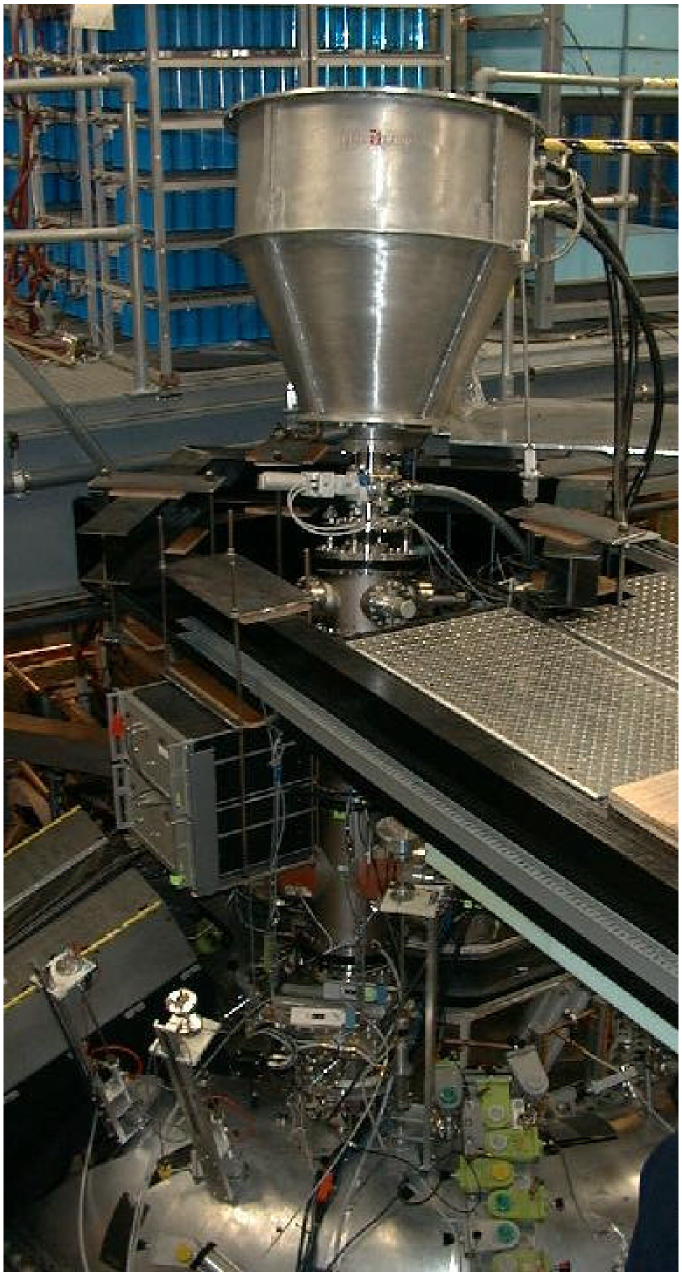
The Application of an HIBP on MST

A Renewal Proposal
Submitted by:

Paul M. Schoch
Kenneth A. Connor
Rensselaer Polytechnic Institute
Troy, NY 12180



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Introduction:

A Heavy Ion Beam Probe, (HIBP), developed for application on the Madison Symmetric Torus, (MST), is now installed and operational, (see appendix B for pictures and a progress report). The fundamental capabilities of an HIBP and the measurement needs of an RFP, such as MST, make an excellent match. We propose using the HIBP to measure the plasma potential $\Phi(r)$, and to obtain simultaneous measurement of potential ($\tilde{\Phi}$) and density ($\tilde{n}_e$) fluctuations in the interior of MST. These measurements have never been achieved in an RFP plasma of even moderate density and temperature. In addition we propose to develop the diagnostic to measure magnetic fluctuations ($\tilde{b}$) and the magnetic configuration ($\mathbf{B}(r)$) because of the particular significance of this information in an RFP. The measurements of $\Phi(r)$, and simultaneous $\tilde{\Phi}$ and $\tilde{n}_e$ are standard measurements for an HIBP. While the HIBP has measured $\tilde{b}$ and $\mathbf{B}(r)$ on TEXT, it will take development work to determine how, or if, the same measurements can be done on MST. All of these measurements are of direct interest to the proposed physics mission of MST, which includes:

Confinement improvement and understanding
Beta limits
Sustainment of the plasma current

Reversed Field Pinch (RFP) experiments have shown dramatic improvements in the 1990s, including a five-fold increase in confinement time.[1] MST and basically three other machines (RFX in Italy, TPE-RX in Japan and Extrap-T2 in Sweden) are in the forefront of this research. The advancement of the RFP concept has been so substantial that experiments are being conducted that address scaling to reactor size machines. Machines outside the US are emphasizing the scaling of confinement with plasma current and the effect on stability of a resistive wall. The mission plan for MST concentrates on the areas listed above, areas that are not being studied in depth by the other large RFP machines. This is a remarkable chance for a U.S. machine to attack a broad range of key scientific issues confronting the RFP, and to do so at a modest cost. The MST-HIBP is central to much of this work.

This proposal depends strongly on the mission and relevance of MST program. As such, the proposal draws heavily from the MST proposal, "The Reversed Field Pinch, A Proposal for RFP Research in the U.S., May, 1998." That document is on the web in pdf format at: http://sprott.physics.wisc.edu/mst/RFP_PoP_proposal.pdf

As of this writing, the MST proposal has been approved, but the final level of funding has yet to be determined. It is worth noting that researchers from 9 universities, 5 national labs and 2 corporations signed the proposal for RFP research.

The application of an HIBP on any fusion relevant device is always, to some extent, a development project, which generally involves two substantial issues. The first is the development of the measurement capabilities. On MST we have a unique opportunity to demonstrate measurements of magnetic fluctuations, a capability that we could only begin to develop in a limited manner on TEXT. On MST, the relative level of these fluctuations is much higher and their importance to RFP physics is fundamental. Thus, we expect both stronger signals and a community of researchers eager to see results. The second issue is the application of well understood measurements on a challenging new geometry. The ability of an HIBP to measure the plasma potential and simultaneous measurements of density and potential fluctuations has been proven on machines with various magnetic configurations, such as ISX-B, ATF, Tara, EBT, CHS, Gamma-10, and others. Each of the unique confinement configurations has presented significant design challenges not previously encountered. On MST, there have been three such challenges: a plasma dependant magnetic field whose structure and magnitude are not completely known, vacuum access ports kept small to minimize errors in the magnetic field, and a large external flux of plasma and UV.

To address the design challenges, three specific tasks were defined:

1) The design and implementation of a crossover sweep beam steering system to allow reasonable plasma coverage using the small MST ports.

2) The design and implementation of a rugged plasma suppression structure to minimize plasma loading of the sweep system.

3) Optimization of the design to minimize the effect of incomplete knowledge of the magnetic configuration with maximizing the plasma coverage.

While the uncertainty in the magnetic field is a particularly problematic issue for an HIBP, the sensitivity of the heavy ion trajectories to magnetic fields makes it possible to obtain information about the confining field. Therefore the alignment and calibration procedure for the HIBP provides information on the magnetic fields of MST.

With the tasks listed above accomplished to various degrees, the HIBP is now set to measure $\Phi(r)$, $\tilde{\Phi}$ and $\tilde{n}_e$ in the interior of MST. As we gain operating experience we will continue to make incremental improvements in all three of these tasks. In addition we propose to address the more fundamental development work necessary to implement the new HIBP measurements of $\tilde{b}$ and $B(r)$.

The remainder of this proposal discusses the physics issues of interest to the RFP community and specifically those, which are being studied, on MST and how an HIBP can contribute. This is followed by a description of the HIBP on MST. Also included are a summary of the work done to date on the MST HIBP and a discussion of what it takes to obtain the best possible plasma information from a beam probe on an RFP. The last section is a short discussion of a proposal to make it possible, using video conferencing and the Internet, for students at other universities to participate in HIBP experiments. The goal of the last part of our program is to build interest in plasma physics and fusion research among graduate students and potential graduate students who would not normally have an opportunity to be part of this kind of research activity. Appendices to this proposal include a progress report. In addition, a reprint of an article is attached[2] which addresses how an HIBP works.

Information about the present status of the HIBP on MST can be found at: http://hibp.ecse.rpi.edu/

Information about MST can be found at: http://sprott.physics.wisc.edu/mst.htm

MST Physics Studies:

In the proposal for RFP research, the Executive Summary lists 6 outstanding issues that are crucial for RFP development. These are:

Confinement understanding and improvement by advanced techniques
Beta limits
Current sustainment
Control of resistive shell instabilities
Power and particle handling
Modifications to the RFP configuration for improved performance

The MST program is addressing the first 3. Each of these areas will be discussed in some detail along with a statement of how the HIBP can contribute. A discussion of the details of what measurements the HIBP can make is following, within this section one only needs to remember that ö(r), and simultaneous $\tilde{\Phi}$ and $\tilde{n}_e$ are standard measurements for an HIBP, and that under some conditions the HIBP can measure $\tilde{b}$ and **B**.

Confinement Understanding and Improvement:

Magnetic fluctuations in the RFP are large and fairly well understood [3] [4] [5]. Experiments have measured a decrease in interior magnetic fluctuations[6] with inductive current profile control and this is correlated with improvements in confinement. Electrostatic fluctuations have not been measured in the interior of these discharges, nor has the radial electric field. The MST group has proposed to improve the current profile control using electrostatic current injection and lower hybrid drive, and at the same time try to understand the origin of the fluctuations, energy transport, particle transport, and current transport (dynamo).

***Origin of Fluctuations*:**

While the understanding of the magnetic fluctuations in the RFP is highly advanced, the understanding of the electrostatic fluctuations is not. Measurements of electrostatic fluctuations in the outer region of the RFP have shown some correlation with the magnetic fluctuations, suggesting a parasitic relationship. The MST group is studying the dependence of the fluctuations on current profile and collisionality to try to determine the origin. The HIBP can measure the electrostatic fluctuations in the interior and much of the outer region of MST during these studies. Measurements of $\tilde{b}$ with the HIBP would also be useful to determine the origin of the fluctuations.

