms and 26 ms. The 16 ms measurements, during full machine operation, indicate the existence of a confining potential well for central cell ions basic to the tandem mirror concept. The lack of a potential well at 26 ms in the plug which

Figure VI.C.2. Measured and expected potential well depths.

has been turned off is consistent with expected performance and adds confidence in the measurement accuracy. The loss of electrostatic plugging at 26 ms correlates with a large increase in end-losses when the plug is turned off.

D. Radial Profile of the Space Potential and Electron Temperature

As discussed at the beginning of this chapter, classical calculations dictate that the maximum ambipolar potential to electron temperature ratio should be

$$\frac{e\phi}{kT_e} = \ln[f(v_{ee}, \tau, e\phi/kT_e)] \quad (20)$$

The logarithmic nature of this expression results in $e\phi/kT_e$ being relatively insensitive to the other parameters, with

$$\frac{e\phi}{kT_e} \sim 4.5 - 5.5 \quad (21)$$

This result is obtained for both simple and tandem mirrors.^{7,15}

The radial profiles of the central cell space potential, ϕ_e , and the electron temperatures in the plug and central cell of TMX are shown in Figure VI.D.1. Data are for puffer valve fueling of the central cell on Sept. 24, 1980.

Electron temperature measurements in the central cell, obtained with Thomson scattering, are only available on-axis. The ratio

Figure VI.D.1. Radial profiles of the central cell space potential and east end-plug electron temperature and the on-axis central cell electron temperature. Data are at 16 ms.

of the on-axis potential to the on-axis electron temperature in the central cell

$$\frac{\phi_e(0)}{T_{ec}(0)} = 6.3 \quad (22)$$

is in good agreement with the expected value. This is just the result obtained in Section B of this chapter, where the expected potential (triangle datapoint in Figure VI.B.3(b)) is slightly less than the experimentally measured potential.

Radial comparisons of ϕ and T_e must be made in the end-plug where the radial electron temperature distribution is measured. The plug potential is obtained from end-loss-analyzer measurements or by adding the central cell potential and the potential well depth between the two regions. The well depth is calculated from the Boltzman relation, $T_e \ln(n_p/n_c)$, using the measured plasma densities in the plug and central cell and the plug electron temperature.

The electron density of the plug and central cell plasmas are obtained from multi-chord neutral beam attenuation diagnostics.¹⁴ A 4th order polynomial was least-squares fit to the integrated data and Abel inverted to obtain the radial profile.¹⁶ Results are shown in Figure VI.D.2 for the Sept. 24, 1980 operation. The plug density, n_p , is peaked at the center of the plasma and falls off monotonically with increasing radius. Measurements are given for the east end-plug and are similar in the west. The central cell density, however, is fairly flat to about 26 cm radius followed by a rapid falloff at larger radii (the

Figure VI.D.2. Radial profiles of the density in the east end-plug and central cell. Data are at 16 ms.

central cell potential is also relatively flat to 26 cm radius as shown in Figure IV.E.7). Plug and central cell horizontal axes in the figure are scaled so that data on the same field lines are compared vertically.

The radial distribution of the expected well depth,

$$\phi_c = T_{ep} \ln(n_p/n_c) \quad (23)$$

calculated from the measured density and temperature profiles is shown in Figure VI.D.3. The expected well depth is relatively constant out to 15 cm radius, followed by a drop of about 5 V/cm. Measurements indicate the well has dropped to ~30 volts at a radius of 30 cm.

The radial profile of the end-plug potential can now be obtained by adding the expected well depth to the central cell potential

$$\phi_p = \phi_e + T_{ep} \ln(n_p/n_c) \quad (24)$$

This is also shown in Figure VI.D.3. A comparison of the result with the central cell potential, ϕ_e , indicates that the end-plug potential decreases with radius considerably faster than the central cell potential. This, of course, is a consequence of the smaller electrostatic well depth at larger radii.

The end-plug temperature and potential profiles are replotted in Figure VI.D.4. These data yield the ϕ/T_e ratio, which is also shown in the figure. As evident from the lower plot,

$$\frac{\phi_e + T_{ep} \ln(n_p/n_c)}{T_{ep}} \approx 6 \quad (25)$$

Figure VI.D.3. Radial profiles of the central cell potential, ϕ_e , the expected well magnitude, $T_{ep} \ln(n_p/n_c)$, and their sum, the expected end-plug potential. Data are for Sept. 24, 1980 at 16 ms.

Figure VI.D.4. The measured end-plug potentials (direct and from $\phi_e + T_{ep} \ln(n_p/n_c)$), the measured end-plug electron temperature, and their ratios.

for radii less than 15 cm (all plug radii are referenced to the central cell along field lines; $r_c \sim \sqrt{10} r_p$). This result is in very good agreement with the central cell ratio on-axis, ϕ_e/T_{ec} (eqn. 22), where a value of 6.3 was measured. For radii greater than 15 cm the ratio increases, reaching a value close to 10 at the plasma edge.

Figure VI.D.4 also indicates the end-plug potential as directly measured by the end-loss analyzer. Shown at the top of Figure VI.D.4, ϕ_p as measured with the ELA decreases more rapidly with radius than ϕ_p obtained from the central cell potential measurement and the Boltzmann relation. Very good agreement, however, is obtained between these measurements at plasma radii less than 15 cm. This is evident from the ϕ_p/T_{ep} ratio also plotted in the figure (this agreement can be restated to indicate that the expected confining well depth, $\phi_c = T_e \ln(n_p/n_c)$, is in agreement with measured potential, density, and temperature profiles for $|r| < 15$ cm). For radii greater than 15 cm the ϕ_p/T_{ep} ratio (with ϕ_p from the end-loss-analyzer) decreases, reaching a value of 3 to 4 near the plasma edge.

E. Space Potential Scaling with Fueling Rate

1. Measurements and Comparison with Electron Temperature

The fueling rate of the central cell plasma has been varied by an order of magnitude to study machine scaling, stability, and radial transport. Data was obtained during a gas box scan on Sept. 26, 1980. The gas input (deuterium) was changed from shot-to-shot, with four to six

shots taken at each of four gas feed rates. Other machine conditions were held relatively constant. The neutral beam current was 167 ± 8 atom-amperes in the east end-plug and 161 ± 12 atom-amperes in the west. The central cell magnetic field was 1 kG.

