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**ADVANCED DEVELOPMENT OF PARTICLE
BEAM PROBE DIAGNOSTIC SYSTEMS**

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PROGRESS REPORT

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I. INTRODUCTION

This progress report covers the period starting with the approval to go ahead with the 2 MeV heavy ion beam probe (HIBP) for TEXT Upgrade (June 1989) to the submission of the Grant renewal proposal (September 1990). During this period the co-principal investigators, R. L. Hickok and T. P. Crowley have each devoted 45% (including summer months) of their time to this Grant. Their effort has been almost exclusively devoted to the design and fabrication of the 2 MeV HIBP system. The 1989 report that described the advantages of a 2 MeV HIBP for TEXT Upgrade compared to the existing 0.5 MeV HIBP and outlined the design of the 2 MeV system is attached as Appendix A.

Since the major effort under the renewal proposal will be the continued fabrication, installation and operation of the 2 MeV system on TEXT Upgrade, we describe in Section II some of the unique results that have been obtained with the 0.5 MeV system on TEXT. For completeness, we also include the preliminary operation of the 160 keV HIBP on ATF. In Section III we present the present fabrication status of the 2 MeV system with the exception of the electrostatic energy analyzer. The energy analyzer which is designed to operate with 400 kV on the top plate is a major development effort and is treated separately in Section IV. Included in this section are the results obtained with a prototype no guard ring analyzer, the conceptual design for the 2 MeV analyzer, the status of the high voltage testing of full size analyzer systems and backup plans if it turns out that it is impossible to hold 400 kV on an analyzer this size.

II. MEASUREMENTS WITH 0.5 MeV HIBP ON TEXT

A schematic of the 0.5 MeV HIBP on TEXT is shown in Figure 1. The 0.5 MeV accelerator is shown in the upper right. As the beam emerges from the horizontal accelerator, it is directed into the plasma by a 74° electrostatic deflection system. Below the deflector is the primary beam line optics chamber that contains toroidal sweep plates, radial sweep plates and focussing ladders for measuring the size and location of the primary beam. This should be compared to Figure 10 which shows the comparable components for the 2 MeV beam probe. The secondary ions created in the plasma, exit out the radial port and enter the electrostatic energy analyzer which is in the vacuum chamber located below the accelerator. A schematic of the energy analyzer is shown in Figure 2. The energy analyzer has three entrance slits and detectors so it samples three positions on the primary beam line, i.e., measurements are made at three sample volumes in the plasma simultaneously. The split plate detectors are shown at the bottom of Figure 2. The detectors, which are simply stainless steel plates, are split up-down (i.e., in the radial direction) and left-right (i.e., in the toroidal direction). The sum of the current from the four split plates provides a measure of the electron density in the sample volume, the difference current between the upper and lower split plates provides a measure of the space potential in the sample volume and the difference current between the left and right split plates provides a measure of the toroidal component of the vector potential in the sample volume. In operation, the current signal from the three sets of four split plates are digitized at 1 MHz, stored in the computer and then analyzed off-line. For a more detailed description of beam probe operation, see references 1 and 2.

Beam probes provide simultaneous measurements of $\tilde{n}/n$, $\tilde{\phi}$ and $\tilde{A}$ from the three sample volumes in the plasma. The separation and orientation of the three sample volumes is shown in Figure 3. The black squares indicate the location of the sample volumes but not the shape which is basically a cylindrical disc. The thickness of the disc is determined

Figure 1 0.5 MeV TEXT HIBP system.

DETECTOR SPLIT PLATES

Figure 2 Top: side view of 0.5 MeV HIBP energy analyzer. Bottom: front and side views of detector split plates.

Figure 3 Location of several typical sample volume sets for the 0.5 MeV HIBP.

by the width of the analyzer entrance slit and is typically of the order of 0.1 cm. The diameter of the disc is determined by the diameter of the beam and is typically of the order of 1.0 cm. Note that for most locations in the plasma, the separation between the centers of the sample volumes has both a radial and a poloidal component. It should also be noted that even when the center-to-center separation of the sample volumes are in a given direction, the finite size of the sample volumes can give rise to elements in the sample volumes that have perpendicular separation.

Using discrete time series analysis we evaluate the auto power, cross power, coherence and phase between the various signals.³ In particular, we evaluate the frequency averaged wave vector k for the turbulent fluctuations over the frequency range 0 - 500 kHz, the phase angle between $\tilde{n}$ and $\tilde{\phi}$, the electrostatic fluctuation driven particle flux, and the localized, low frequency (MHD), coherent fluctuations in the poloidal magnetic field⁴. In addition to the fluctuation measurements, the HIBP also provides measurements of the steady state radial potential profiles. For this report we will only mention some of the highlights of the various types of measurements that have been carried out with the 0.5 MeV beam probe on TEXT.