Energy Transport:

The energy transport in the interior of the RFP is assumed to be dominated by parallel transport in a stochastic magnetic field region. Such diffusion is expected to be constrained by ambipolarity and indeed the thermal flux appears to have a speed characteristic of the ion thermal speed as would be predicted [7]. The simple minded ambipolarity constraint then predicts a radial electric field pointing outward, retarding the electrons and accelerating the ions, as has been seen on mirror devices and on the edge of TEXT with an externally applied stochastic edge magnetic field. The radial electric field profile will be part of the information used to determine which regions of the RFP are stochastic and which regions have closed flux surfaces.

Current profile control experiments have been shown to improve energy confinement; in some cases this may be the result of **E**x**B** shear flow as is seen in Tokamaks. The potential profile measurement will be extremely useful in correlating regions of improved confinement with regions of shear flow.

Particle Transport:

Core particle transport from fluctuations is largely undiagnosed, though measurements show it is due to magnetic fluctuations just inside of the toroidal reversal radius. Outside of the reversal radius it is measured to be electrostatic[8]. The HIBP can measure the electrostatic transport over much of the plasma radius. While this may only confirm the expected transport mechanism for a standard RFP, the particle transport mechanism might be different during current profile modification experiments (enhanced confinement).

***Current Transport and Dynamo*:**

The RFP functions by the self-generation of current and magnetic field -- the dynamo effect. At least 3 dynamo models have been proposed to explain the RFP dynamo: MHD dynamo, kinetic dynamo, and diamagnetic dynamo. The Reversed Field Pinch proposal refers to this as “a rich topic for research.” To explain the RFP dynamo, one has to locally measure the flow velocity, electron pressure, parallel electron pressure and the magnetic field. The HIBP can be useful to estimate the flow velocity by measuring **E**x**B**.

***Improvement of Confinement*:**

The dynamo drives the field reversal of a standard RFP; this provides the confining magnetic geometry. The dynamo occurs as discrete events -- sawtooth crashes. In principle, auxiliary driven edge current can provide the field reversal and perhaps eliminate the dynamo and associated fluctuations. Confinement in MST has already been improved by modifying the current profile and by altering the **E**x**B** velocity flow profile. Inductively driven currents have indeed decreased magnetic fluctuations and increased the confinement time [5]. Current sources inserted into MST have also been able to modify the current profile. Neither inductively driven nor electrostaticly driven currents can offer the fine control promised by electromagnetic current drive. The MST program will use lower hybrid waves to provide this fine control. The HIBP will provide measurements of the electrostatic fluctuations during these experiments. It is unknown if the electrostatic driven transport will respond in step with the reduction in the magnetic transport. If not, then the electrostatic fluctuations may limit the amount of improvement that can be achieved by modifying the current profile. In addition the HIBP may be able to measure the change in the magnetic field associated with the driven currents, which will indicate the drive efficiency.

Confinement has also improved in MST during the presence of **E**x**B** flow shear, similar in nature to the improvements seen in Tokamaks. The **E**x**B** flow shear has been self generated in certain plasmas or imposed by using biased electrodes. The HIBP can measure the radial potential profile, and thereby the radial electric field to determine when and where the **E**x**B** flow shear appears. At the same time the HIBP can measure changes in the electrostatic fluctuations and perhaps the magnetic fluctuations.

Beta Limits:

It is proposed to use auxiliary heating -- lower hybrid waves and perhaps neutral beams -- to study the beta limits of the RFP. The HIBP will measure the electrostatic fluctuations and again try to measure the magnetic fluctuations as beta increases. It is reasonable to expect that pressure driven instabilities may dominate at high beta. The ion beam trajectories will in themselves offer confirmation of high beta.

Current Sustainment:

Oscillating field current drive has been proposed as a method of achieving steady state operation in an RFP. Issues to be studied on MST are the efficiency of the current drive and effects on fluctuations and transport. The HIBP will measure the electrostatic fluctuations, possibly the magnetic fluctuations and possibly the field associated with the driven current (drive efficiency).

The HIBP Will Contribute to Each of the Major Objectives of MST:

Measurement of the plasma potential profile, and therefore the radial electric field is of interest in the study of the stochastic magnetic field region and **E**x**B** flow shear during improved confinement. Measurements of electrostatic fluctuations will extend the work of Langmuir probes to the entire plasma radius, also giving measurements in all density and temperature regimes. Measurements of the fluctuating magnetic field by the HIBP would be important to all of the MST objectives. Measurements of the magnetic field profile would have direct impact on the improved confinement and beta limit studies. The measurement of the potential profile and the electrostatic fluctuations have never been accomplished in the interior of a high performance RFP discharge.

The HIBP System

The attached paper by Crowley describes a typical HIBP. This section will give some specifics of the HIBP on MST (see figures B1 and B2). The HIBP on MST uses the accelerator, power supplies and some vacuum chambers from the HIBP that was on ATF (some of those pieces came from the HIBP that was on ISX-B). The analyzer for the HIBP on MST and some chambers are from the HIBP on TEXT, and some of the bellows, gate valves and pumps are from the HIBP on TEXT-U. Therefore this is the ISX-B/ATF/TEXT/TEXT-U/MST HIBP.

Accelerator:

The accelerator and power supplies are rated for 170kV if SF_6 insulating gas is used. For MST only 120kV is required and the accelerator has been tested to this voltage with room air as the insulating gas.

Analyzer:

The analyzer has a geometric gain of 3 and the detected ions have a charge state of 2, which results in an analyzer anode voltage that is 1/6 of the accelerator voltage, or 20kV maximum. This is well below its original design limit of 100kV. The analyzer has been modified since it was used on TEXT. It now uses a shaped anode and a shaped grounded boundary condition plate to eliminate the need for intermediate electrodes. This concept was proven on the TEXT-U HIBP and has several advantages. The lack of intermediate electrodes eliminates the need for very accurate high voltage dividers. More importantly, the boundary condition plate produces a more uniform electric field. Calibration runs of the analyzer at both RPI and the University of Wisconsin, showed nearly perfect agreement with the predicted response based on the analyzer model. This is particularly true when the ion beam is not centered in the analyzer or when the ion beam enters the analyzer away from the ideal angle. The net effect will be more accurate measurements of the plasma potential. Careful modification and testing has resulted in what should be the best behaved analyzer used on any HIBP to date.

Sweeps:

The unique feature of this HIBP is the cross over sweep system in the primary beam chambers, and 3 sets of sweep plates in the secondary, (see figure B5 in appendix B). This is the first HIBP to have this number of parallel steering plates. CHS in Japan had multipole steering in the primary and secondary, but was not designed for the wide range of steering angles which has been achieved by the MST system. ATF had four sets of steering plates in the primary, but the first 2 sets were only used to compensate for external magnetic fields. The extensive steering system for MST is required by the small ports.

The primary sweep system is a crossover sweep. In each plane, (the local toroidal and poloidal directions), the beam is first bent away from the center line by one set of plates, and then bent back by a second set of plates. The net effect mimics steering plates located in the MST vessel wall, with the remarkable ability to steer ±20º in the poloidal direction and ±5º in the toroidal direction. This is done with a 2” diameter hole in the 5cm thick MST vessel wall. On the secondary, 3 sets of steering plates allow ions that leave the 4.5” output port to hit the entrance slits of the energy analyzer. The range of exit angles of the ions is similar to the range of entrance angles, though the steering on the secondary is not as extensive. To cover the full range of secondary trajectories, the analyzer must be moved. There are 3 nominal positions for the energy analyzer, with each position associated with different plasma coverage. Complete coverage using only conventional steering plates would have required either a redesign of the existing MST port or much larger diameter vacuum chambers for the HIBP.

This sweep system allows coverage of a substantial fraction of the plasma cross-section, (see figure B3 in appendix B). This system also came with a heavy time penalty; the design process took significantly longer than first expected. Options such as multiple small entrance holes and/or a movable primary system were considered and discarded. Lengthy discussions with the MST staff led to the use of an existing 4.5” hole for the exit port. Then it took thousands of ion trajectory calculations using many hours of Cray time to find an optimal entrance port location. The vacuum chambers were the final design constraints, resulting in a custom spun transition vacuum chamber and a 14” diameter bellows. We feel that this design will prove it was worth the time and effort by providing the maximum possible plasma coverage.

Another feature used for the first time on an HIBP is the installation of permanent magnets inside the vacuum chambers near both the entrance and exit ports. The confining fields of MST are generated by currents in the plasma and currents in the vessel wall. The field external to the machine is extremely small. The result is that any plasma that crosses the plasma edge boundary, perhaps due to field errors at a port, is not confined and will flow out the port. Such plasma flow would make it impossible to use steering plates as close to the plasma as this system requires.

We tested two schemes to control this plasma flow; installation of magnets was found to work while collecting the plasma on biased plates did not. Tests with biased plates indicated that the plates would have to collect the order of 10A of equivalent current at the 4.5” secondary port. Magnets however showed better than an order of magnitude reduction in equivalent current flow. In addition, the magnet holder reduces the effective port size, reducing both the plasma flow and UV loading.

Initial Operation:

The entire system has been operated for several test runs. The analyzer performed well. The accelerator and the sweep system have substantial loading effects. Indications are that this loading is dominated by plasma produced UV and not plasma leakage, though additional tests will be done to confirm this.

The tests were done on relatively dirty plasma discharges and therefore this loading may decrease as MST plasmas become cleaner. Improved confinement discharges, with higher ion temperatures, may also have reduced UV flux due to the burnout of low Z impurity lines. The tests show that it is clearly easier to hold negative voltages on the plates than it is to hold positive voltages. This is what is expected if the loading it either plasma leakage or UV photons. If the loading is plasma leakage, one would expect the sweep plates to act like large Langmuir probes, with the electron saturation current being much larger then that of the ion. If the loading is UV, one also expects larger electron current due the fact that more UV strikes the vacuum chambers than strikes the plates themselves. The UV can knock off electrons, which will be attracted to a positive potential. Current for positive plates will flow because of the electrons generated on the vacuum chambers, while current for the negative plates will flow because of electrons generated on the plates themselves.