The temporal profile of the on-axis ($r = 0$) potential was monitored with the heavy ion beam probe during the pressure scan. The resulting potential variation, during the plasma equilibrium at 16 ms, is shown in Figure VI.E.1(a) (complete temporal profiles for several of the fueling rates were shown in Section V.D.1). Total gas flow, which is equally divided between the two gas boxes, is indicated on the plot abscissa. The central cell potential decreases with increasing gas feed, although not drastically. A drop of about 100 volts occurs for a tenfold increase in gas input. A linear least-squares fit to the measured data is also shown in the figure, yielding the relation

$$\phi_e \approx 448 - 0.028 i_{\text{gas}} \quad (26)$$

with ϕ_e in volts for i_{gas} in equivalent atom-amperes of deuterium. A fit parameter r^2 of 0.74 was obtained ($0 < r^2 < 1$).

The central cell electron temperature, obtained with Thomson scattering¹⁷, is shown in (b) of Figure VI.E.1. The electron temperature also decreases moderately with increasing gas feed, dropping about 30% over the scan. A least squares fit has also been applied to this data, yielding

$$T_{\text{ec}} \approx 53 - 0.0050 i_{\text{gas}} \quad (27)$$

Figure VI.E.1. (a) The central cell space potential, (b) the central cell electron temperature, and (c) their ratio, as a function of central cell fueling. Least squares fits are indicated to the measured data points.

with T_{ec} in electron-volts and i_{gas} in atom-amperes of deuterium as before. The fit parameter for this data, r^2 , is 0.37. More data points exist for the electron temperature than for the space potential measurement, since higher order charge states were monitored with the beam probe during some of the shots which cannot be processed until trajectory simulations are obtained (Section II.B). (Scatter in the beam probe data is smaller than that of Thomson scattering, with fewer points required for good statistics).

With the slight decrease in both the space potential and electron temperature with increased gas feed their ratio, ϕ_e/T_{ec} , remains relatively constant. Over the entire fueling range

$$\frac{\phi_e}{T_{ec}} \approx 8 \quad (28)$$

as shown in Figure VI.E.1(c). The triangles indicate the ϕ_e/T_{ec} ratio for individual shots where both ϕ_e and T_{ec} were obtained.

2. Theoretical Potential and Electron Temperature Scaling with Fueling Rate

The space potential to electron temperature ratio is governed by the Pastukhov relation

$$\frac{e\phi_e}{kT_e} = \ln \left[\frac{2.8 (n\tau)_c}{g(R)(n\tau)_{ee} e\phi_e/kT_e} \right] \quad (29)$$

if radial transport is not significant and the machine is otherwise behaving as a classical mirror device. This ratio has been investigated over a tenfold range of central cell fueling.

For small changes in the central cell potential and electron temperature a simple expression for the expected change with fueling can be obtained. Equation (29) yields

$$\Delta \left(\frac{e\phi_e}{kT_e} \right) = \left(\frac{e\phi_e}{kT_e} \right)_H - \left(\frac{e\phi_e}{kT_e} \right)_L = \ln \left[\frac{(n\tau)_{cH}}{(n\tau)_{cL}} \right] \quad (30)$$

where subscripts H and L refer to high and low gas inputs. From equation (9)

$$\Delta \left(\frac{e\phi_e}{kT_e} \right) = \ln \left[\frac{n_H^2 j_L}{n_L^2 j_H} \right] \quad (31)$$

The axial loss currents, j , from the east and west end-plugs increase dramatically during the pressure scan, as shown in Figure VI.E.2. Measurements are obtained with biased Faraday cups, and from the electrostatic end-loss-analyzers.¹⁸ Both were biased to collect ion current from the plasma. On-axis ($r = 0$) measurements are shown. Least squares fits to the data are indicated, with r^2 fit parameters .92/.92 for the Faraday cup data and .90/.87 for the end-loss-analyzers (east/west). As previously discussed, these end-loss currents are dominated by losses from the large volume central cell plasma. A factor of 3 increase in axial losses occur over the 400 to 3700 atom-ampere fueling range.

Figure VI.E.2. End-loss current from (a) Faraday cup and (b) end-loss-analyzer measurements. The current density is referenced to the central cell midplane.

The central cell density, on-axis, is shown in Figure VI.E.3 as a function of gas feed. Measurements from both calibrated Thomson scattering and the neutral beam attenuation diagnostic are shown. Thomson scattering should give a good relative indication of the on-axis changes during the scan, with less accuracy in absolute values. Beam attenuation measurements are complicated by the non-gaussian radial profiles at the higher gas feeds, with inverted (hollow) density profiles existing at the higher levels. Data shown in the figure are from Abel inverted polynomial fits to the integrated measurements.

Overall scatter in the Thomson scattering and beam attenuation data are large, but measurements indicate a slightly increasing central cell density with gas feed. About a factor of 2 change occurs from the lowest to highest gas pressures, from $\sim 2.5 \times 10^{12}$ to $\sim 3.6 \times 10^{12} \text{ cm}^{-3}$.

From the measured changes in end loss current and plasma density, equation (31) yields

$$\Delta \left(\frac{e\phi_e}{kT_e} \right) = \ln \left[\frac{(3.6 \times 10^{12})^2}{(2.5 \times 10^{12})^2} \frac{(0.68)}{(2.09)} \right] \quad (32)$$

$$= -0.39$$

which implies

$$\left(\frac{e\phi_e}{kT_e} \right)_H \approx \left(\frac{e\phi_e}{kT_e} \right)_L \quad (33)$$

Figure VI.E.3. Central cell density as a function of fueling. A least squares fit to the Thomson scattering data is shown.

a large increase in axial loss current is almost balanced by the smaller increase in density, since density enters as a squared term. The ϕ_e/T_{ec} ratio remains essentially constant, which is the experimentally observed result as shown in Figure VI.E.1(c) (actually a slight decrease in the ϕ_e/T_{ec} ratio is predicted at higher gas feeds, which is also experimentally observed. However, this small a change is within the uncertainty in the experimental measurements). For a large range of central cell fueling and a factor of three change in end losses the on-axis ϕ_e/T_{ec} appears governed by classical end-loss processes.

3. Potential Well Scaling with Fueling

The potential well depth, ϕ_c , is experimentally determined by comparing beam probe measurements of the central cell potential, ϕ_e , with end-loss-analyzer measurements¹¹ of the end-plug potential, ϕ_p

$$\phi_c = \phi_p - \phi_e \quad (34)$$

Data for the September 26 gas box scan are shown in Figure VI.E.4(a). Measurements at 16 ± 2 ms during the plasma equilibrium are given.