II.A Space Potential Profile Measurements

The Ergodic Magnetic Limiter, EML, causes substantial changes in the radial space potential profile as shown in Figure 4. For r/a less than 0.6, the EML has very little effect on the confining magnetic field and there is very little effect on the radial electric field. In the ergodic region, however, ($r/a > 0.6$), the radial electric field becomes less negative and switches signs at about $r/a = 0.75$. This is in qualitative agreement with the concept of the EML producing an enhanced electron loss from the ergodic region. Strong MHD fluctuations produce a change in the radial potential profile that is similar to that produced by the EML. Again this is in qualitative agreement with the concept that the

Figure 4 Plasma potential $\phi(r)$ for different EML currents. $I_h = 0$ kA has no EML field.

island structure in the outer region of the plasma leads to enhanced electron loss.

Small changes in the radial potential profile have also been observed with ECH. This change is probably consistent with the change in the ion momentum distribution. Strong differences have been observed in the potential profiles of H and He plasmas. W. Rowan has measured the toroidal and poloidal velocity profiles for these two plasmas and shown that the potential profiles are consistent with ion momentum balance.⁵ It is not clear whether the difference is due to the different radial electric field driving the velocity profiles or vice versa.

II.B Magnetic Fluctuation Measurements

We have recently shown that HIBP can provide a localized measurement of the fluctuation in the toroidal component of the electromagnetic vector potential during large MHD fluctuations⁴ by measuring the fluctuation in the toroidal position of the secondary ion signal at the detector. This is illustrated in Figure 5. The solid curve is the measured signal level vs. radius, the dashed curve is the assumed A_ϕ used in a computer simulation, and the triangles are a set of predicted measurements from the computer simulation. The prediction matches the $A_\phi(r)$ profile and the measured fluctuation level for over 1/2 the minor radius.

In addition to the measurements of low frequency, coherent magnetic fluctuations we have some evidence that we have been able to detect high frequency turbulent magnetic fluctuations. What we have observed is turbulent fluctuations in the toroidal position of the secondary ion beam at the detector, but we have not done sufficient analysis of the experimental setup to insure that this signal is not due to some unexpected cross talk from the density fluctuation channel. It will also take considerable amount of computer modeling to fully understand this turbulent left-right signal.

Figure 5 Radial profile of $\tilde{A}_\phi$ during an $m=2$ mode in TEXT. Solid line is HIBP data. Dashed line is a fit to the data which is normalized to obtain an $\tilde{A}_\phi(r)$. This is used as input to a computer simulation of the HIBP experiment. Simulated signal output is given by the triangles. Path effects are small from $0.2 < r/a < 0.7$.

II.C Turbulent Fluctuation Measurements of $\tilde{n}/n$ and $\tilde{\phi}$

II.C.1 Fluctuation Induced Particle Transport

The cross field particle transport driven by the turbulent fluctuations is given by

$$\Gamma = \gamma k_{\theta} \langle \tilde{n} \rangle \langle \tilde{\phi} \rangle \sin \beta \quad (1)$$

where Γ is the particle flux, γ is the coherence between the density and space potential signals and β is the phase angle between the two signals. All of the quantities on the right hand side of Equation 1 can be measured simultaneously. It should be noted that k_{θ} can only be measured along one line that extends from the center of the plasma to the outside edge. $\tilde{\phi}$ can only be determined for $r/a > 0.7$. At smaller radii, $\tilde{\phi}$ is less than the noise level. The autopower spectra for $\tilde{n}$, the autopower spectra for $\tilde{\phi}$, the coherence and the phase angle between the two signals is shown in Figure 6. In Figure 7 we show similar plots for $\tilde{n}$ signals from two different sample points whose centers are separated poloidally. The phase difference between these two signals provides a measure of k_{θ} . Generally, the $\tilde{n}$ signal is used to evaluate k_{θ} since it gives the same value as $\tilde{\phi}$ and it has a better signal-to-noise ratio. This provides enough information to evaluate the localized particle flux at the point where the measurements were made. For given values of the minor radius between $0.7 < r/a < 1.0$, we can evaluate the radial particle flux for a specific poloidal and toroidal location. If we assume poloidal and toroidal symmetry we can integrate the flux over all poloidal and toroidal angles and obtain an estimate of the total particle flux driven by the electrostatic turbulence. This can be compared with the total particle flux obtained from H_a measurements. The results are shown in Figure 8. To the accuracy of the measurements, the electrostatic driven particle flux can account for all of the particle transport.