Because of the excessive loading on plates that are biased positively, the test runs of the system were done with one plate of each of the sweep pairs grounded and the other biased predominately negative. The power supplies are fast and operate in all four quadrants (positive and negative voltages with both sourcing and sinking current). At reduced accelerator voltages, this technique allows for the full range of plasma coverage by alternating which of the plates is grounded and which is driven. This works for all of the sweep sets except the pair closest to the plasma on the secondary side. There are several regions of the plasma that can be probed without these plates; so initial runs will concentrate on those regions. The long term solutions include the following:

1) Reduce the output aperture size to reduce the loading
2) Reduce the sweep plate size, (will also reduce plasma coverage)
3) Replace the plates with wire grids, (will help only if UV dominates the loading)
4) Increase the strength of the magnetic field in the apertures, (will only help if the loading is dominated by plasma leakage)
5) Loading may decrease as the impurity level in MST decreases
6) Higher current power supplies, (will help only if the loading is current limited)
7) Install retarding grids between the sweep plates and the ports

The progress report, appendix B, details the latest efforts to detect signal. Tests indicate that UV loading of the accelerator may be sufficient to defocus the ion beam. There are several solutions if this is a problem.

Standard HIBP Measurements:

Potential and Fluctuation of Potential:

The attached paper by Crowley discusses the types of measurements that an HIBP is capable of making. The HIBP on MST is designed to measure the plasma potential, which is standard. The potential is determined by the relative signal strength on a pair of detector plates. The measurement is continuous in time with a 500kHz frequency limit set by the electronics, so the system measures fluctuations in the potential. Fluctuations in MST have been shown to have significant power only at frequencies well below 500kHz.

Density Fluctuations:

Electron impact ionization dominates the production of HIBP secondary ions in MST. The number of detected ions (detected current) is proportional to the electron density. Usually it is difficult to determine the absolute density, so the HIBP measures the relative level of density fluctuations from the variation in the total signal strength. Both potential and density measurements are made simultaneously, providing information about the relative phase and coherence of $\tilde{n}_e$ and $\tilde{\Phi}$.

Profiles:

The sweep system uses fast 4 quadrant power supplies to scan the sample location with a kilohertz response time. The potential can be taken during a sweep, or fluctuation measurements taken at several locations using a staircase sweep waveform. These result in profiles of the potential and of fluctuations in the potential and density. The energy of the primary ion has to be varied to reach different regions of the plasma. The energy is only changed between shots. In addition, the energy analyzer position has to be changed to reach near the plasma center or near the plasma edge, (the present position is optimized for the middle region of the plasma). While the analyzer position has not yet been changed, the process should take about an hour. All together it is expected that it will take more than one run session to achieve the maximum plasma coverage.

The basic proposed program is to measure the potential profile and fluctuations of density and potential in MST. The equipment is fully capable of doing these measurements.

Additional Measurements:

Magnetic Fluctuations:

In an axisymmetric system such as MST, it can be shown by angular momentum conservation, that the toroidal velocity of the secondary ion is related to the magnetic vector potential at the point of ionization. Specifically the velocity is related to the toroidal component of the vector potential. The MST-HIBP measures the toroidal position of the secondary ion, not the velocity. On TEXT, it was shown that the toroidal position was actually a good measure of the toroidal velocity and the HIBP was used to map out an m=2 island chain.[9] (The magnetic islands in that case were exceptionally large and rigid body toroidal rotation was assumed.)

MST routinely runs with large magnetic fluctuations, so fluctuations in the toroidal position of the secondary ions are expected. It is proposed to study the detected signal and determine if position alone is sufficient to measure the fluctuations of the vector potential. If position is not sufficient, we proposed designing velocity detectors. Velocity detectors have been built for other machines, (none in the U.S.), but MST may be the best test of the technique. The relatively large magnitude and relatively well known structure of these fluctuations combined with the high degree of toroidal symmetry all indicate that this will be a fruitful endevor. If the HIBP can demonstrate the measurement on standard MST discharges, then it will be a very useful tool in the study of plasma with improved confinement.

Equilibrium Magnetic Configuration:

Another proposed area of study is to use the HIBP to understand the equilibrium magnetic configuration of MST. External measurements on MST can provide important but limited amounts of information, including total current, total toroidal magnetic field, and information about mode rational surfaces. The HIBP, in theory, can provide much more.

At the simplest level, just acquiring data is a confirmation of the equilibrium field calculated from the external measurements. Most HIBP systems only provide position information of the secondary ions. This system also provides angle information because of the relatively small apertures and known sweep voltages. In other words, with this HIBP one will know the energy, position and angle of the ions both at the entrance to MST and at the exit. This information can be collected for different input sweep angles and energies. In principle, enough information should be collected to determine the magnetic configuration using a standard inversion process on a set of trajectories.

At a minimum, the position and angle information will be compared to the field model. This work ties directly to the effort to verify the sample location. If the model proves reliable, then the sample location calculations will also be reliable. If the HIBP results indicate that the field model is not accurate, then there is a need for a joint effort to improve the model. Both the overall MST program and the HIBP diagnostic will benefit from any improvements made to the MST field model.

Other Methods to Measure the Equilibrium Magnetic Field:

Detector Array:

The standard HIBP only collects a small fraction of the secondary ions from the fan of secondary ions produced along the primary beam. Typically about 1% of the secondaries will fall on the entrance slit of the analyzer. InterScience, a small company located in upstate NY, has in the past proposed collecting more of these secondary ions to gain additional information. They had a brief test of a detector array on TEXT-U, and a more extensive test on CHS. Those tests involved simple detectors that could be located very close to the plasma. We propose doing a design study to determine if this type of detector could measure the position of multiple parts of the secondary ion fan. In principle this information could be inverted to determine the magnetic configuration. This work is considered speculative and will progress only if there is sufficient funding.

***Image the Primary Beam*:**

We propose a simple test to attempt to image the trajectory of the primary beam in MST. Ions used for the HIBP (Na, K, Cs) have several bright spectral lines. These ions are also not common impurities in MST. If one of these lines could be seen using a filter and a camera, then the entire primary trajectory could be determined. (One would actually need two views to get the 3-D trajectory, but a test with one view is sufficient for a proof of principle.) Accurate measurements of the trajectory directly lead to a measurement of the magnetic field. This work is also considered speculative but should be relatively easy to attempt.

Concerns About the HIBP:

The installation of a HIBP on MST has and will continue to be both an application of a proven diagnostic and a development effort. The proven diagnostic capabilities were listed above as well as several possible development options. In this section we address issues about the limitations of a HIBP. As will be stated, some are not a concern on MST; some are central to our efforts.

Beam Attenuation:

Beam attenuation is not a major concern on MST, due to the moderate density of the plasma and the use of ions such as Sodium and Potassium. Attenuation was studied to the extreme for the HIBPs on TEXT and TEXT-U. Due to energy constraints, those probes used Cesium and Thallium ions which have significantly larger ionization cross-sections. Attempts were made to use attenuation to explain away a fast moving fluctuation found in TEXT and TEXT-U. While beam attenuation on those machines was shown to be a factor for high density discharges, ($>3x10^{13}cm^{-3}$), it was not for the relatively low density discharges used for the ECH studies (typically $1x10^{13}cm^{-3}$). During the last few months of TEXT-U operation, the phase contrast imaging diagnostic measured a fast moving fluctuation[10], supporting the HIBP measurements. During this same time period, the HIBP also measured a driftwave type feature in the interior of TEXT-U on the low field side, demonstrating the HIBP's capability of measuring slower features when they dominate the signal. The HIBP still measured a fast feature on the high field side of the same discharge, which confirmed that this is a real feature.

The basic concern with beam attenuation is that the attenuation modulates the beam current, mostly due to density fluctuations. This modulation of the beam cannot easily be distinguished from the intended measurement of density fluctuations at the sample volume. The amount of beam modulation depends on several factors, including the plasma density, the cross-section for ionization, the ion velocity, the wavelength of the fluctuation, and the correlation length of the fluctuations. Calculations indicate that for moderate density MST discharges ($1x10^{13}cm^{-3}$) and 35kV Na ions, that 92% of the primary beam will reach the sample volume. This is large enough to state that beam modulation will not be a significant factor. This HIBP offers the opportunity to vary the ion and beam energy, and thus vary the amount of attenuation to experimentally confirm the existence or non-existence of beam modulation. Data from the same region can be taken with 115kV Lithium, 35kV Sodium, 21kV Potassium or even 9kV Rubidium. Potassium under these conditions has a cross-section that is 6 times larger than Sodium, which makes it more susceptible to modulation effects. (It also results in stronger signals.) The slower moving and larger Rubidium will have significant attenuation and might show modulation effects, while the smaller and much faster Lithium will have so little attenuation that there is concern about having sufficient signal. The effects of attenuation, or more accurately the lack of effect, can be experimental documented by operating with a range of ions on a given discharge. Since fluctuation measurements will be a key contribution of the MST-HIBP, the unique capability of this system to make identical measurements with varying levels of attenuation will make the results obtained of interest to the tokamak and stellarator communities.

Sample Location and the Time Varying Magnetic Field:

Accurate knowledge of the sample location and accurate knowledge of the magnetic field are one and the same issue. Therefore this is an issue of diagnostic development. As stated in the section on measurements, the HIBP will be used to at least confirm the MST field model and is capable of adding information to improve that model. Initially the sample location will not be accurately known. The issue is even more challenging in that the sample location will move during sawtooth oscillations. Again, based on the MST model, the motion can be large (15 cm of radial motion for sample locations in the outer regions), or moderate (a several cm of mostly poloidal motion in the middle regions of cross section).

Experiments will be done to verify the sample location. Typical experiments used on past HIBPs included: 1) finding fluctuations localized to mode rational surfaces, 2) loss of signal at the plasma edge, and 3) loss of signal due to the beam striking apertures. The data collected will dictate the direction of this work.

Planned MST experiments will aid in this work, most notably experiments to study steady state operation which usually do two things: 1) eliminate the sawtooth and 2) perturb the plasma in one region. The first will reduce the location motion during a shot; the second may offer another surface with distinguishing characteristics. Measurements of a steep radial electric field, and the implied velocity sheer would be a fascinating example.