End-loss-analyzer measurements show potential profiles in the end-plugs differing substantially from that of the central cell. A potential well for ions is only indicated at the two lowest gas feed

Figure VI.E.4. (a) Measured space potentials and (b) measured east end-plug to central cell density ratio as a function of central cell fueling. Density data are from Thomson scattering.

rates, with the measured west plug potential dropping several hundred volts below the central cell at 2400 atom-amps of fueling. Both plug measurements are ~200 volts below the central cell at the highest (3600 atom-amp) gas feed.

The expected potential difference between the plug and central cell regions is given by the Boltzmann relation (11)

$$e\phi_c = kT_e \ln(n_p/n_c) \quad (35)$$

Measurements indicate the plasma density in the end-plugs are considerably above that in the central cell at all gas feeds, as shown in (b) of Figure VI.E.4. A constant electron temperature in the east end-plug was measured during the fueling scan, with an average value of 58.6 eV and a 13 eV standard deviation. Therefore a positive potential well should exist at all gas pressures with a magnitude of about

$$\begin{aligned} \phi_c &= 59 \ln(3) \\ &\approx 65 \text{ Volts} \end{aligned} \quad (36)$$

No dramatic change in the plasma occurs when the measured well goes negative; measurements of n, j , and other parameters change smoothly from low to high gas feed rates. Large increases in end-loss current from the plug turned off early, an indirect indication of electrostatic stoppering, was evident at all gas feeds.

In addition, end-loss-analyzer measurements, which determine the plug potential from the minimum energy of escaping ions, should not be capable of measuring a potential below the central cell value. If operating as expected, they would begin measuring the central cell potential when the plug potential drops below the central cell value. A possible explanation for the measured versus expected well depth discrepancy may be with these end-loss-analyzer measurements. Charge exchange on the background gas may create new particles born with a lower potential than ϕ_p , the maximum plug potential. If important, this effect could substantially lower the potential indicated by the end-loss-analyzers, particularly at high gas feeds. Difficulties in accurately knowing the neutral pressure of the background gas make calculations of this effect difficult.

CHAPTER VII

Fluctuation Measurements

A. Introduction

Considerable low frequency ($f < 20$ kHz) fluctuation activity has been observed in TMX. Oscillations in plasma density and space potential are especially strong during gas box fueling, with amplitudes typically 5 to 10% on axis ($\tilde{n}_{p-p}/\langle n \rangle$, $\tilde{\phi}_{p-p}/\langle \phi \rangle$) and 100% near the plasma edge. Fluctuations are of low amplitude ($< 10\%$ of the mean density) or non-existent during puffer operation.

Two well defined modes have been observed in the central cell. A mode at about 12 kHz is peaked on-axis and is present at all gas feed levels. A mode at about 5 kHz is peaked near the plasma edge and is present only at high central cell fueling rates. These fluctuations are also observed in the end-plugs, and are correlated with the central cell oscillations.

The heavy ion beam probe is well suited for making fluctuation measurements. Sufficient bandwidth exists to record most low frequency activity (40 kHz for measurements presented here although 1 mHz is available) and measurements are spatially and temporally resolved. A direct measurement of the fluctuating potential is obtained, with a resolution of about 2 volts. Fluctuations in the secondary current intensity, $\propto n f(T_e)$, provide information on plasma density and

temperature oscillations. If the density fluctuations can be extracted (Section II.B.4) a local measurement of fluctuation induced transport can be made.¹

The low frequency oscillations are observed on several TMX diagnostics in addition to the heavy ion beam probe. The primary measurement of density fluctuations was made by monitoring the attenuation of a neutral beam directed through the plasma.² Measurements along seven chords yielded the integrated line density as a function of chord position and time. The oscillations are also observed on electrostatic probes at the plasma edge, which can be used to determine the azimuthal mode numbers.

B. Beam Attenuation

Up to 40% attenuation of the primary beam occurs with T1 operation of the beam probe, as indicated in Table III.D.1. Secondary ions are also subjected to attenuation as they exit the plasma, primarily by further electron impact ionization of the ions ($2^+ \rightarrow 3^+$, $2^+ \rightarrow 4^+$, etc.). With significant beam attenuation the detected current level becomes modulated by density and temperature fluctuations along the beam trajectories. Although beam attenuation does not affect the space potential measurements (unless the spatial wavelength of fluctuations is comparable to the sample volume), the secondary current level becomes a function of the integrated loss of beam through the plasma as well as the

ion production rate within the sample volume. This leads to a loss in spatial resolution in the $nf(T_e)$ measurement and difficulty in interpreting the phase between the potential and $ni(T_e)$ signal.

To obtain a local measurement of both the secondary ion current and space potential for fluctuation analysis tertiary, ($1^+ \rightarrow 3^+$) transitions were monitored rather than secondary, ($1^+ \rightarrow 2^+$) transitions. A measurement using tertiaries is shown in Figure VII.8.1, where the sample volume was located on-axis with an accuracy of ± 1 cm. The overall profile of the space potential is identical to that measured using secondaries, as expected. The attenuation of the injected beam and exiting tertiary ions is reduced, however, since the beam energy is higher, greater than 30 keV rather than 11 keV, reducing the effective cross section for electron impact ionization. The tertiary current intensity, (b) of Figure VII.8.1, is now only a function of the plasma density and temperature within the sample volume. One indication of this is the drop in the current intensity at the end of the shot (22 ms) when one end-plug is switched off. When monitoring secondary ions this signal actually increases (Figure V.D.1) with the drop in plasma temperature, since more primary beam current is delivered to the sample volume (beam attenuation is exponential compared to approximately linear production with temperature in the sample volume).

Figure VII.B.1. On axis measurements of a) plasma space potential and b) total secondary current level using Tertiary ($1^+ \rightarrow 3^+$) ions.

C. The 12 kHz Mode

1. Structure

A temporal profile of the space potential and total secondary current level (sum) during the equilibrium of a typical shot is shown in Figure VII.C.1. The sample volume was fixed on-axis, with an accuracy of approximately ± 4 cm. Fluctuations appear coherent and are well defined, with

$$\frac{\phi - \bar{\phi}}{\bar{\phi}} \approx 5\% \quad (1)$$

and

$$\frac{\tilde{i}_s}{\bar{i}_s} \approx 50\% \quad (2)$$

where the peak-to-peak value of the oscillations is used. When compared with the central cell electron temperature, T_{ec} , the fluctuation amplitude is about unity

$$\frac{e\tilde{\phi}}{kT_{ec}} \approx 1 \quad (3)$$

The onset of $nf(T_e)$ fluctuations is tied to the central cell gas feed and/or stream gun turn off, as evident from Figure V.D.2 and the timing diagram shown in Figure V.C.1. Oscillations are of low amplitude

Figure VII.C.1. Temporal profile of typical space potential and $nf(T_e)$ oscillations.

until about 8 ms into the shot, at which time the fluctuation level rapidly increases to $\sim 50\%$. The gas boxes are switched on at 6 ms, and gas begins flowing to the central cell a few milliseconds later. The stream guns are switched off at 8 ms.