TYPICAL FREQUENCY SPECTRA

Figure 6 Density and potential fluctuation spectra from a single sample volume in TEXT including coherence and phase between the two signals.

TYPICAL FREQUENCY SPECTRA

Figure 7 Density fluctuation spectra from two sample volumes in TEXT including coherence and phase between the two signals. The phase is used to determine the average wavenumber.

Figure 8 Electrostatic fluctuation induced particle flux measured by the HIBP and total particle flux determined from H_{α} . Circles (o) are Γ obtained with measured k_{θ} and squares (□) are Γ obtained with an interpolated value of k_{θ} .

II.C.2 Interior k Values

The frequency averaged wavenumbers measured by the HIBP are approximately 1 cm^{-1} in the edge region of the plasma ($r/a > 0.8$), and 0.3 cm^{-1} in the interior of the plasma ($r/a < 0.6$). An example of HIBP measurements in the edge and interior of the plasma is shown in Figure 9. The edge numbers disagree with Langmuir probe⁶ and FIR scattering measurements⁷ by about a factor of 2. The FIR scattering measurements are obtained with sample volumes that include the central and edge regions, but the largest signals are believed to come from the edge. The discrepancies between the diagnostics is being investigated. The HIBP results also indicate statistical phase velocities that are up to an order of magnitude larger than linear drift wave phase velocities. In addition to the small k-values, HIBP measurements also indicate long ($> 2 \text{ cm}$) radial correlation lengths. This does agree with the long radial correlation lengths reported by Fonck for the interior of the PBX-M tokamak.⁸

Two separate phenomena can affect the interpretation of the HIBP measurements: finite sample volumes and beam modulation. Ross⁹ has analyzed the effect of finite sample volumes and for the measured beam size, it should not affect the interpretation of the results. Reducing the sample volume by using small apertures on the primary beam reduced the measured k-values by 0 to 40%.⁴ In addition edge and interior k measurements have been carried out on the same plasma pulse and they clearly indicate smaller k-values in the interior.¹⁰ The intensity of the primary beam can be modulated by attenuation in the outer region of the plasma where the amplitude of the fluctuations is quite large. If this happens then we would still observe fluctuations on the secondary signal from interior points even if there were no fluctuations in the interior. This would lead to fluctuations from two interior sample volumes that are in phase and would be interpreted as a $k = 0$ fluctuation. Since we do obtain finite k-values in the interior, this cannot explain the entire signal. Beam modulation could, however, distort the apparent k-value and this

Figure 9 Two point density fluctuation spectra. Darker line - $r/a = 0.85$. Lighter line - $r/a = 0.55$.

would show up as a smaller k than what actually exists. It should also be noted the modulation of the secondary ion intensity as the secondaries travel through the plasma could also distort the interpretation of the measurements.

Analysis of the beam modulation effects is difficult since it strongly depends on the fluctuation correlation length in the beam trajectory direction. Our best estimates at this time are that beam modulation is not causing a strong distortion of the measured k -values. We have performed several experimental tests to determine the effects of beam attenuation, and the results of these experiments are still being studied. The tests include:

1. Comparing the wavenumbers calculated using sample volumes with spacing Δx and $2 \Delta x$. The agreement between the two is generally good. If attenuation was a large component of the signal, the wavenumbers would disagree, particularly when the phase shift of one of the signals was near π .
2. Comparing wavenumbers measured at two different poloidal locations, but the same radial location. Positions with larger attenuation often show lower wavenumbers as might be expected if modulation was important. However, the coherence tends to be lower, which is the opposite of what is expected when a larger modulation is present. These measurements are difficult to interpret since the direction in which k is measured changes as well as the poloidal location.
3. Comparing cesium and thallium beam measurements since the cross-sections for ionization are different.
4. Analysis of frequency spectra from the interior and the edge.

Work is continuing on this analysis. The strongest experimental test would be to measure fluctuations in the primary beam after it passes through the plasma. We have been unsuccessful in these tests so far, but hope to improve this measurement with the 0.5 MeV

and 2 MeV accelerators.

Given the caveats noted above we strongly believe that we are observing very small k -values in the interior of the TEXT plasma. This is important for transport studies because if it is true then conventional drift wave theory can not explain the transport in the interior of tokamaks.¹¹

II.D Additional Measurements

In the above sections we have highlighted what we consider to be some of the most important measurements that have been carried out with the 0.5 MeV beam probe on TEXT. In addition there have been quite a few other measurements and we will briefly list some of them here.