Small Ports and Sweep Plate Loading:

Most HIBPs have had very large access ports on machines; this is not the case on MST. In addition, as stated above, the MST plasma tends to load the electrostatic sweep plates used by the HIBP. Designing a crossover sweep system has solved the small port issue. This process took longer than first anticipated but has resulted in a design that is very compatible with MST ports. The issue of loading of these plates is still a concern and is discussed in the progress report. The preliminary results, based on several operating days, are that the sweeps can produce half the designed steer by grounding one plate of each pair and operating the other plate with negative voltages. The beam can be steered the opposite direction by reversing which plate is grounded and which is biased.

The first set of plates on the secondary is the exception. These failed to hold voltage on the first few shots and were grounded for the remainder of the runs. The first runs concentrated on conditions that didn't require voltage on these plates, but eventually they will be needed. Options being considered include: 1) trying a higher current power supply (the one used only supplies 10mA), 2) replace the solid plates with wire grids (this will help if the loading is predominately UV photons), 3) install a smaller aperture in the secondary beamline (helps no matter the cause of the loading but limits the plasma coverage), 4) test again with cleaner MST discharges. Initial tests with a high current power supply indicate that the first option listed may be practical. Other options exist, but tend to be more costly in terms of time and money. One additional choice is to use magnetic steering, which has not been implemented previously on an HIBP. Thus, it represents a major change which we would prefer to avoid.

Outreach to Prospective Graduate Students:

One of the more difficult problems facing graduate research programs these days is attracting the best available students. The pool of good domestic graduate students has been rapidly shrinking in recent years due, primarily, to the outstanding job market, particularly for students in electrical and computer engineering. This problem is exacerbated by the additional decline in student interest for traditional electrophysics topics such as plasma physics and electromagnetics. In order to increase our pool of prospective graduate students, we propose to combine some new technology and a fundamental truth about research to get some students involved in our program who would not, in the past, have had much of a chance to participate.

One important lesson that all scholars learn early in their careers is that it is only possible to find out what research is by doing it for a significant length of time – generally at least for several months. There are many students at colleges with no real opportunity to work on the kind of hardware intensive research that is typical in plasma physics. A small number of such students, including one of our present grad students, get this experience in one of the several internship programs available at US universities and national labs. We propose to add to these opportunities by offering a few students per year the chance to participate in our program via the Internet. We will also encourage them to spend short periods of time in Troy and/or Madison to get a more complete sense of what it is like to work in fusion research.

This outreach program will be based on some work one of us (K. A. Connor) is doing in instructional development. We have a general engineering course on electronic instrumentation that is being prepared to be offered at a distance as part of a degree program for the Nuclear Navy. When completed, this course will provide part of the laboratory experience required for an accredited degree in nuclear engineering. In addition to this program, we also have an NSF funded project to develop engineering courses in what we call the studio method, over the Internet. In studio style instruction, we combine lectures, problem solving, computer simulation and experimentation in the same classroom. Thus, both of these programs address doing experimentation over the Internet. In the Nuclear Navy program, students will have some equipment at their local site, but will also run experiments on the RPI campus via the Internet. They will also receive the instruction and experimental assistance usually found in a lab course in the same way. Using a combination of video conferencing hardware and software and remote computer operation software, students will be able to communicate with their instructors, show them what they are doing, look at and operate working versions of their experiments, etc.

We are presently implementing a version of this methodology to create a closer tie between our students and staff in Madison and Troy. Initially we will be using just the video conferencing capability to meet more-or-less as a group on a regular basis. Once the computer control of the HIBP experiments in both locations is operational, we plan to assist in the operation regardless of our physical location. We will follow the same approach when we bring in students from other colleges to participate in our HIBP work. In the beginning, they will be able to observe our meetings and contribute via the telephone, email and/or message board. For the more engaged students, we hope to have them participate more directly via video conferencing, using either equipment at their school or equipment we will loan them. The next stage will be to allow them to actively participate in experimental runs. Finally, as noted above, we hope to have them come to

Troy or Madison for short periods of time. Ideally, this should occur soon after becoming virtual group members.

At present, this video access to our work at MST will involve only our staff, students and equipment. There will be little actual access to MST proper. However, once we get things working, we expect that others in Madison will want to participate. We hope that this activity can become a model for other groups in the fusion program, since the work going on at all participating universities and labs sells itself to prospective students, once they get a real sense of what it is all about. Access to a demo for the instrumentation course will be available shortly through at the url: http://www.rpi.edu/~connor

Summary of Proposed Work:

Use the HIBP to measure Φ, $\tilde{\Phi}$, $\tilde{n}_e$, $\tilde{b}$ and $\mathbf{B}$ in MST discharges. These measurements will directly contribute to the physics studies, (understanding and improvement of confinement, Beta limits, and current sustainment).

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Appendix A: Statement of Work and Justification of Equipment:

Two budgets are submitted with this proposal. The budget option 1 (the smaller of the two), covers the requirements to use the HIBP to make what was referred to as the standard measurements, Φ, $\tilde{\Phi}$, and $\tilde{n}_e$ with only preliminary information obtained on the new measurements that require significant development activity. This budget assumes that a suitable replacement can be found for the Post Doc position, since we expect the present Post Doc, Dr. Diane Demers, will find a permanent job sometime during the contract period. The budget option 2 is sufficient to also pursue the measurements of the magnetic fields, both the equilibrium and the fluctuations. It is sufficient to change the Post Doc position to a full time staff position, which we would expect would permit us to keep Dr. Demers working on this project. The differences are:

1) Changing the Post Doc position to a research staff position (RPI position but located at MST)
2) An additional graduate student
3) Additional engineering staff support at RPI for design of new detectors
4) Additional faculty time
5) Additional equipment money for new detectors

Both budgets also include modest amounts for equipment. The funds are necessary because the vacuum pumps and the high voltage supplies (18 in all) are all relatively old and subject to failure. Already 3 supplies used to sweep the ion beam have failed at a cost of $3000 each.

Budget option 1:

Funding period 4/1/2000 to 3/31/2001

Measure Φ, $\tilde{\Phi}$, and $\tilde{n}_e$ on MST, demonstrate the capability.

Work on determining the accuracy of the sample location.

Implement computer control

Modify secondary beamline support to ease movement of analyzer.

Set up on-line view of HIBP operation.

Funding period 4/1/2001 to 3/31/2002

Continue measurements of Φ, $\tilde{\Phi}$, and $\tilde{n}_e$.

Coordinate with physics program of MST

Current control, Beta studies, transport studies, …

Study sawtooth activity (challenging because sample volume moves.)

Determine best content for outreach access to HIBP data and operation.

Funding period 4/1/2002 to 3/31/2003

Continue measurements of Φ, $\tilde{\Phi}$, and $\tilde{n}_e$.

Obtain preliminary information on $\tilde{b}$ and $\mathbf{B}$

Coordinate with physics program of MST.

Budget option 2:

All of the tasks in budget option 1 plus:

Funding period 4/1/200 to 3/31/2001

Attempt to optical image the beam for B(r) measurement.

Use trajectory codes to determine if velocity detectors are necessary or if the existing detectors can supply information about magnetic fluctuations.

Look at signal motion due to magnetic fluctuations

Use ion beam information to confirm MST field model

Funding period 4/1/2001 to 3/31/2002

Develop most promising path determined in previous year for magnetic fluctuations or equilibrium field.

Funding period 4/1/2002 to 3/31/2003

Continue most promising path for magnetic measurements.

Appendix B: Progress Report 4/1/1997 - 11/1/1999

During the term of this grant, a Heavy Ion Beam Probe was designed, built and installed on MST, (see figures B1 and B2). The installation was done during the summer and fall of 1999, after a port was machined into MST for the primary beam line. The HIBP is operational, but in a manual mode; the computer control has not yet been implemented. The system has been operated, although no signal has been detected at present. Detecting signal is the focus of our present work. We have every confidence that signal will be acquired presently.

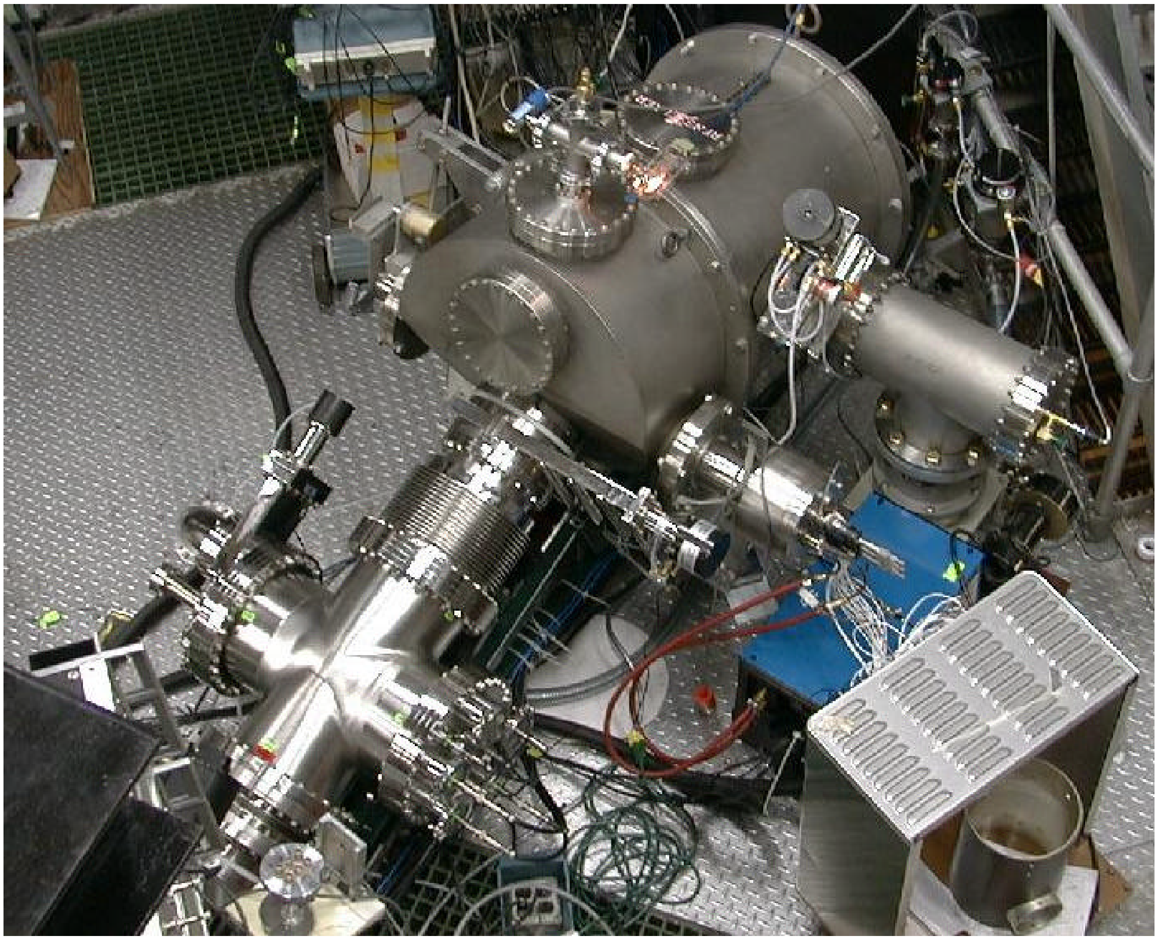

Figure B1 Secondary system mounted on MST. MST is located off the bottom left of picture. Visible are the chambers housing the secondary sweeps and the energy analyzer.