Auto power spectra of the space potential and secondary current level are shown in Figure VII.C.2 (Spectral analysis of beam probe fluctuation data has been provided by Powers.³). The power spectrum indicates a strong oscillation at 12 kHz in both the potential and $nf(T_e)$ signals. The spectra were obtained with a 1024 point Fourier transform, using data beginning 12 ms into the shot and continuing for 10.24 ms. This covers the equilibrium duration of the discharge.

The phase spectrum of the potential and $nf(T_e)$ oscillations is shown in (c) of Figure VII.C.2. The phase between the signals is random at most frequencies, indicated by the rapid oscillation, except at 12 kHz where a well defined phase difference of 2.79 radians (~ 160 degrees) exists. The signals are close to out of phase at the 12 kHz oscillation frequency, which is also evident from a close examination of Figure VII.C.1.

The potential and $nf(T_e)$ oscillations are well correlated at the 12 kHz oscillation frequency, with a correlation coefficient approaching unity. At other frequencies the signals are essentially uncorrelated, as indicated in (d) of Figure VII.C.2.

Figure VII.C.2. Auto power spectrum of the (a) $nf(T_e)$ and (b) space potential. The phase between the signals is given in (c) and their coherency in (d). Data are for shot 43 on Sept 26, 1980 with on-axis measurements of tertiary ions.

Time-dependent spectral analysis, where a 512 point cosine bell shaped "sliding window" was used to follow the temporal profile of the oscillations during a shot, is shown in Figures VII.C.3 and VII.C.4. A contour plot is given in (b) of the figures, indicating regions of constant amplitude during the discharge. The 12 kHz mode dominates, and is seen to increase from a lower frequency at the beginning of the shot and decrease to a lower frequency near the end of the discharge.

During plasma buildup, from 8 ms into the discharge to ~12 ms, the oscillation frequency increases from ~10 kHz to an equilibrium value of ~12 kHz. The frequency remains fairly constant during the main equilibrium, and begins to drop off again at 21 ms, when the west end-plug is switched off. During this single plug, non-tandem mirror operation extending from 21 to 28 ms the frequency shifts to about 7 kHz. The oscillation frequency changes smoothly as a function of time during the discharge; no jumps or discontinuities occur on the time-dependent plots. A single mode is most likely being followed as it evolves through the shot.

Contour plots of constant phase between the density and potential oscillations and their coherency are shown in Figure VII.C.5. Results are similar to the non-time dependent data (Figure VII.C.2(c,d)), with a well defined phase and strong coherency at the dominant oscillation frequency. Little coherency and random phase is obtained at other frequencies.

Figure VII.C.3. Time dependent auto-power spectrum of the $nf(T_e)$ signal.

Figure VII.C.4. Time dependent auto-power spectrum of the space potential.

Figure VII.C.5. Contour plots of constant (a) phase and (b) coherency between the space potential and $nf(T_e)$.

2. Correlation with E x B Drift

The central cell space potential profile is parabolic to at least 20 cm radius during moderate fueling with the gas boxes

$$\phi = \phi_{\max} [1 - (r/r_0)^2] \quad (4)$$

The radius and amplitude of the parabola change during various phases of the shot, as described in Section V.E.1. Initially, when the plasma is being formed by the stream guns, the potential is low and the plasma radius small, with $r_0 \sim 25$ cm. During equilibrium, from ~ 10 to 21 ms, the maximum potential is attained and the typical plasma radius r_0 is ~ 32 cm. When one of the end-plugs is turned off at 21 ms, the potential drops to $1/2 - 2/3$ of its equilibrium value and the plasma radius increases, typically to $r_0 \sim 35$ cm.

The parabolic potential profile and solenoidal magnetic field in the central cell of TMX result in rigid body rotation of the plasma at the $E \times B$ frequency. With a 1 kG field the rotational frequency is given by

$$f_{E \times B} = 3.18 \times 10^4 \phi_{\max} / r_0^2 \quad (5)$$

with $\phi_{\max}$ in volts and r_0 in centimeters.

The maximum potential, $\phi_{\max}$, for shot 43 on September 26, 1980, is given in Table VII.C.1 for the three main equilibrium intervals. The observation point was fixed on-axis for this shot, yielding the temporal

profile used to obtain the fluctuation spectra. The radial fit parameters, r_0 , indicated in the table are from single-shot radial scans during similar conditions.

<u>Time</u>	<u>$\phi_{\max}$</u>	<u>r_0</u>	<u>E x B</u>	<u>Measured</u>
Early (8 ms)	200 volts	24 cm	11 kHz	10 kHz
Equil (16 ms)	400 volts	32 cm	12.4 kHz	12.3 kHz
Late (26 ms)	200 volts	35 cm	5.2 kHz	7.1 kHz

Table VII.C.1

Calculated E x B rotational frequency and measured fluctuation frequency for shot 43, Sept. 26, 1980.

The E x B rotational frequency of the plasma, from the measured potential profile and eqn (5), is given in the "E x B" column of Table VII.C.1. The frequency early in the shot, ~11 kHz, increases slightly to a value of 12.4 kHz during the main equilibrium. After one end-plug is turned off the rotational frequency drops considerably, to ~5.2 kHz.

The calculated rotational frequency of the plasma agrees very well with the measured fluctuation frequency obtained from the contour plot in Figure VII.C.3 and shown in the right most column of Table VII.C.1. An $m = 1$ mode in the central cell is suggested, and substantiated by the close tracking of the frequencies during the entire shot.

The observed amplitude dependence of the 12 kHz mode, largest at the plasma center and decreasing with radius, is not what is expected of an $m = 1$ mode, however. Furthermore, electrostatic probes located at the plasma edge at azimuthal angles of 90° , 180° , and 270° are in phase, indicating an even ($m = 0, 2, 4, \dots$) mode number.⁴ Cross correlation of neutral beam attenuation channels also show the mode peaked on-axis, suggesting $m = 0$. The excellent agreement with $E \times B$ indicates the overall mode is probably a combination of $m = 0$ and $m = 1$, so that the oscillation couples to, and locks onto the $E \times B$ frequency.