It has been shown that impurities increase the amplitude of the space potential fluctuations in the interior of the plasma. With a normal Z_{eff} of about 2, the space potential fluctuations are less than the noise level (about 3 volts rms) for $r/a < 0.7$ but for a Z_{eff} of 3, the fluctuation amplitude is greater than 10 volts rms all the way to the center.

In typical plasmas, we find no poloidal asymmetries in the amplitude of the $\tilde{n}/n$ fluctuations over the approximately 100° range where we can carry out measurements. With the Ergodic Magnetic Limiter however we observe a definite poloidal asymmetry. It appears that the amplitude increases near the x points and decreases near the o points, but it is difficult to judge which m/n mode is dominate.

We have shown that inside the inversion radius there is an abrupt positive change in the space potential of about 60 volts with a sawtooth crash. The change in potential is the same for all points inside the inversion radius, i.e., the sawtooth does not generate an electric field inside the inversion radius and it does not destroy the existing field.

There are strong density fluctuations (as much as 20%) during large MHD fluctuations. The fluctuations are localized radially near the rational q - surface. There are weak potential

fluctuations associated with the MHD activity but they are not localized. It appears that the potential of the whole plasma oscillates weakly at the MHD frequency.

The amplitude of the $\tilde{n}/n$ fluctuations in the interior ($r/a < 0.5$) of the plasma increase by about 15% with both central and edge ECH. There is very little change in the edge fluctuations. There is a strong increase in T_{eo} with central heating but very little change in T_{eo} with edge heating.

We have measured the radial potential profile for a limited range of plasma densities and to within the accuracies of our measurements and that of the density and temperature profiles we find good agreement with the ion momentum balance equation.¹²

Oscillating gas feed produces an approximate 30% variation in the amplitude of the central $\tilde{n}/n$ fluctuations with only a 10% variation in n_{eo} . The $\tilde{n}/n$ oscillation is not in phase with the oscillating gas feed.

Over a limited range of densities, we find that central $\tilde{n}/n$ fluctuation amplitude decreases with increasing density. It appears that this trend stops at a density of about $4 \times 10^{13}/cm^3$ which is approximately equal to the density where there is no further increases in the particle confinement time. This is close to the highest density at which we can carry out measurements so we do not have a well documented measurement of the leveling off of the fluctuation amplitude.

II.E ATF Status

The basic system hardware for the ATF Heavy Ion Beam Probe was installed at the end of May, 1990. Secondary ion current was detected at that time demonstrating that we are able to accurately follow the transit of injected ions through the complex magnetic field structure of a stellarator such as ATF. There was, frankly, some general skepticism about our prospects for detection of signal so soon after the apparatus was installed. It is a tribute to the quality of the magnetic field model developed at Oak Ridge

that the predicted trajectories were very close to reality. The mechanical engineering staff responsible for locating our ports in the frame of the magnets have also done an excellent job.

During the summer months, we were able to characterize the operating environment experienced by a beam probe on ATF to the extent that clearly recognized fluctuation signals were evident and ultraviolet loading on the analyzer was seen to be too large for accurate potential measurements. The UV photons strike the guard rings causing secondary electrons to be emitted. This current unbalances the currents in the voltage divider used to produce the very uniform electric field required to determine plasma potentials. During the ECH phase of the discharge, the electric field was modified by this effect but the secondary ion beam remained on the detector plates. Fluctuation measurements could therefore be made throughout the full discharge time. During neutral beam heating, however, the electric field in the analyzer was changed to such an extent that the secondary ions were no longer detected.

We had previously addressed the loading problem on TEXT by building an external voltage divider with a high current power supply. This assures that the currents drawn by the guard rings as a result of UV loading will be much less than the current from the power supply. The TEXT shutdown made it possible to borrow their divider to test its application on ATF. The operating environment was sufficiently different so it was not a trivial matter to ship and install this device. Since the operating voltage is less than half that of the TEXT beam probe, additional resistors had to be added to obtain a large current drain. Also, the UV levels are much higher on ATF due to the use of neutral beams as the primary heating source. Finally, safety regulations necessitated the installation of the divider in a distant vault rather than near the analyzer as on TEXT.

Data was taken with the original ATF beam probe system augmented by the TEXT external divider late in September. The order of one hundred shots were recorded. Pre-

liminary assessment of the quality of this data is that useful fluctuation and potential information will be extracted by proper processing. A simplified version of the software for this purpose is now nearly ready. Three papers are to be presented at the APS Conference describing these and earlier measurements of fluctuations, potential, and signal level.