Figure B2 Primary system mounted on MST. Accelerator is at the top of the photograph; below it are the sweep chambers, vacuum pumping and MST.

In addition, during this funding period, work was completed on data from TEXT-U. That work resulted in a Ph.D. thesis by Dr. Diane Demers, which includes the first measurements of particle flux driven by electrostatic fluctuations deep in the core of a tokamak plasma. The measured flux was too small to explain particle or heat transfer in

TEXT-U. The HIBP on TEXT-U was only sensitive to fluctuations with wavenumbers of 2 cm^{-1} or smaller, so it is possible that shorter wavelength fluctuations could drive significant flux. This work also demonstrated that the flux measured, though small to start with, drops to essentially zero when ECH is applied to the plasma. These discharges did not enter an H-mode regime, so the reduction in electrostaticly driven flux was not associated with gross changes of confinement, see figure B3. There is a large collection of data from TEXT-U that has not yet been studied as our efforts were shifted to the HIBP for MST.

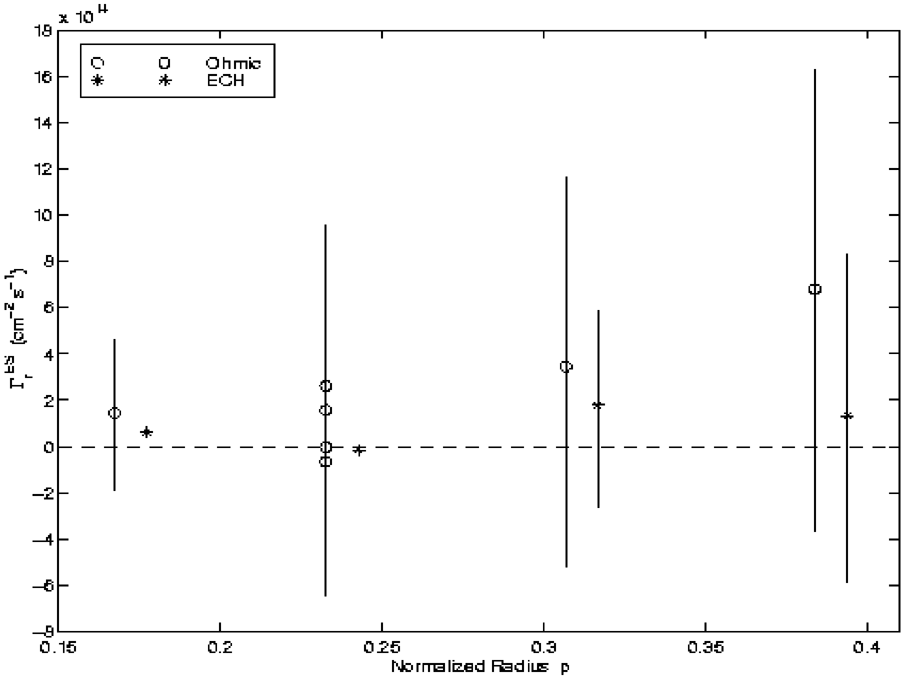

Figure B3, Particle flux measurements using the HIBP on TEXT-U.

The remainder of this report will cover four topics:

The capabilities of the HIBP on MST

The MST-HIBP system

Efforts to acquire signal

A discussion of the effort it took to design and build this system.

Capabilities of the HIBP on MST:

***Plasma Coverage*:**

The HIBP was designed to provide the maximum plasma coverage while using small ports. Figure B4 shows the coverage that can be obtained for one typical MST plasma condition. The figure shows volumes for a few beam energies; other energies will fill in the region. By changing the accelerator energy and the beam sweep angles, similar coverage is expected for other MST conditions. During operation to date, the sweep system has only been able to supply about 70% of the designed sweeping voltage. This is

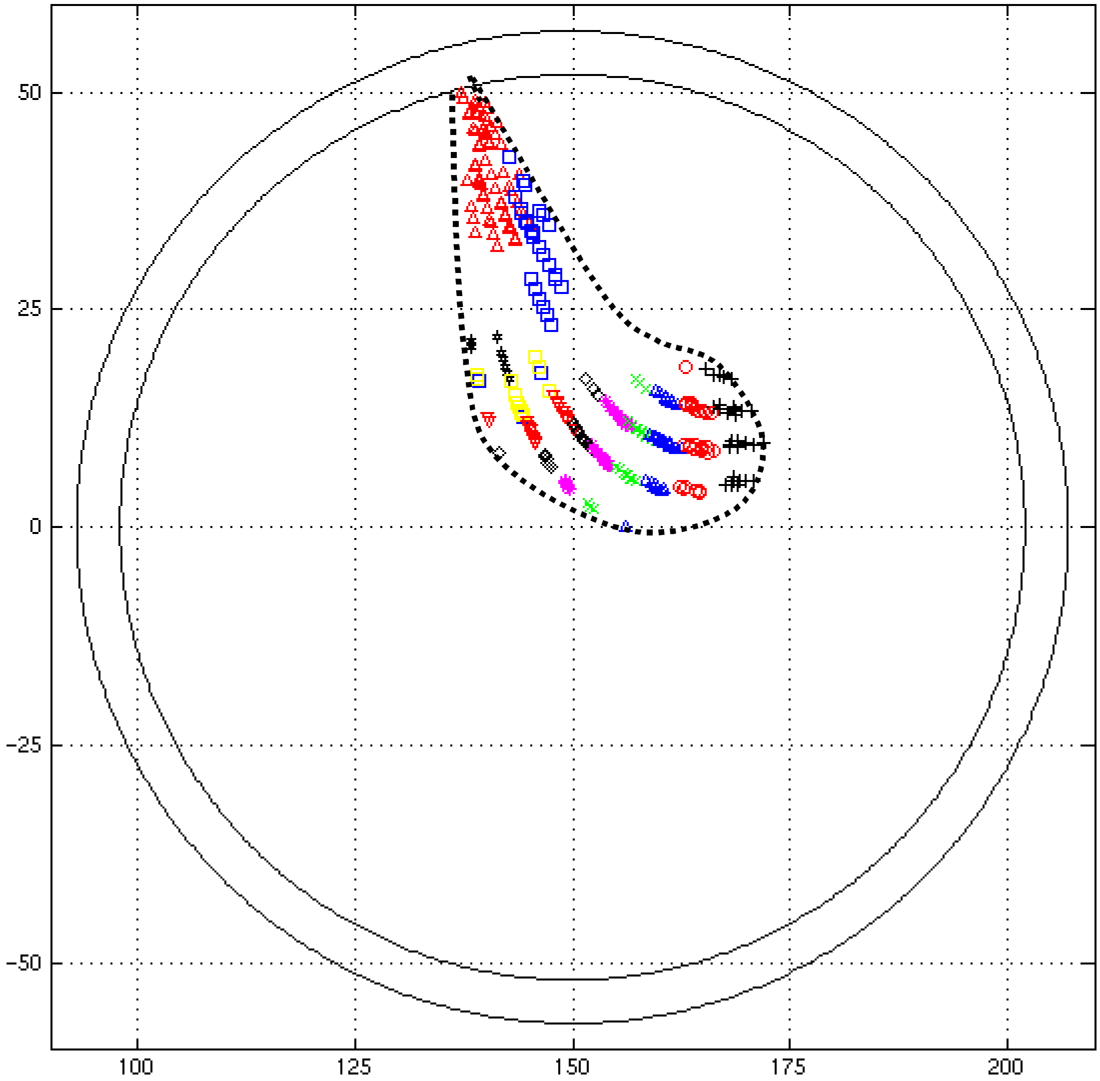

Figure B4 Plasma coverage using multiple beam energies and sweep angles.

not a limitation yet because the required beam energy for present operation is only about 30% of the maximum expected operation voltage, a 30% steer voltage provides full steering of these reduced energy beams. The issue of steering is described later in this report.

The plasma coverage shown in figure B4 requires changing the ion beam energy, which can only be done on a shot by shot basis. In addition, the energy analyzer has to be physically moved to obtain the full coverage. There are 3 nominal positions for the analyzer, which will give plasma coverage of overlapping regions. The system has a bellows and pivot pin to allow this motion without a vacuum vent. While we don't have operating experience with moving the analyzer, it is expected a move will take about one hour. Thus, to cover the full region displayed in the figure will require many shots and most likely more than one run day.

Measurements:

This is a standard HIBP, so the standard measurement of Φ, $\tilde{\Phi}$, and $\tilde{n}_e$ will be made on MST. (See attached paper by Crowley.) The potential measurements on MST can be done directly relative to machine ground, as opposed to some high energy HIBPs that could only do potential measurements of one point relative to another. Many factors contribute to the ability of this system to make accurate "absolute" potential measurements. These are the use of high precision voltage dividers, accurate knowledge of the angle the ions enter the analyzer, and a better analyzer. The sweeps in the secondary and the relatively small port on MST provide the increased knowledge of beam angles and this analyzer was improved by using the no-guard-ring technology proven on the analyzer for the 2MeV HIBP on TEXT-U.