D. The 5 kHz Mode

A shot where beam probe measurements were taken off-axis is shown in Figure VII.D.1. A radial position of 23 ± 2 cm was monitored in the negative y direction. Well defined oscillations are again present in both the potential and $nf(T_e)$ data.

This shot was obtained by monitoring secondary, ($1^+ \rightarrow 2^+$) transitions rather than tertiary, ($1^+ \rightarrow 3^+$) transitions. For this shot beam attenuation should be small since the sample volume is located near the plasma edge and neither primaries or secondaries travel very far through the plasma.

Spectral analysis, shown in Figure VII.D.2, again shows the 12 kHz oscillation observed strongly at $r = 0$, but at reduced amplitude. In addition, the off-axis measurement indicates a lower frequency mode at

Figure VII.D.1. Typical space potential and $nf(T_e)$ oscillations off-axis.

Figure VII.D.2. Auto-power spectrum of the off-axis $nf(\tau_e)$ oscillations.

about 5 kHz. This mode, small or non-existent near the plasma center, increases in amplitude toward the plasma edge where fluctuations up to 100% of the mean signal are observed (Figure V.E.4). The time dependent auto power spectra for this shot is shown in Figure VII.D.3.

A shot with high central cell gas feed, ~ 2350 atom-amps, is shown in Figure VII.D.4. Measurements are on-axis, with an accuracy of ± 4 cm. Beam injection conditions are set to monitor tertiary ions. At this gas feed both the 5 kHz and the 12 kHz modes are present, with the 12 kHz mode about a factor of two larger in amplitude.

The amplitude of the 5 kHz mode is a strong function of the fueling rate. With low to moderate fueling (~ 425 atom-amps in Figure VII.C.2) only the 12 kHz mode is observed near the plasma center, although the 5 kHz mode is present off-axis (Figure VII.D.2, fueling ~ 1350 atom-amps). At high fueling rates (~ 2350 atom-amps in Figure VII.D.4) the 5 kHz mode is detectable over most of the plasma. The amplitude of the 12 kHz mode decreases off-axis, and is not sensitive to the fueling rate.

The 5 kHz mode is also detected by the neutral beam attenuation diagnostic and electrostatic probes. Probe phase shift measurements indicate an $m = 1$ mode, consistent with beam probe and beam attenuation measurements of an off-axis peak in the mode amplitude. The mode identification is uncertain; candidates include drift waves, flute perturbations driven by the centrifugal force from plasma rotation, and Kelvin-Helmholtz instability driven by shear from non-uniform $E \times B$ rotation (the electric field at large radii is not accurately known although it deviates from parabolic falloff and averages 8 to 10 V/cm).

Figure VII.D.4. Time dependent auto-power spectrum of the $nf(T_e)$ oscillations on-axis during high gas feed.

CHAPTER VIII

Conclusions and Suggestions for Future Work

A. Conclusions - Physics

1. The space potential in the central cell of TMX has been accurately measured, with an absolute error of ± 25 volts and a resolution of ~ 2 volts. Radial profiles have been obtained in a single shot.
2. Substantially different radial profiles of the central cell potential are obtained with gas box and puffer fueling. The space potential is parabolic to at least 25 cm radius during moderate fueling with the gas boxes, and relatively flat to at least 27 cm radius during puffer operation.
3. The on-axis magnitude of the central cell potential is consistent with the measured electron temperature and tandem mirror theory.
4. The electrostatic confining potential, ϕ_c , has been obtained from heavy ion beam probe measurements of the central cell potential, ϕ_e , and end-loss-analyzer measurements of the end-plug potential, ϕ_p . At moderate gas feeds a confining well depth consistent with the Boltzmann relation is measured (on-axis).

5. For an order of magnitude change in the central cell fueling rate, causing a factor of three change in end-losses, the on-axis central cell potential to electron temperature ratio is relatively constant and appears governed by classical end-loss processes.
6. Fluctuation measurements indicate oscillations in space potential and $n(T_e)$ close to the fundamental $E \times B$ rotational frequency of the central cell plasma. This frequency is also close to the sound speed divided by the machine length.

B. Conclusions - Heavy Ion Beam Probe Development

1. Off-line processing of the space potential, by individually recording the signals from the energy analyzer's split-plate detector, can provide significantly improved performance over conventional feedback operation. Off-line processing maximizes bandwidth, allows various noise reduction techniques to be applied to the same data set (software implemented), and provides complete stability from closed loop oscillations. The off-line processing technique has been verified through simulation by modulating the injected beam energy.
2. A microcomputer based digital control and data acquisition system has been successfully implemented. Computer control of the beam probe simplifies operation, enhances reliability, and

provides a highly flexible system. Digital storage of data is facilitated, allowing the power of computer processing display.

3. A wideband, low noise current-to-voltage converter has been developed for the first stage amplification of the split plate signals, and located in vacuum within the analyzer. A equivalent input noise of 1 na (p-p) was obtained at a bandwidth of 1 MHz. Reliable performance (no failures) occurred over 1 1/2 years of operation.

C. Suggestions for Future Work

1. Beam probe measurements have been obtained during several scans not reported in this thesis. Data remains to be analyzed for a neutral beam energy scan and a neutral beam current scan. The cleanup process and the effects of wall conditioning have not been investigated in detail.
2. Impurity injection experiments were performed in TMX to study radial transport. The potential typically increased slightly, the order of ten to fifteen percent, when impurities such as oxygen or nitrogen were puffed into the central cell plasma. Experimental results and the underlying physics remain to be investigated in detail.
3. Substantial low frequency fluctuations are present in TMX during certain conditions; initial analysis is presented in Chapter VII of this thesis. Although a consistent picture is

emerging, considerable work remains to understand the various modes, driving forces, profile effects, etc. In addition to the physics understanding, the response of the beam probe itself must be well defined. For instance, the normally localized $nf(T_e)$ measurement (total secondary current) becomes integrated through the plasma if beam attenuation is significant.

4. A radial profile of the central cell electron temperature in TMX can theoretically be obtained from the secondary ion current level ($\propto nf(T_e)$) and density profiles obtained with the neutral beam attenuation diagnostic. The calculations must include beam attenuation and electron impact ionization cross sections for secondary, tertiary, and possibly higher order reactions. Results can be verified on-axis with the Thomson scattering measurements.
5. Open loop operation of the energy analyzer and the subsequent off-line processing of the split plate signals to obtain the secondary ion energy should be verified on a test stand. Although extensive calibration and simulations were performed on the TMX system to verify this technique, questions remain which can be most directly addressed under controlled test stand conditions and direct beam injection (no magnetic field) into the analyzer.

