NASA TECHNICAL MEMORANDUM

NASA TM X-71840

NASA TM X-71840

SUMMA HOT-ION PLASMA HEATING RESEARCH AT NASA LEWIS RESEARCH CENTER

by J. J. Reinmann, R. W. Patch, M. R. Lauver,
G. W. Englert, and A. Snyder
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at
Sixth Symposium on Engineering Problems of
Fusion Research sponsored by the American Nuclear Society
San Diego, California, November 18-21, 1975

(NASA-TM-X-71840) SUMMA HOT-ION PLASMA HEATING RESEARCH AT NASA LEWIS RESEARCH CENTER (NASA) 14 p HC $3.50 CSCL 20I

N76-14933

Unclas

G3/75 07370

SUMMA HOT-ION PLASMA HEATING RESEARCH AT NASA LEWIS RESEARCH CENTER

by J. J. Reinmann, R. W. Patch, M. R. Lauver,
G. W. Englert, and A. Snyder

NASA Lewis Research Center
Cleveland, Ohio 44135

E-8563

Abstract

This report describes the SUMMA superconducting magnetic mirror facility at the NASA Lewis Research Center and the hot-ion plasma research conducted therein. SUMMA is characterized by intense magnetic fields (designed for 8.6 T at the mirrors) and a large-diameter working bore (41 cm diameter) with room-temperature access. The goal of the plasma research program is to produce steady-state plasmas of fusion reactor densities and temperatures (but not confinement times). The program includes electrode development to produce a hot, dense, large-volume, steady-state plasma and diagnostics development to document the plasma properties. SUMMA and its hot-ion plasma are ideally suited to develop advanced plasma diagnostics methods. Two such methods whose requirements are well matched to SUMMA are: (1) heavy ion beam probing to measure plasma space potential; and (2) submillimeter wavelength laser Thomson scattering to measure local ion temperature. Two NASA University Grants were established to identify major requirements for developing these two diagnostic techniques in SUMMA.

Introduction

SUMMA* is described in detail in ref. 1. Plasma heating experiments were conducted in SUMMA for about eight months in CY 1974.[2] Several modifications were made to SUMMA since then, including the installation of a fourth magnet module. The facility was placed back in operational status in July 1975.

The plasma heating process used in SUMMA was originally studied at Oak Ridge National Laboratory where it was known as "Burnout".[3] A steady-state $\underline{E} \times \underline{B}$ plasma discharge is formed and heated by applying a strong (several kV/cm) radially inward d. c. electric field near the mirror throats. The plasma ions and electrons acquire an azimuthal $\underline{E} \times \underline{B}$ drift velocity corresponding to an ion drift energy in kilovolts. Turbulence may be responsible for preferentially heating the ions in this process.[3] In SUMMA, ion temperatures in excess of 5 keV have been obtained for helium plasmas.[2] The theory for this heating process indicates that the ion density should scale as the square of the magnetic flux density.[3] Ion densities in excess of 10^{13} cm^{-3} are predicted for SUMMA. This plasma heating process is also under study in HIP-1 (Hot-Ion Plasma), a water-cooled magnetic mirror facility at LeRc.[4,5,6]

Ion temperatures are determined from measurements of the energy spectrum of charge-exchange neutrals emerging from the plasma, and also by observing the Doppler-broadened optical line profiles of excited charge-exchange components in the plasma. A laser Thomson scattering experiment is being installed in SUMMA to measure the electron density.

SUMMA and its hot-ion plasma are ideally suited to develop advanced plasma diagnostics methods such as heavy ion beam probing and submillimeter laser Thomson scattering. Because of its high magnetic flux density, SUMMA may also be suitable for performing synchrotron radiation experiments which are needed for plasma energy balance assessment.

The topics covered in this report include: (1) a description of SUMMA; (2) results of the plasma diagnostics program; (3) a summary of the SUMMA plasma heating results; and (4) a discussion of NASA grants to investigate requirements for developing heavy ion beam probing and submillimeter laser Thomson scattering in SUMMA.

SUMMA

A photograph of SUMMA is shown in Fig. 1. There are four magnet modules and three spacers which are presently arranged in the simple mirror configuration shown in Fig. 2. Each magnet module was designed to produce a central field of 5.0 T when operated alone. When two magnet modules are operated as a closely spaced pair, they were designed to produce a central field of 8.8 T. Each magnet module is made up of three concentric solenoids that can be independently powered. The maximum design currents were 425 A, 300 A, and 300 A in the outer, middle, and inner windings, respectively. The outer and middle windings are layer wound with Nb-Ti superconducting wire consisting of 18 strands of Nb-Ti embedded in a square cross section of OFHC copper substrate for stability. The inner windings, which were designed to operate in a maximum field of 10.3 T, used Nb_3-Sn superconducting ribbon (strengthened with stainless steel and stabilized with copper) wound into 20 pancakes. Each magnet module is contained within a sealed (welded) type 310 stainless steel vessel which contains the liquid helium.