III. STATUS OF THE 2 MeV TEXT HIBP

In this section, we will describe the present status of the construction of the 2 MeV HIBP for TEXT-Upgrade. We will begin with a brief description of the system and follow with more complete descriptions of the individual parts.

III.A Description of 2 MeV HIBP

The 2 MeV HIBP hardware is shown in Figure 10. The major components of the system shown in the Figure are the 2 MeV accelerator, the dual electrostatic bending system, and the energy analyzers. Other important system components are the sweep system and the primary and secondary beamlines. The region of the plasma that can be studied depends on the beam energy, the sweep point from which the beam originates, the vacuum vessel ports, and the location of the entrance slit for the energy analyzer. The dual electrostatic deflector and the two analyzers will be used to study over 90% of the plasma cross-section, including all three divertor null points. The 44° deflector and the lower energy analyzer will be used to study the plasma region shown in Figure 11. This configuration is the first one that will be used when the 2 MeV system is installed. Initial divertor operation in TEXT-Upgrade will use a single center null divertor and this configuration will be able to study that null point. The 68° deflector and the upper energy analyzer will be used to study the plasma region shown in Figure 12. Funding for the upper analyzer is being requested in the second year of this proposal. The dual deflector has already been ordered since the design and alignment of both deflectors has to be done in-conjunction with the 2 MeV accelerator.

A pair of sweep plates is used to electrostatically steer the HIBP primary beam across the plasma for each primary beam line. They are located at the sweep points shown in Figure 10. They allow us to change the sample volume location during a single shot. (Two-dimensional coverage of the plasma is obtained by changing the beam energy as well

Figure 10 2 MeV HIBP layout.

Figure 11 Plasma region accessible by a thallium beam using the 44° electrostatic deflector and the lower energy analyzer when $B_t (R = 100) = 2.16\text{T}$.

Figure 12 Plasma region accessible by a thallium beam using the 68° deflector and the upper energy analyzer when $B_t (R = 100) = 2.16\text{T}$. A cesium beam requires 1.5 times higher energy and is expected to be used in this configuration.

as the sweep plate voltage). The primary beam line also contains beam diagnostics that determine beam size and focussing, as well as bellows sections for alignment purposes.

The energy analyzers are the detectors that we use to measure secondary beam current, beam energy, and toroidal beam position. These are used to determine plasma density, potential, and magnetic field, respectively. The most difficult measurement to make is the beam energy measurement.

III.B Accelerator and Deflectors

A 2 MeV pelletron accelerator and a dual electrostatic deflector have been ordered from the National Electrostatics Corporation (NEC) of Middleton, Wisconsin. The accelerator is based on a standard accelerator model that is sold by NEC. Several non-standard items are required for the HIBP experiments including very stringent voltage stability requirements, five second pulse operation (normal operation is DC), compatibility with our heavy ion sources, an internal sweep system to switch the beam between deflectors, an external sweep system for alignment purposes, a quick-opening flange, and an energy modulator. 50% of the accelerator construction has been completed through August 1990. NEC has promised completion of the accelerator two months after delivery of the accelerator platform that is being designed and built by the TEXT group. The earliest date on which the platform can be delivered to NEC is December 1990. The item that is most likely to further delay NEC's delivery is obtaining a pulsed beam with the desired voltage stability. If all goes well, the accelerator will be delivered to TEXT in early 1991.

The dual electrostatic deflectors were also 50% complete as of August 1990. These are custom made deflectors that allow us to steer the beam into the plasma at the desired range of angles. Alignment of the beam optics for two beam lines is more difficult than for a single beam line as has been used in the past. However, the addition of two sweep systems to the accelerator is expected to alleviate this difficulty.

III.C Sweep System and Beam Lines

The initial design of the sweep system was completed in the Fall of 1989. The design is very similar to previous HIBP sweep plate designs. The maximum electric field between the plates is 10 kV/cm, which is 27% higher than for the 500 keV HIBP and the sweep plate length is 1.5 times longer. The sweep plate design will allow us to look at the largest possible plasma cross-section for all beam energies. Minor modifications to the design are liable to be made as the primary beam line is designed.

An initial design for the lowest section of the primary beam line was completed in Fall 1989. Preliminary work has been carried out for both beam lines in order to determine the torque frame modifications that will be needed. Final design will be completed during Fall 1990 and Spring 1991.