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APPENDIX I

Data Processing

A. Introduction:

Obtaining the space potential and $nf(T_e)$ from the raw data requires several processing steps. These include noise reduction, determining the spatial location of measurements, and calculating the secondary ion energy. The complexity of the required processing varies, depending on whether the plasma was scanned during the shot, and on the intensity of noise sources.

Data recorded for the full shot includes the analyzer split plate signals (4 channels) and a selectable sweep waveform. The sampling period is $10\mu s$, beginning at $t=0$ and recording for 40.96 ms. Ten bit resolution is provided with a full scale range of ± 100 nA for the analyzer signals. Analyzer channels 1 and 3 are also optionally recorded with a $0.5\mu s$ sampling period from 16 ms to 16.512 ms. Eight bit resolution is provided.

Secondary ion current is detected within the analyzer on an aluminum plate split four ways, as shown in Figure AI.1. Up-down displacement of the beam, monitored by split plate pairs 1,3 and 2,4 is sensitive to the beam energy. All data processing makes use of channels 1 and 3, located on the west side of the analyzer. Beam displacement out of the central cell midplane is monitored by split plate pairs 1,4 and 3,2.

The beam probe data for each TMX shot are stored in separate

Figure AI.1. View of the electrostatic energy analyzer showing the 4-way segmented detector.

files. These files contain a variable length comment string, the system status (accelerator and analyzer voltages, etc.), the analyzer split plate currents (16384 words), a sweep waveform (4096 words), and optionally data from the high speed "burst" recorders (2048 words).

B. Noise Reduction

The noise level on the analyzer detector plates is sensitive to i) the amount and source of cold gas injected into the central cell, and ii) neutral beam injection, particularly from the central cell diagnostic beam (a full 50 Ampere source). The analyzer noise is most likely deuterons from the neutral beams, which become ionized through charge exchange on the background gas as described in Section V.A.

Several methods have been evaluated for reducing the analyzer noise. Although the signal-to-noise ratio of the split plate signals varies substantially with machine operating conditions, the order of 1:1 to 20:1, the predominant noise is low frequency simplifying its extraction. The noise occurs as a slowly varying offset added to the secondary ion signals.

Initially, noise reduction was obtained by subtracting the east split plate signals from the west, with the secondary ion current centered on the west plates with toroidal steering. This "common mode rejection" worked very well, since the noise current is fairly uniform across the entrance slit. However, there is some spillover ($\sim 10-20\%$) of secondary ion current to the subtracted plates, since the axial beam width of 2^+ secondaries is slightly greater than the width of a split

plate. This introduces an error, since the axial gain of the analyzer is not constant (the gain increases to the east, as shown in Figure IV.C.12) and the spillover current is not properly subtracted. The noise current introduces a similar error, since its distribution on the upper and lower plates also changes as a function of axial position (The energy spectrum of the noise is not uniform, but peaked near $1/2$ the energy of the neutral beam injectors.).

Measurements presented in this thesis were processed by simple subtraction of the baseline noise level. This technique is completely adequate for low noise shots (moderate fueling with the gas boxes), and during high noise operation if the injected beam is chopped, at a rate sufficient to separate out the lower frequency noise.

During single shot radial scans, sufficient overscan is applied to allow obtaining the baseline between sweeps when the observation point is outside of the plasma. The resulting S/N ratio is typically greater than 100:1, as evident from the secondary current for a typical shot shown in Figure V.E.2.

The diagnostic neutral beam is on several milliseconds before and after the end-plug beams, as shown in Figure V.C.1. Since no plasma exists during these intervals, but most of the analyzer noise is present (>90% during gas box fueling) these intervals provide convenient baseline subtraction for temporal profiles when the injected ion beam is not chopped or spatially varied. As evident in Figures V.D.2, V.D.3, and V.D.4, the split plate current rapidly increases at 1 ms into the shot, reaching an equilibrium which is maintained until 3 ms (This is the interval when

only the diagnostic beam is on, as shown in the timing diagram.).

At 30 ms another rapid drop in secondary current occurs, from almost the same baseline level, when the diagnostic beam is switched off.

C. Off-Line Processing

1. Introduction

All space potential data were obtained by operating the energy analyzer with a fixed top plate voltage and recording the beam location on the split plate detector. Since previous beam probe systems have operated the analyzer in a feedback mode, where the beam remains centered on the detector¹, extensive simulation and calibration was done to verify this technique. This section provides a derivation of the basic off-line processing equations and the analyzer sensitivity and dynamic range when operated open loop.

2. Derivation of the Off-Line Processing Equations

The horizontal distance a beam with energy E_s and charge q_s travels in the analyzer field region is given by²

$$x = \frac{E_s}{q_s V_A} 2d \sin 2\theta \quad (1)$$

where V_A/d is the electric field intensity and θ is the beam entrance angle, as shown in Figure A1.2. Taking the derivative of this expression with respect to the beam energy,

Figure AI.2. Schematic of the energy analyzer defining parameters used in the off-line processing calculations.

$$\frac{\partial x}{\partial E_s} = \frac{2d \sin 2\theta}{q_s V_A} \quad (2)$$

yields the exact expression

$$\Delta x = \frac{2d \sin 2\theta}{q_s V_A} \Delta E_s \quad (3)$$

The change in beam current on the split plates for a shift Δx in beam position is derived in Figure AI.3. The result

$$\Delta x = \frac{\Delta i_U}{i_t} \frac{\bar{w}}{\sin \theta} \quad (4)$$

when combined with eqn.(3) yields

$$\frac{\Delta i_U}{i_t} = \frac{2d \sin 2\theta \sin \theta}{\bar{w} q_s V_A} \Delta E_s \quad (5)$$

where Δi_U is the change in current on the upper split plate for a change in beam energy ΔE_s of a beam of width $\bar{w}$ and current i_t .