Measurement of the fluctuations of potential and density are also standard for the HIBP and are straightforward on MST. The dominant fluctuations have relatively long wavelengths and relatively low frequencies, well within the measurement capabilities of the HIBP. Beam attenuation has been estimated and will not be a problem for most discharges. Beam signal has also been estimated and will be smaller than the signal obtained in many other HIBP experiments, but is well within the range required to measure the potential and to do fluctuation studies. The signal will be the weakest near the plasma edge; in this region Langmir probes may still be the most effective diagnostic. If the near edge becomes too hot and dense for Langmir probes, then the HIBP signal will become stronger. The two diagnostics should compliment each other.

In addition to the more or less standard measurements, this HIBP is expected to provide information about the magnetic configuration and magnetic fluctuations. Given the small ports and the use of multiple sweep plates, this HIBP will have relatively accurate information about the position and angle of the ion beam at both the entrance and exit ports. This information will be compared to the trajectory program and will indicate if the magnetic field model for MST is accurate. In principle, running with enough different beam energies and injection angles, one could invert the position and angle data to measure the magnetic field in MST. Measuring the magnetic field is not a goal of this HIBP but it is worth noting the theoretical capability. Also, in principle, the HIBP could be used to gather more information about the magnetic fields, as is discussed in the proposal.

The MST_HIBP System:

As with all HIBP systems, there is a primary beamline and a secondary beamline. The primary consists of an ion injector, accelerator, beam profile monitor, 4 sets of sweep (steering) plates and an aperture. The secondary consists of 2 aperture plates, 3 sets of steering plates, and an energy analyzer.

The injector, accelerator, and associated power supplies of the primary system were previously used on both ISX-B and ATF. The system was designed for operation at voltages up to 170kV with the use of SF_6 as an insulating gas. The maximum operating voltage required for MST is 120kV. Tests of the system at RPI in 1998 proved that it could be operated at voltages over 100kV in room air. Operation with dry air or nitrogen may allow operation at 120kV and avoid the expense and complications of SF_6. Present operation only requires 40kV operation and air insulation has been sufficient. The accelerator has been operated on MST with sodium ion currents of up to 100uA and voltages from 30 to 80kV.

The beam profile monitor, BPM, is also from the ATF system. It is located below the accelerator and after a short drift region. The BPM is a commercial unit that gives information on the ion beam size and shape. Beams with 0.5cm FWHM have been obtained during initial operation with MST plasma.

The primary sweep plates are a crossover design (see figure B5). In two planes, the local toroidal and poloidal directions, the ion beam is first deflected off the centerline and then back onto the centerline. This results in the remarkable ability to achieve ±20 degrees of steering in the poloidal direction and ±5 degrees of steering in the toroidal direction through the 2” diameter hole located in the 5cm thick MST vessel wall, drilled specifically for the HIBP. No other HIBP has achieved this amount of beam steering through such a small port.

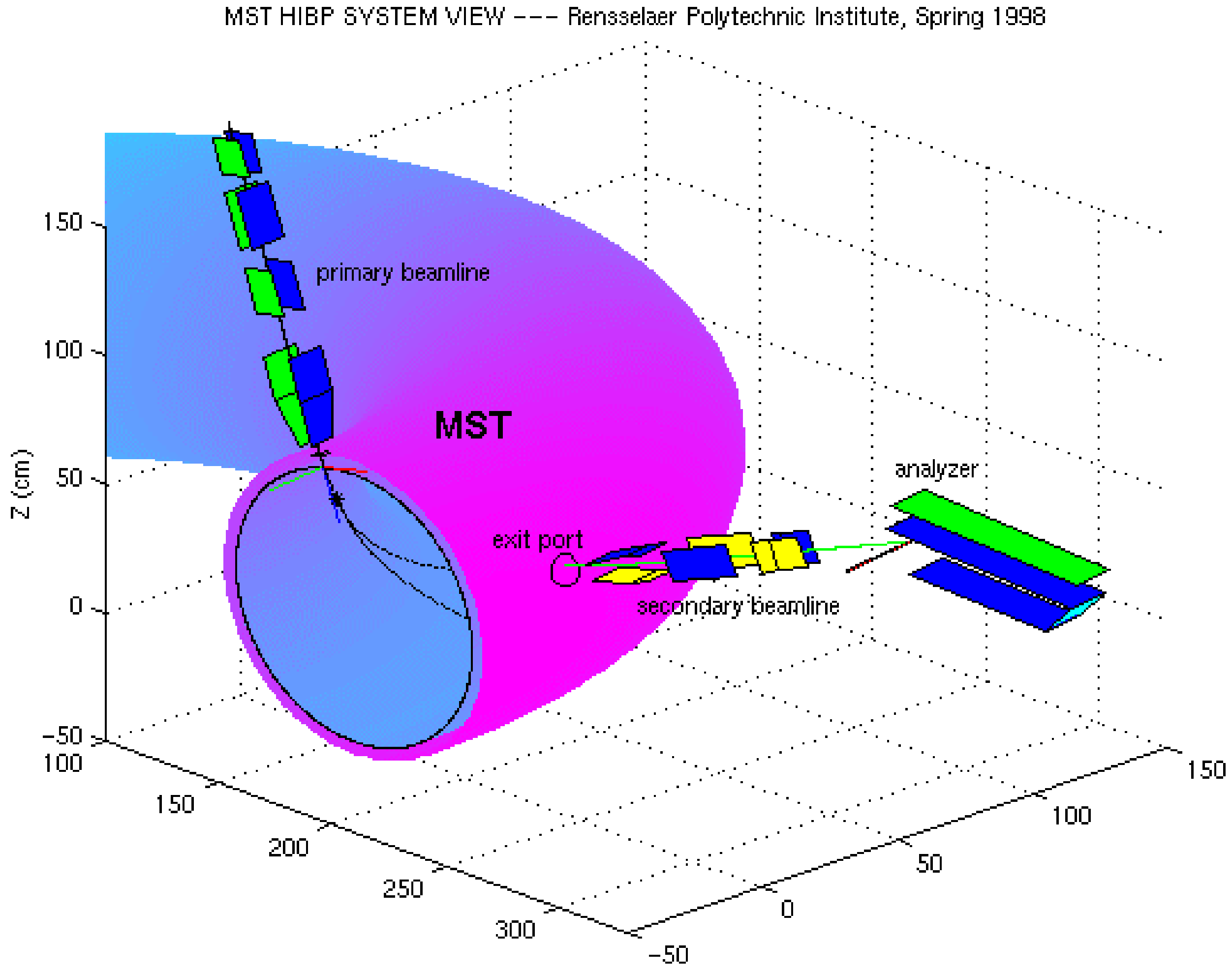

Figure B5 View of all sweep plates. Primary beamline has 4 sets of sweep plates; secondary beamline has 3 sets of sweeps.

An aperture plate with permanent magnets has been installed between the sweep plates and the MST plasma. This aperture was necessary to reduce the flux of both plasma and UV photons into the primary beamline. The opening is rectangular and has a centerline magnetic field of 1.5kG. This has proved to be very effective at reducing the plasma leakage from MST, to the point where all the remaining loading is probably only due to the UV flux from MST. Future experiments will better determine if there is still some plasma leakage through the aperture.

The secondary beamline is attached to MST through a pre-existing 4.5” port. Due to the larger port size, we have placed 2 apertures in this system. These apertures reduce the plasma coverage that can be obtained with the HIBP. The plan is to build several apertures that allow different coverage with each pair. The present apertures are design to cover the middle radii of MST. We have not yet fully analyzed our trajectory information to determine how much this pair of apertures limits data collection at other radii. These apertures have larger rectangular openings than the aperture on the Primary beamline and have less than a 1kG centerline magnetic field. The outboard aperture can be replaced without venting MST. Replacing either the primary aperture or the inboard secondary aperture requires an MST vent.

There are 3 sets of sweep plates in the secondary beamline. These can steer secondary ions from a wide set of operating conditions into the energy analyzer, but not ions from all operating conditions. To get full coverage, the energy analyzer and secondary beamline must be moved. There are 3 nominal positions that result in overlapping plasma coverage. In general there is one position for the analyzer for probing the center of MST, one for middle radii, and one for the outer radii. The analyzer is presently located to detect signal from the middle radii.

The energy analyzer on MST is the one used on the 500kV HIBP that was on TEXT, although it has been modified in many ways. It now has a shaped top plate (anode), a boundary condition shield, and no longer has guard rings. This design was proven to be far superior on the 2MeV HIBP on TEXT-U. The analyzer has a geometric gain of 6 for 2+ ions, so it will operate at 20kV or less, far below the 100kV it routinely operated at on TEXT.

Efforts to Acquire Signal:

At the time of writing this report, the HIBP has not detected signal. This is rather surprising. Initial efforts took the usual shotgun approach that has worked so well on past systems. The primary ion beam was swept in a raster scan mode much like that used in a cathode ray tube, while we look for signal in the analyzer. Since then the effort has been crudely broken down into 3 efforts. The first is to determine that a focused ion beam is entering the plasma. The second is to determine that the trajectory code and magnetic field model are reasonably accurate. And the third is to verify that the secondary beam line (and analyzer) should be able to measure the signal if it was there. While each of the efforts has found some limits to the operation of the system, and led to experimental runs with increased expectation of detecting signal, no signal has been measured as of this writing. Presently we are reasonably confident that the secondary beam line is working, somewhat confident in the accuracy of the magnetic model, and concerned about the quality of the primary ion beam.

The initial runs have been with a 300kA, low density ($\leq 1\mathrm{x}10^{13}\ \mathrm{cm}^{-3}$), discharge which was believed to have reasonable confinement and modest radiation levels. The HIBP was operated with sodium at 35kV. This combination requires only modest sweep voltages, and no sweep voltage at all on the first set of sweep plates in the secondary beamline. Under these conditions, beam attenuation is less than 10% and can be ignored. Signal levels will be relatively weak, with only about 1nA of detected signal per uA of primary, but should be more than sufficient. The detector signal shows about 5nA of dc noise during a shot with about 1nA of broadband noise and 10nA noise spikes during a sawtooth crash. Signals at the 5nA level will be easily spotted, and levels down to 1nA could be spotted. The beam has been operated with currents in excess of 40uA. The following paragraphs will outline the efforts to date to verify the operation of the primary system, the secondary system and the trajectories.