IV. ENERGY ANALYZER

IV.A Introduction

A flat parallel plate electrostatic energy analyzer is being designed for the 2 MeV HIBP. A view of the energy analyzer and its vacuum tank is shown in Figure 13. The design is similar to the energy analyzer used with the 0.5 MeV HIBP shown in Figure 2, but there are some important differences. They are:

1. The necessity of holding 400 kV on the large (155 x 47 cm) anode during operation. This voltage must be maintained in the presence of UV emission from the plasma which produces photoelectrons that can initiate arcing.
2. The creation of a uniform electric field by using an appropriately shaped corona ring on the anode. Guard rings, which are sensitive to UV radiation, will not be used.
3. The entrance slits, detector plates, and detector electronics will be readily accessible. This will allow a more flexible set of experiments and make it simpler to replace detector electronics damaged by 400 kV arcs.

The energy analyzer is the critical item in the 2 MeV HIBP construction. Previous groups have reported limits in obtaining high voltages on large surfaces that depend on voltage and not electric field¹³⁻¹⁵. A large percentage of our effort since the Spring has been devoted to obtaining the voltages necessary for our analyzer. In addition, the vacuum vessel design is more complex than previous energy analyzers. These two factors result in its longer design time.

IV.B Obtaining a Uniform Electric Field Without Guard Rings

Previous HIBP energy analyzers have used a set of guard rings to maintain field uniformity. A precision resistor divider has been used to achieve the proper voltages on the guard rings. However, UV-induced photoelectrons emitted from the guard ring surfaces

Figure 13 2 MeV analyzer, including vacuum tank. Top is front view with equipotential contours.

Bottom is side view (similar to Figure 2).

provide an extra current source through the resistor divider, and as a result, the guard ring voltages are distorted. UV induced changes in the guard rings were a significant problem in the ISX-B HIBP experiments. As a result, the 0.5 MeV system on TEXT incorporated changes that reduced these problems. The analyzer was designed with a wire screen rather than solid metal over much of the anode surface. In addition, an electrical screen box was not included in the design. As a consequence, less UV was reflected directly onto the guard rings, resulting in improved performance. The performance was further improved after operation had begun by using a higher current power supply for the analyzer and an external resistor divider. UV induced currents in the resistor divider are now substantially smaller than the power supply driven current. This power supply and divider are being used on the ATF HIBP experiment during the TEXT shutdown.

The use of an analyzer without guard rings is a further improvement in reducing our sensitivity to UV radiation. Using an external resistor divider as in the 0.5 MeV system would require an order of magnitude more power and the use of a set of approximately four high voltage feedthroughs operating at 100 kV to 400 kV. The no guard ring analyzer is a more attractive and practical solution.

The top part of Figure 13 shows a cross-section view of the analyzer with equipotential lines obtained from a numerical solution to Poisson's equation. In the region through which the ion beam traverses, the calculated electric field varies by less than 0.2%. This is a better uniformity than is achieved with the 0.5 MeV HIBP energy analyzer. The anode has a corona ring around its outer perimeter that is a key ingredient in obtaining the uniform field, and also reduces the maximum field in the analyzer. The vacuum vessel and a grounded plate serve as the cathode. The shape of the vacuum vessel is determined by the need for field uniformity and to allow easy access to the entrance slits and detector plates.

An experimental test of a smaller energy analyzer without guard rings has been carried

out at RPI using a 140 kV primary beam. Some preliminary information was presented on this with the initial proposal (see Figure 7 in the Appendix). The analyzer design was optimized for an existing vacuum tank. The solution to Poisson's equation indicates that the electric field also varies by less than 0.2% in this analyzer. Figure 14 shows the experimental gain curve obtained for this analyzer. The gain is the ratio of beam voltage to analyzer voltage required by the detector. The variation in the gain has to be known to a high degree of accuracy to measure the potential change across the plasma. In the operating region near 30° , the experimental curve differs from the model curve by 0.2%. The differences could be due to errors in either curve. The agreement between the two is comparable or better than what has been obtained with standard guard ring analyzers. Thus, we feel confident that we can obtain the field conditions necessary for measuring the potential profile in TEXT.

IV.C Access to Entrance Slits and Detector Plates

The detector electronics in the ISX-B, 0.5 MeV TEXT, and ATF HIBPs have been mounted inside the analyzer vacuum chamber to reduce capacitive effects. Analyzer arcs can damage one or more channels, and replacing the electronics requires the opening of the analyzer vacuum chamber. With a 400 kV anode, it is likely that the detector electronics would have to be replaced fairly often, since the arcs will be more violent. A large number of vacuum openings will make it difficult to maintain the high voltage conditioning that is critical for proper operation of the analyzer. It also would require a lot of manpower. Thus, the vacuum vessel has been designed to let the detector electronics be placed outside the vacuum. The indentations in the bottom of the analyzer are largely a result of this requirement.