The analyzer gain, $G_A(\theta)$, is given in Chapter IV as q_s^{-1} times the ratio of the beam energy to the top plate voltage when the split plates are balanced (Note that this definition differs from typical closed-loop analyzer analysis³)

$$q_s G_A(\theta) = \left. \frac{E_s}{V_A} \right|_{\text{bal}} \quad (6)$$

The secondary energy, E_s , after exiting the plasma is given by

$$\frac{\Delta x}{\sin(180 - \gamma - \theta)} = \frac{\Delta l}{\sin \theta}$$

$$\frac{\Delta x}{\sin(\gamma + \theta)} = \frac{\Delta l}{\sin \theta}$$

$$\frac{\Delta l}{\sin 90} = \frac{\Delta b}{\sin[90 - (90 - \gamma - \theta)]}$$

$$\Delta l = \frac{\Delta b}{\sin(\gamma + \theta)}$$

c)

$$\frac{\Delta i_U}{i_t} = \frac{\Delta b}{w} \quad \text{where } i_t = i_U + i_L$$

combining a), b), and c) yields

$$\Delta x = \frac{\Delta i_U}{i_t} \frac{w}{\sin \theta}$$

Figure AI.3. Derivation of the change in x location of the beam, Δx , for a change in beam position Δb causing a change Δi_U in the current measured on the upper detector plate.

$$E_s = q_p V_G + (q_s - q_p) \phi \quad (7)$$

where V_G is the accelerating voltage of the primary beam with charge q_p and ϕ is the space potential at the ionization point. Substituting this into eqn.(6) yields

$$q_s G_A(\theta) = \frac{q_p V_G + (q_s - q_p) \phi + \Delta E_s|_{bal}}{V_A} \quad (8)$$

where $\Delta E_s|_{bal}$ is the change in beam energy required to balance the split plates. This change is given by eqn.(5), letting

$$\Delta i_U = \frac{1}{2}(i_L - i_U) \quad (9)$$

Substituting eqn.(9) into eqn.(5)

$$\frac{\frac{1}{2}(i_L - i_U)}{i_t} = \frac{2d \sin 2\theta \sin \theta}{\bar{w} q_s V_A} \Delta E_s|_{bal}$$

$$\Delta E_s|_{bal} = \frac{i_L - i_U}{i_L + i_U} \frac{\bar{w} q_s V_A}{4d \sin 2\theta \sin \theta} \quad (10)$$

and substituting the result into eqn.(8) yields

$$V_A q_s G_A(\theta) = q_p V_G + (q_s - q_p) \phi + \frac{i_L - i_U}{i_L + i_U} \frac{\bar{w} q_s V_A}{4d \sin 2\theta \sin \theta} \quad (11)$$

The final requirement is to relate $\bar{w}$, the beam width at the detector, to w , the entrance slit width. As shown in Figure AI.4

$$w = \frac{\bar{w}}{\sin(\beta+\theta)} \quad (12)$$

where β is the entrance slit angle as defined in the figure. Substituting eqn.(12) into eqn.(11), and solving for the space potential

$$(q_s - q_p)\phi = q_s V_A G_A(\theta) - q_p V_G - \frac{(i_L - i_U)}{(i_L + i_U)} \frac{w q_s V_A \sin(\beta+\theta)}{4d \sin 2\theta \sin \theta} \quad (13)$$

yields the basic off-line processing equation. For convenience, define

$$\xi(\theta, \beta, d, w) = \frac{w \sin(\beta+\theta)}{4d \sin 2\theta \sin \theta} \quad (14)$$

yielding

$$(q_s - q_p)\phi = q_s V_A G_A(\theta) - q_p V_G - \frac{(i_L - i_U)}{(i_L + i_U)} q_s V_A \xi(\theta, \beta, d, w) \quad (15)$$

For the special case where primary beam is injected into the analyzer (for calibration) eqn.(7) reduces to

$$E_s = q_p V_G \quad (16)$$

and $q_s = q_p$, yielding

$$V_G = V_A G_A(\theta) - \frac{(i_L - i_U)}{(i_L + i_U)} V_A \xi(\theta, \beta, d, w) \quad (17)$$

$$\frac{w}{\sin 90} = \frac{\bar{w}}{\sin(180 - \beta - \theta)}$$

$$w = \frac{\bar{w}}{\sin(\beta + \theta)}$$

Figure A1.4. Derivation of the beam width $\bar{w}$ inside the analyzer as a function of the entrance slit width, w , the angle of the entrance slit, β , and the beam angle, θ .

3. Sensitivity and Dynamic Range

An important consideration during open loop analyzer operation is the change in space potential which may be followed before the beam is deflected completely off one of the split plates. The total dynamic range is obtained from eqn.(15), setting

$$\frac{i_L - i_U}{i_L + i_U} = 2 \quad (18)$$

This represents moving the beam from completely on one split plate to completely on the other. The resulting maximum potential change which may be followed is given by

$$\Delta\phi|_{\max} = \frac{2q_s V_A \xi(\theta, \beta, d, w)}{(q_s - q_p)} \quad (19)$$

The dynamic range of the TMX analyzer when monitoring 2^+ secondaries ($V_A = 3900$ Volts, $\theta \sim 30^\circ$, $d = 6.595$ cm, $w = 0.5$ cm, $\beta = 60^\circ$ for typical thallium operation with 1 kG central cell magnetic field) is equal to

$$\Delta\phi|_{\max} = 682 \text{ Volts} \quad (20)$$

The measurement sensitivity is also obtained from eqn.(15)

$$S = \frac{2q_s V_A \xi(\theta, \beta, d, w)}{(q_s - q_p)} \frac{\Delta i_{\min}}{i_t} \quad (21)$$

where $\Delta i_{\min}$ is the resolvable split plate current (The factor of two

in eqn.(21) occurs from defining Δi_{min} as the resolvable current on each of the two split plates.). From eqn.(19)

$$S \approx \Delta \phi |_{max} \frac{\Delta i_{min}}{i_t} \quad (22)$$

The split plate current resolution is determined by the noise levels (external and internal amplifier noise) and by the resolution of the data recorders. Resolution and dynamic range are inversely related and can be controlled by varying the analyzer entrance slit width. A small entrance slit provides high sensitivity but a small dynamic range.

The basic resolution of the IMX analyzer (external noise sources not considered) is limited by the 10 bit analog-to-digital data recorders. Substituting

$$\Delta i_{min} = \frac{200 \text{ nA}}{1024} = 0.20 \text{ nA} \quad (23)$$

$$i_t \approx 100 \text{ nA (typical)} \quad (24)$$

into eqn.(22) yields

$$\begin{aligned} S &= 682 \text{ Volts} \left(\frac{0.20 \text{ nA}}{100 \text{ nA}} \right) \\ &= 1.36 \text{ Volts} \end{aligned} \quad (25)$$

D. Data Processing Examples

1. Temporal Profile

The raw split plate currents for a typical shot where on-axis measurements were made detecting 2^+ secondaries is shown in Figure AI.5. Data are for shot 39 on Sept. 26, 1980, which was discussed in Section V.D.1. The beam has been centered on the west split plate pair, as evident from their larger signals.