Tests of the Primary Beamline:

The operation of the primary beam has been confirmed without plasma, and we are attempting experiments that can confirm operation with the presence of plasma. Without plasma, the beam can be monitored at 3 locations: the BPM, on a movable plate located just outside the 2” port, and on a detector located in a MST pumping port opposite the primary port. The following lists the improvements made to the system to provide quality high current beams:

1) Initial beam currents were limited by a shorted turn in the ion source. It has been replaced.
2) Initial beam focus was poor because the voltages used are well below the design voltages of the accelerator. The majority of the accelerator is now shorted to ground to allow a high voltage gradient in the remaining section. Beams with 0.5cm FWHM can now be obtained at 35kV.
3) At beam currents above 40uA, the beam has been defocused. This is due to a combination of low operating voltages and an apparent design flaw in the injector. Some ions from the source strike the extractor electrode, which ideally should not happen. This ion current is not of consequence as long as it is smaller than the bias current of the extractor power supply. At greater currents the extractor power supply loses regulation and the extractor voltage increases. This defocuses the beam. The bias current is proportional to the extractor voltage so is sufficient when the primary is operated at voltages above 60kV. For low voltage operation the solution is to add a resistor from the extractor to ground. This increases the bias current and voltage control is maintained. Focussed beams with 100uA can now be produced.
4) A circuit to allow pulsing the ion source heating has been installed. This will greatly extend the source lifetime at the higher beam currents. Other HIBP systems have used such a pulsing circuit.

During plasma pulses, it was noted that the poloidal sweep plates closest to MST couldn’t hold positive voltages. The plates can hold negative voltages relative to the vacuum vessel. The negative voltage is not necessarily held during the entire shot, but is reasonably controlled during most of the plasma pulse. The inability to hold positive voltage is the result of electrons in the region of the sweep plates. These electrons could be due to plasma leakage or produced by UV photons striking the vacuum chamber wall and knocking electrons free. In both cases one would expect more electron current than ion current, and thus the supplies can hold negative voltage and not positive. The short term solution is to ground one plate and use negative voltages on the other plate. This allows steering in only one direction. The beam can be steered in the other direction by reversing which plate is grounded and which is biased. This solution also limits the average electric field between sweep plates to 50% of the design value. This will only be a problem when operating with beam energies at or above 60kV. The long term solution will require addressing further the source of the loading.

Experiments have been started to confirm the beam operation with plasma, and initial indications are that the beam losses focus during shots or is somehow deflected. The results are preliminary but if confirmed will explain the lack of signal and indicate the path to a solution. The tests consisted of using a sweep plate in the primary system as a beam detector. Before and after shots, the beam can be detected on the plate. During the shot, the beam signal is lost, even though all beam supplies appear to be functioning. The logical explanation is that some element in the injector or accelerator is either charging or discharging due to UV from the plasma. This then grossly defocuses the beam. If proven, then the solution could be a simple as adding resistors to the injector electodes. A less logical explanation is that the beam is still there, but our ability to detect it on a sweep plates is lost due to plasma loading of the sweep plate. Experiments in the near future will concentrate on this issue.

Initial tests also indicate that the apparent loss of the primary beam during plasma is not related to external magnetic fields or neutral gas pressure. The beam is detected if only the gas feed is pulsed or if only the coils are pulsed without gas feed. Presently, a problem with the primary beam during plasma is the leading explanation for lack of signal.

Tests of the Secondary Beamline and Analyzer:

Recently the secondary beamline and analyzer had to be moved away from MST during the installation of a lower hybrid antenna. To test the secondary, the injector system was removed from the accelerator and installed onto the secondary beamline, aimed at the analyzer. This allows a test of the secondary sweeps and of the analyzer. All performed as expected.

Even though the secondary system has been proven to be working, it doesn't mean they works ideally during plasma. The energy analyzer and detector plates are believed to operate as designed during plasma, but that is not true for the sweep plates. The first set of sweep plates, the poloidal steer plates close to MST, have not been used for tests to date. These plates receive the most loading of any part of the system and have not been effective at holding voltage. The experiments to date have not required any steering voltage on these plates. The long term solution will again depend on the source and magnitude of the loading. If the loading is mostly UV, then replacing the plates with wire grids will provide the steering with reduced loading. If the loading is plasma leakage, then modifying the apertures may be necessary. Initial tests indicate that negative voltages may be held on these plates by simply using higher current power supplies. The lack of steering with these plates results in a stronger dependence on the trajectory calculations, which is the next topic.

Trajectory Calculations and the Magnetic Model:

The actual trajectory computer code is not likely to be a problem. More than one code has been used and the codes have been tested using simple geometries, which have analytical solutions. Errors could be the result of not properly inputting the port locations, beam angles or the MST magnetic model. Both RPI and MST have reviewed these. None-the-less there is room for error, particularly given the difficulty in determining the magnetic fields in MST. Because of the inability to hold voltage on the poloidal sweeps in the secondary, initial runs have been for conditions we have determined do not need voltage on these plates. It is difficult to determine how sensitive these trajectories are to errors in either beam parameters or the field model, so initial runs involved simply changing the beam energy and injection angles, and looking for signal. These runs were done before it was noted that the primary beam might be severely defocused during plasma. These runs were not excessively systematic and may be repeated if other attempts to acquire signal fail. If in the end, if it is determined that the field model is found to be insufficient to predict our trajectories, then the HIBP will have delivered on one of the original goals, that of verifying the MST field model. The beam parameters that ultimately result in signal will then be useful in work to improve the model.

In the short term, we are attempting a rather radical experiment. The secondary beamline, which was removed for the antenna installation has not be reinstalled. A simple detector is being built and installed in its place. This detector is similar to one tested on TEXT and used on CHS, and consists of metal plates surrounded by a biased box. The box has slits to allow beam to enter and strike the plates. External electronics measure the current on the plates, which is the combined current due to plasma particles, plasma produced UV and the ion beam signal. The bias on the box is adjusted on a shot-to-shot basis until the net current due to plasma sources is nearly zero. Then a chopped ion beam can be detected even if the ion beam current is much smaller than either the plasma particle flux or the plasma UV flux. If this experiment works, it will prove that secondary ions are passing through the exit port. It will provide an estimate of the signal level and the signal position, but no information about the angle at which the signal exits the plasma. If we detect this signal we are confident we can do additional experiments to determine the angle and measure that signal with the energy analyzer.

Design Efforts:

MST represented quite a different challenge for an HIBP compared to previous systems. The need to avoid field errors in MST resulted in small ports. This in turn resulted in the design of a cross-over sweep system. The sweep system designed and built has the capability of steering the beam though a 2"input port in the 5cm thick MST vessel with ±20 degrees of steer in the local poloidal direction and ±5 degrees of steer in the toroidal direction. No such sweep system has ever been built for an HIBP. We don't know of any other sweep system for any purpose that meets these requirements for high energy beams.

Another challenge presented by MST is a relatively large plasma and ultraviolet flux out of the ports. The plasma flux is the result of the near lack of external fields for this device. Any plasma particles that enter the port, either due to collisions or field errors, are essentially not confined. This plasma flux can flow into the HIBP chambers and load the sweep system to the point were it would not function. Aperture plates with permanent magnets have been installed in the transition chambers of the HIBP to curtail this plasma flow. These have proved to be remarkably effective; to the point were all remaining loading effects may be due to UV radiation.

UV radiation on MST is also more severe than on previous machines with an HIBP. A simple comparison with TEXT demonstrates this issue. Typical ohmically heated discharges on TEXT radiated 60kW of power; MST can radiate more than 1MW. The MST vacuum vessel has about twice the surface area as TEXT, so the radiative power density on MST is about an order of magnitude greater.

The requirement of a cross over sweep and the need to limit the loading of the sweep are in direct conflict with each other. The sweep plates need to be located close to MST or else they become excessively large, but putting the plates close (or making them large), results in greater plasma loading. The result was the design of a remarkable sweep system and aperture with permanent magnets. (See figure B6). The aperture is actually located at a radius that is partly inside the MST vessel wall. The aperture for the primary beamline has a 1.5kG centerline magnetic field, yet it produces an error field at the plasma surface of less than 5G.

The sweep primary plates closest to MST are so close that there is no room for a gate valve, so these plates are part of the MST vacuum system. The gate valve is located between these plates and the next set of sweep plates. The next set of plates, which provide toroidal steer, also needed to be close to MST, so they actually extend partway into the gate valve. Given these constraints, a bellows to allow alignment is located around the plates closest to MST. This is the first time we have ever used an aperture with magnets, sweeps within bellows, sweeps partly within a gate valve. This design is remarkable and was time consuming.