Figure 14 Measured and model gain curve of the prototype analyzer without guard rings.

IV.D High Voltage Testing

IV.D.1 Introduction

The largest amount of effort in the 2 MeV design so far has been spent on determining whether we can hold 400 kV on the anode structure. The literature contains reports in which maximum voltages of 230 kV to 540 kV were obtained on large electrodes in various geometries¹³⁻¹⁵. The limitations in many of these experiments are voltage related rather than electric field related. We have begun a series of tests to determine whether 400 kV can be maintained in our analyzer geometry. Our tests have used the original anode design as well as various anodes and cathode ground planes similar to the original design. We will refer to the anode and cathode structures in this section as an analyzer despite the fact that the entrance slits and detector plates necessary for an analyzer are not being used in the high voltage tests.

IV.D.2 Testing Arrangements

The analyzer has been tested inside a 6 foot diameter, 10 foot long aluminum vacuum tank. A combination of four roughing pumps, two turbo pumps, and a cryo pump has been used to bring the pressure down to the 10^{-6} - 10^{-7} Torr range. High voltage is provided by a (400 kV, 1 mA) power supply which is presently enclosed in a large Faraday cage but will be in a SF_6 pressurized tank in the final system. The insulating material on the high voltage vacuum feedthrough is made of cast epoxy. Four glass windows provide direct visual access to the equipment under high voltage. The diagnostics used include TV cameras, camcorders with set of mirrors, radiation meters (including alarm detectors), TLD's around the tank and other lab areas, and current and voltage monitors (power supply). The capacitance of the analyzer is $C_a \approx 82$ pF while the shielded portion of the cable has a capacitance $C_c \approx 50$ pF and stores about four Joules at full voltage.

A schematic of the experimental set-up and the equivalent electric circuit is shown in Figure 15.

IV.D.3 RESULTS AND STATUS

IV.D.3-a Feedthrough

The type of feedthrough we are using was the only 400 kV bushing readily available. Although advertised to work in vacuum, we have recently discovered that previous users had not used it in vacuum. Nevertheless, our first high voltage tests in vacuum were satisfactory. We obtained stable operation at 400 kV with $p = 10^{-6}$ Torr (without analyzer) on two occasions shortly after receiving the feedthrough.

However, after several months of experiments, the feedthrough failed to hold more than 320 kV. We subsequently obtained two similar feedthroughs as replacements that also failed to hold more than 320 kV. Due to the fact that the only other source that can provide a 400 kV feedthrough has a three month delivery time, we are in the process of modifying the present one in cooperation with the manufacturer. The modifications include baking and changes in the geometry. Use of a shield on the feedthrough has allowed stable operation up to 350 kV.

IV.D.3-b Analyzer with Insulators in Vacuum Gap

The first tests were made with a 20 cm vacuum gap maintained by plastic insulators (delrin, and torlon). The anode was made of stainless steel and consisted of a corona ring, a set of 5 mil wires, and a pair of metal plates which sit on the insulators and support the wires. The wires are used to reduce the surface area of the anode whose size is 155 x 47 cm. The ground plate was made of rolled stainless steel. The surface of the ground plate was modified several times as the tests progressed. We have experimented with chemically cleaned surfaces, machined surfaces, hand polishing, and electro-polishing. We

Figure 15 High voltage setup for tests with insulators in the vacuum gap.

also experimented with two cathode triple point designs. One used a recessed socket to reduce the electric field at the triple point. The second, simpler design used a threaded insulator which screwed into the ground plane. The highest voltage obtained in these tests was 85 kV. At that voltage, a continuous current was being drawn.

Evidence of current flowing along the insulators at these relatively low voltages has been established. The triple point design appeared to have failed to prevent breakdown at the cathode-insulator-vacuum junction. No improvement was obtained when delrin was replaced by torlon as insulating material.

Using insulators to establish the size of the vacuum gap between the anode and the ground plane is a convenient way to maintain the desired gap size. It is very important that the anode and ground plane be parallel in order to maintain the field uniformity of the energy analyzer. However, since the insulators seemed to be a cause of the high voltage problems, we elected to set up the analyzer so that there were no insulators in the gap.

IV.D.3-c Analyzer Without Insulators in the Vacuum Gap

While preparing for this set-up, we tested the anode by itself (no cathode other than the vacuum tank), supported by four 36" long plexiglass posts. This test was conducted in order to check the reaction of the wires or any other structure of the anode when subjected to very high voltage. The peak voltage obtained was 300 kV. The anode was stable at 280 kV (no arcing, no current drawn). While conditioning, the only observed arcing was along the plexiglass posts. The radiation level at 300 kV became very high and we had to stop this experiment and install a concrete wall around the tank.