The analyzer top plate voltage has been set to approximately balance the top and bottom split plates during the main equilibrium (~ 10 to 21 ms). This maximizes the measurement accuracy, since $(i_L - i_U)$ is small and errors from this term in eqn.(15) are minimized.

Near the end of the shot the split plate current increases substantially on the bottom plate and decreases on the top. This corresponds to the drop in space potential when the neutral beams in one end-plug are switched off; The lower energy secondaries drop toward the bottom plate under the influence of the analyzer's constant electric field (Figure AI.2).

Removing the offset noise is illustrated in Figure AI.6. The split plate current from 2 to 3 ms is averaged, and the result subtracted from the data (The offset averaging interval is manually selected when the shot is processed.). This forms the upper and lower split plate currents for processing.

The plasma space potential during this shot may now be calculated, using eqn.(15) and eqn.(8) from Section IV.C.4 for $G_A(\theta)$. The fixed parameters (V_A , V_G , etc) required in the calculations are obtained from

IMX HEAVY ION BEAM PROBE RPI/LLL

Figure A1.5. Raw split plate currents for a typical on-axis temporal profile.

TMX HEAVY ION BEAM PROBE RP1/LLI

Figure A1.6. West split plate currents before and after the offset noise is removed.

the status information stored at the beginning of the datafile. The resulting potential is shown in Figure V.D.1.

2. Radial Profile

The split plate currents for a typical shot where the plasma was radially scanned is shown in Figure AI.7. Data are shown for shot 88 on Sept. 26, 1980. A small toroidal offset has again been applied to center the beam on the west split plates.

Removing the noise is now accomplished by subtracting the offset between sweep intervals. This is illustrated in Figure AI.8, where no secondary ion current exists around 16, 18, and 20 ms. An offset averaging interval of 15.8 to 16 ms is selected, with the result shown in Figure AI.9. This provides increased accuracy over subtracting the offset at the beginning of the shot, which can be seen from Figure AI.9. The processed top plate (upper right graph) shows ≤ 2 nA of offset from 2 to 4 ms, with the offset removed completely from 15.8 to 16 ms. The improvement in accuracy is ~ 10 to 20 Volts for this relatively low noise shot. A high noise shot, where the subtraction interval is much more critical, is shown in Figure V.D.6.

Since the beam trajectory is being scanned the beam entrance angle into the analyzer is no longer constant, as shown in Figure III.B.3(a,b). To determine this angle, and the location of the observation point within the plasma, the radial sweep waveform is stored during the shot. The radial sweep plate voltage is shown in Figure AI.10, where 1 Volt indicates positive and negative 500 Volts on the two sweep plates.

IMX HEAVY ION BEAM PROBE RPI/LLL

Figure A1.7. Raw split plate currents during a typical radial scan.

Figure A1.8. Expanded time scale for selecting the offset averaging interval.

IMX HEAVY ION BEAM PROBE RPI/LLL

Figure A1.9. West split plate currents before and after the offset noise is removed.

TMX HEAVY ION BEAM PROBE RP1/LLL

Figure A1.10. Radial sweep waveform and the calculated analyzer gain (G_A) and X_i (ξ).

From this voltage, and eqn.(6) from Section III.F, the injection angle of the beam (θ_I in Figure III.B.1) may be obtained. The location of the sample volume may then be calculated, from θ_I , the injected beam energy, and the computer trajectory simulations. The result for a radial scan through the plasma center (along the coordinates shown in Figure V.B.2 for constant injection energy) is shown in Figure AI.11(a).

The beam angle at the detector, θ_A , is determined in a similar manner from the injected beam angle and the computer trajectory simulations. The result for the constant energy scan through the plasma center is shown in Figure AI.11(b). The beam entrance angle into the analyzer, θ , is obtained from θ_A by subtracting the angle at which the analyzer is positioned (The analyzer rotates about the entrance slit.). All data were taken with

$$\theta = \theta_A - 5.5^\circ \quad (26)$$

The space potential may now be calculated, using eqn.(15), eqn.(8) in Section IV.C.4, and the equations determining the beam angle at the detector and the location of the sample volume. The analyzer gain, $G_A(\theta)$, and X_i , $\xi(\theta, \beta, d, w)$ during the radial scans are shown in Figure AI.10. The resulting space potential from 18 - 20 ms is shown in Figures V.E.2, V.E.3, and V.E.4.

Figure AI.11. (a) Measurement location, and (b) secondary ion angle at the analyzer as a function of beam injection angle for a scan through the plasma center.

APPENDIX II
Photographs of the System

Figure AII.1. View of the beam line, from under the machine looking up. Two of the central cell solenoidal coils are visible straddling the optics tank. The racks in the lower right contain the ion gun power supplies, providing no exposed high voltage and short cable runs. The rack on the left contains the high voltage sweep supplies, again providing short cable runs.

Figure AII.2. View of the analyzer tank, from the top of the machine looking north-east. Signal cables and water cooling travel through the pipe visible near the front of the tank. This pipe also supports the analyzer and allows rotation about the entrance slit. High voltage is fed to the analyzer through a pipe on the opposite side.

Figure AII.3. View of the energy analyzer with the main tank and shield box removed. The boron nitride heat sink for the guard ring divider resistors is visible on the front plate of the analyzer. A Delrin bushing insulates the analyzer from the tank ground.

Figure AII.4. Plan view of the analyzer with the ground plate and guard ring assembly removed. The current-to-voltage converters are visible in the center of the analyzer. The variable entrance slit and 4-way split plates are visible at the front and rear of the analyzer, respectively.

Figure A11.5. 4-channel current-to-voltage converter assembly. Bonding of the integrated circuits and FET's to the water cooled copper plates is evident.

Figure AII.6. The 3-element ion gun. Connections to the gun electrodes are made with teflon insulated copper rods. The last lens element is adjustable.

Figure AII.7. The primary beam detector and mounting enclosure. The three shielding screens (one grounded and two biased) have been mounted in the box. The resistors connecting the copper bars are mounted underneath on solder lug, on the copper bar mounting screws.

Figure A11.8. View of the operator's station. The LSI-11 computer is located below the CAMAC crate. The upper oscilloscope is for monitoring the beam profile between shots, and the lower one is used to display acquired data via an analog output CAMAC module.

Figure AII.9. The Tandem Mirror Experiment. View is to the west. The energy analyzer, although not visible, is located directly below the left rack on the top of the machine.

APPENDIX REFERENCES

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