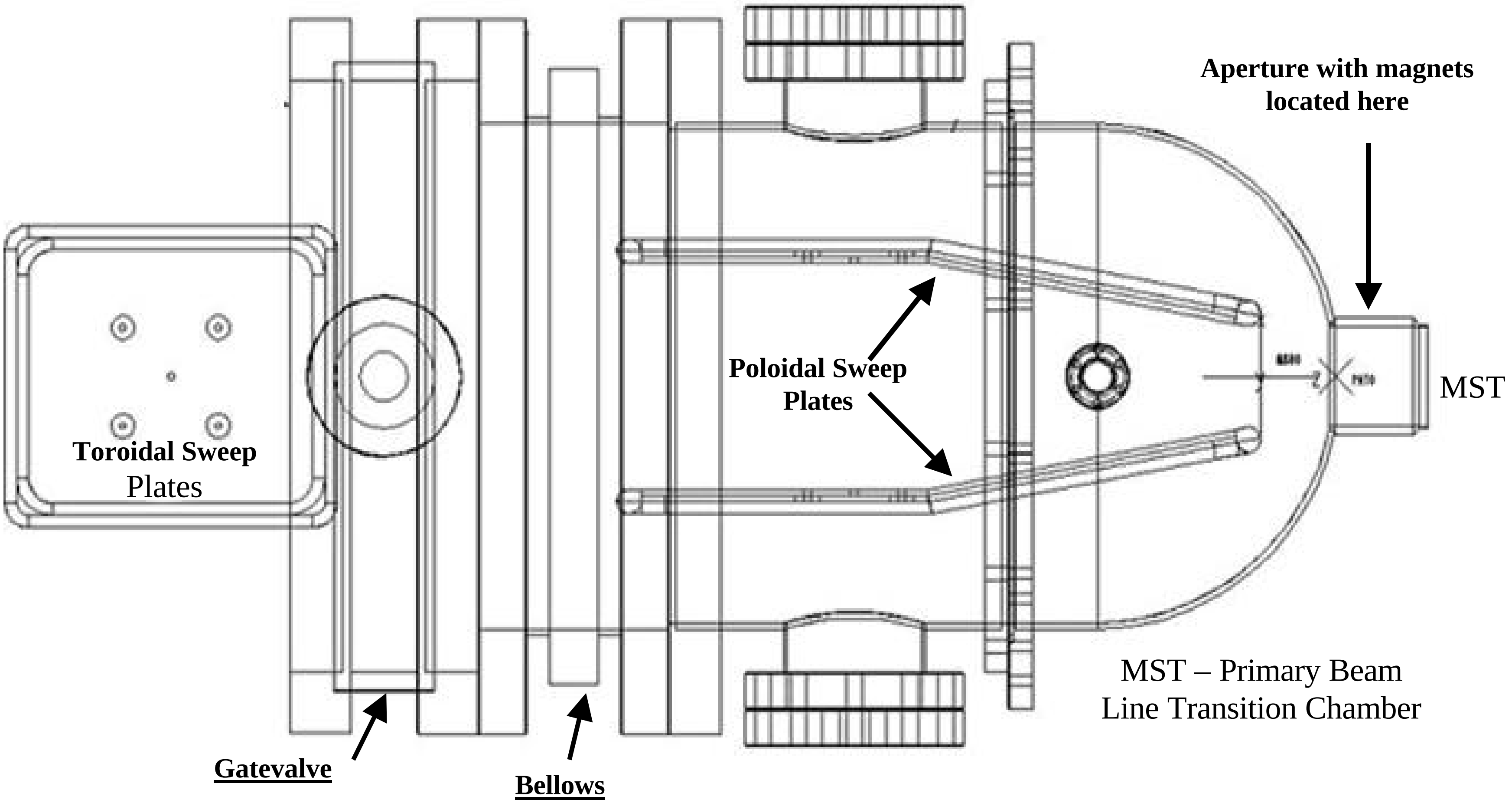

Figure B6 Transition chamber for primary beam line. One set of poloidal and one set of toroidal sweep plates shown. Also indicated is the location of the aperture plate that contains magnets.

The design was also time consuming because the RPI group was offered something we have always requested but never actually had, almost complete freedom to locate the port. Fairly early the design focussed on using one of the existing 4.5” ports for either the primary or secondary port, but that the other port would be drilled into the vessel. This freedom was both a blessing and a curse; it allows better optimization of the system but at the price of a virtually limitless number of possible designs. The choice of port location did indeed have several constraints, such as the location of the iron core on MST, the location of other ports and other diagnostics, and of course the need to simultaneously design a sweep system that matched the requirements of a given port location.

Once the port location was chosen (during the fall of 1998), the detailed chamber drawings were completed and sent out for bids. The more complicated primary chambers were completed by March of 1999. The chambers for the secondary were not completed until September of 1999. The primary port was drilled in June of 1999, with the installation of the primary during July and August. The secondary chambers and energy analyzer were installed in late September and early October. While the design took much longer than predicted, fabrication and installation have proceeded at a very respectable pace. We feel that the end result will justify the time it took.

The lack of detected signal is frustrating but will be temporary. Knowledge gained while finding signal may prove useful in confirming or modifying the model for the magnetic fields in MST. The optimist would say that the lack of signal proves that this is a diagnostic development effort and not just installing on a magnetic loop or some other standard diagnostic. While we are all optimists here, we will still sleep better when we confirm signal.

Appendix C: Biographical Sketches and Bibliography of Literature

The two lead people for this proposal are Professor Paul M. Schoch and Professor Kenneth A. Connor. Between them they have worked on, consulted on or at least advised on almost every HIBP system in the world. They were principle investigators, or co-principle investigators for HIBP systems on the following machines:
EBT
ISX-B
TEXT
ATF
TEXT-U
MST
They also either consulted or worked directly on the HIBP systems on the following machines:
TMX
NBT
Tara
CHS
LHD (presently being installed)
JIPT-2U
TdeV

Professor Paul M. Schoch
Electrical, Computer and Systems Engineering Department
Rensselaer Polytechnic Institute
Troy, New York 12180-3590
Telephone: [518] 276-6072
Fax: [518] 276-6261

Education

B.S.E.E.	Rensselaer Polytechnic Institute, 1976
M.E.E.E.	Rensselaer Polytechnic Institute, 1981
Ph.D.	Rensselaer Polytechnic Institute, 1983

Professional Experience

1983 - 1991	Joint appointment between Rensselaer (Research Associate) and the Univ. of Texas (Research Fellow).
1991 - Present	Associate Professor

Professor Kenneth A. Connor
Electrical, Computer and Systems Engineering Department
Rensselaer Polytechnic Institute
Troy, New York 12180-3590
Telephone: [518] 276-6084
Fax: [518] 276-6261

Education

B.S.E.E.	University of Wisconsin, 1968
M.S.E.E.	University of Wisconsin, 1970
Ph.D.	Polytechnic Institute of New York, 1975

Professional Experience

1974 - 1980	Assistant Professor
1980 - 1987	Associate Professor
1987 - Present	Professor
1980	Visiting Scientist -- Nagoya Bumpy Torus Group, Nagoya University, Japan
1984	Visiting Scientist -- Plasma Diagnostics Group, Ioffe Institute, USSR
1987 - Present	Scientific Advisor -- Magsoft Corporation, Troy, NY
1992 - Present	Director -- Plasma Dynamics Laboratory, Rensselaer

<u>Relevant and Recent Publications</u>

"Use of a Heavy Ion Beam Probe to Measure the Plasma Potential on the Advanced Toroidal Facility", S. C. Aceto, K. A. Connor, J. G. Schwelberger and J. J. Zielinski, Rev. Sci. Instrum., <u>63</u>, pp. 4568-4570 (1992).

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"In-situ Analyzer Calibration Methods for Heavy Ion Beam Probes Installed on Stellarator-Like Devices", J. J Zielinski, S. C. Aceto, J. G. Schwelberger, K. A. Connor, J. F. Lewis, J. C. Glowienka and A. Carnevali, Rev. Sci. Instrum., <u>63</u>, pp. 4574-4577 (1992).

"Internal Magnetic and Electrostatic Fluctuation Measurements of MHD Modes in the TEXT Tokamak", Physics of Fluids B, <u>5</u>, 1576 (1993).

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"Temperature and Density Measurements in a Non-Axisymmetric, Continuously Operating Fusion Experiment Using a Heavy Ion Beam Probe", J. R. Goyer, K. A. Connor, R. L. Hickok and L. Solentsten, IEEE Trans. Plasma Science, <u>22</u>, 403 (1994).

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"Heavy Ion Beam Probe Sample Volume Effects in Helical Devices," T. P. Crowley, H. Iguchi, A. Fujisawa, S. Lee, Y. Hamada, S. C. Aceto, and K. A. Connor, Fusion Engineering and Design vol. 34-35, 653 (1997).

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“A Spatial Detector Array for Measuring Plasma Turbulence with the Heavy Ion Beam Probe,” J.A. Beckstead, S.C. Aceto, T.P. Crowley, D. Demers, P.E. McLaren, A. Ouroua, J.G. Schatz, and P.M. Schoch, Review of Scientific Instruments, vol. 68, 328 (1997).

“Current Density Profile Measurement on the Texas Experimental Tokamak Using a Heavy Ion Beam Probe,” J. G. Schwelberger, T. P. Crowley, K. A. Connor, P. M. Schoch, Review of Scientific Instruments, vol 69, 3828 (1998).

“ Investigation of the Dielectric Properties of Particles by Finite Element Analysis,” K. Connor, J. Braunstein, S. Salon, H-S. Kim, IEEE Transactions on Magnetics, vol 34, 2779 (1998).

“Microwave Radiation from Slant Cut Cylindrical Antennas – Modeling an Experiment,” C. Vollaire, L. Nicolas, K. A. Connor, S. J. Salon, B. G. Ruth, L. F. Libelo, IEEE Transactions on Magnetics, vol 34, 2712 (1998).

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“Preliminary design of a heavy ion beam probe diagnostic for the National Spherical Torus Experiment,” F.H.Mull; T.P. Crowley; P.M. Schoch, K. A. Connor et al., Review of Scientific Instruments, vol 70, 959 (1999).

“A heavy ion beam probe for the Madison Symmetric Torus,” U. Shah; K. A. Connor; J. Lei, et al., Review of Scientific Instruments, vol 70, 967 (1999).

“Sweep system design for a heavy ion beam probe on Madison Symmetric Torus,” J. Lei; T. P. Crowley, U. Shah, K. A. Connor et al., Review of Scientific Instruments, vol 70 (1999).

Appendix D: Current and Pending Support

for Paul M. Schoch

Current and Pending Support for Ken Connor

Appendix E: Facilities and Resources:

The hardware for this program is mounted on MST. Rensselaer has a Post Doc and 2 graduate students located on site. They have had full use of MST facilities and support staff. The on site support has been excellent.

In addition, Rensselaer maintains a support facility on campus in Troy, NY. This support includes:

1) Lab space that was used to test the accelerator and associated supplies before they were shipped to Wisconsin.
2) A 150keV ion test stand. This was used to calibrate the energy analyzer before it was shipped to Wisconsin.
3) A design office, staffed by an engineer. All of the vacuum chamber designs were done here. Presently the engineer supports the program by designing modified apertures and technical support on issues such as ion beam focusing. The engineer also makes the ion sources used for the HIBP.
4) Faculty offices, graduate student offices and related equipment such as computers.

Attachments:

1) “Rensselaer Heavy Ion Beam Probe Diagnostic Methods and Techniques,” T. P. Crowley and the Rensselaer Plasma Dynamics Laboratory Team, IEEE Transactions on Plasma Science, Vol. 22, No. 4, August 1994.

2) Letter from Dr. S.C. Prager