To test the analyzer without insulators, we wanted a ground plane without holes. The two stainless steel ground plates had holes that were originally machined to hold the insulators, so a new ground plane with a clean surface had to be made. We used two solid aluminum plates, 80% in size of the actual analyzer, which were available for immediate

use. We had previously obtained 360 kV between two smaller (14 x 45 cm) aluminum plates. The anode had no wires and no corona ring and was held from the top by long (24") high voltage stand-offs made of cast epoxy (Figure 16). A 20 cm vacuum gap was then held between the two hand polished aluminum plates. The maximum voltage achieved between these plates was 320 kV but was not stable long enough to allow conditioning of the plates. The plates were very stable at 265 kV (no arcing, no current, and no radiation) maintaining an average electric field $E > 13 \text{ kV/cm}$. Feedthrough arcing limited this and subsequent tests.

We decided to reduce the gap between the plates to determine if the electric field (20 kV/cm) required in our design was a limiting factor. With a 5 cm gap, stable operation at 220 kV was obtained. The 44 kV/cm electric field is more than twice the value of the field we need. We have since modified the feedthrough to improve its operation and restarted the analyzer tests.

IV.D.3-d Future Work

A number of experiments are planned for the high voltage tests. We will continue to try and optimize the performance of the present feedthrough. Whether we achieve 400 kV with it or not, further tests are planned to optimize the voltage of the aluminum plates used in recent experiments and to test the ability to maintain high voltage in the presence of UV radiation. The UV radiation can knock photoelectrons off of the cathode which may induce a vacuum breakdown.

Some of the experiments will involve testing different materials and geometries. For example, although our best results have been obtained with aluminum plates, we have not yet fully investigated a stainless steel anode and ground plane without insulators. There are some advantages to stainless steel since it is a higher quality vacuum material. In addition, the wire geometry of the original stainless steel geometry would allow many

Figure 16 High voltage setup for tests without insulators in the vacuum gap.

electrons emitted from the cathode surface to pass through the anode rather than striking it. This may improve the analyzer's ability to operate in a UV environment. In addition, we would like to try insulators in the vacuum gap once more, if other features can be optimized first.

If the present feedthrough continues to be unreliable, we plan to purchase a 400 kV feedthrough from National Electrostatics. They performed similar work once before and achieved a reliable feedthrough. In addition, we have found them to be a reliable high voltage manufacturer.

IV.D.4 Summary of High Voltage Tests

In our high voltage results to date, we have achieved 44 kV/cm electric fields at 220 kV, and stably maintained 280 kV at much lower electric fields. These numbers do not represent a limit to operation. At the moment, our voltages are limited by the high voltage feedthrough. We are working to overcome this problem. In a worst case scenario, we are confident that this obstacle can be overcome by ordering the NEC feedthrough. A significant time delay will result if that occurs. It is also apparent that maintaining a high voltage on a large anode structure has unexpected difficulties. Nevertheless, we are confident that we can improve on the parameters that have been obtained so far.

IV.E Cylindrical Energy Analyzer

As part of RPI's base program, we began development of a 127° cylindrical energy analyzer¹⁶ in 1987. The cylindrical energy analyzer uses the electric field more efficiently than our standard flat plate analyzers, and as a result, they can be made smaller and with lower anode voltages. This is a significant advantage with high energy beam probes such as the 2 MeV. A small cylindrical analyzer was built and tested at RPI. The experimental gain curve shown in Figure 17 indicates that a first order focussing of the beam could be achieved

Figure 17 Measured gain curve of cylindrical analyzer.

and that the sensitivity of the gain to entrance angle was similar to that obtained with flat plate analyzers, although over a narrower angular range (see Figure 14 for comparison). In addition, there were some disagreements between a computer simulation of the trajectories and the experimental results.

The computer simulation relied on a very simple fringe field model at the entrance and exit of the detector. One of the disadvantages of the cylindrical analyzer is that there is a much stronger fringe field region through which the beam particles must pass. These fringe fields affect the shape of the gain curve and have a very large effect on fluctuation sensitivity.

Our present effort is aimed at modeling the electric fields and particle trajectories in the analyzer. We hope to compare the model with the experimental results and use these results to improve the design. If we are unable to maintain 400 kV on our anode, then a cylindrical energy analyzer may be needed for the 2 MeV HIBP. Even if it is not needed for the 2 MeV HIBP, a cylindrical analyzer may be necessary for higher energy beam probes.

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