Originally all four magnets were wound in the same manner and each module performed satisfactorily when tested in a large test dewar. When the magnets were retested at a latter date, magnet module B (Fig. 2) was very unstable and would quench at low fields. When the magnet was removed from the test dewar, some of the polyester film insulating tabs and G-10 packing strips were found in the dewar. It was suspected that the adhesive that bonded the polyester film to the Nb-Ti wire was destroyed, possibly by some cleaning

*SUperconducting Magnetic Mirror Apparatus.

fluid originally left in the magnet. Without the polyester film tabs the wire was free to move, and the movement gave rise to a local quench.

The outer and middle windings of the defective magnet were unwound and the polyester film tabs were removed. The wire was pulled through round dies and then it was twisted to a pitch of about four turns per foot. Next the wire was pulled through square dies and its final dimensions were 0.211 cm square. Finally, the modified wire was coated within insulating varnish. The outer and middle solenoids were rewound at Lewis Research Center. The turns of wire were tightly packed together. Any free space resulting from the winding lead was filled in tightly with custom-fitted strips of G-10 insulation at the second or third turn from the end of each layer. This construction method minimized conductor movement in the axial direction and also locked the G-10 packing strips in place. Although this construction eliminated radial flow of helium coolant, the conductors were cooled via the flow passages between the winding layers. The rebuilt magnet was exceptionally stable when operated alone at currents of 425 A, 300 A, and 100 A in the outer, middle, and inner windings, respectively.

The pancake windings of the inner solenoids also experienced mechanical problems at their hub (inside diameter). Upon partial disassembly of one of the inner solenoids, it was found that the ribbon slid under the insulator disks that separated the pancakes. This resulted in shorts between pancakes. To avoid trouble with the inner solenoids, their current is limited to 100 A which is only one-third of their design current; this reduces the attainable mirror field by about 10 percent.

At present, the outer windings of magnet modules A and D (Fig. 2) exhibit finite resistance. Each of these outer windings developed its finite resistance after a quench in which it was one of two adjacent modules operating at maximum design currents. One magnet module was damaged before, and the other after the installation of the fourth magnet. To repair these windings, they must be removed from their sealed helium vessels and unwound. When they are repaired, they will be rewound with a newer multifiliment twisted conductor and fabricated in the same manner as the rebuilt magnet. In the meantime the current in the damaged outer windings will be limited to about 100 A to avoid excessive helium usage.

The best magnetic flux densities that can be produced under the above enumerated limitations is approximately 6.4 T under the mirrors and 3.8 T at the midplane. These magnetic flux density levels are adequate to carry out most of the planned research program on plasma heating and diagnostics.

With magnets B and C powered (Fig. 2), the liquid helium usage is typically 150 liters/hr.

Hot-Ion Plasma Experiments

Details of the SUMMA and HIP-1 hot-ion plasma experiments are found in refs. 2, 4, 5, and 6. The following sections summarize the hot-ion plasma results.

Apparatus

Plasma Test Section. - A schematic view of the plasma test section and magnet configuration is shown in Fig. 3. The discharge chamber is a cylinder 3.75 m in length and 36.6 cm in diameter made from 304 stainless steel. There is a 10-inch oil diffusion pump at each end of the test section. Both horizontal and vertical diagnostic ports are located near the midplane. Two 25-cm diameter ports at the ends of the test section provide excellent viewing via the mirrors shown. The centerline magnetic field profile is also shown in Fig. 3 for the case where only magnets B and C (Fig. 2) are powered.

Electrode Assembly. - Fig. 3 also shows the location of the anodes, cathodes, and electrically floating shields. A photograph of the electrode assembly removed from the test section is shown in Fig. 4.

Gas is introduced through the cathodes to produce a hollow-cathode discharge. The tips of the cathodes were located at the mirror throats. The tungsten cathodes used in SUMMA were not water-cooled. Therefore, they were heated to thermally emitting temperatures by fast-ion and charge-exchange neutral particle bombardment. Without adequate cooling, true steady-state operation was not possible. Therefore, several water-cooled hollow-cathode designs were developed and tested in HIP-1. These successfully produced true steady-state operation. Water-cooled cathodes have been installed in SUMMA and they will be bested in the near future. A photograph of the uncooled tungsten cathode and three water-cooled cathodes is shown in Fig. 5.

The electrically floating shields, which are also water-cooled, protect the cathode support from charge-exchange and ion bombardment, and help inhibit arcing along magnetic field lines from cathode to ground points.

The anodes are also water cooled. They are cylinders which are concentric with the magnet axis and located about 7.5 cm inboard from the tips of the cathodes. The annular gap between the cathodes and anodes can range from about 3/4 to 1 cm.

Most water-cooled electrode components are fabricated from copper. To minimize sputtering, the copper surfaces exposed to energetic plasma were coated with tungsten via a commercial plasma flame-spraying process.

For the results reported herein, the cathodes were connected in parallel to a 0-22 kV, 0-10 A power supply. (A 0-50 kV, 0-10 A power supply is now installed in SUMMA). Gas flow to each cathode is remotely adjusted by precision variable leaks. Gas flows are adjusted to maintain approximately equal current into each cathode. The plasma can be operated with neutral background pressures ranging from 10^{-5} to 5×10^{-4} torr.

Plasma Diagnostics

To document the plasma ion temperature, it was necessary to develop and calibrate suitable instruments, and to devise plasma models for reducing the experimental measurements to ion temperatures. Both the charge-exchange neutral particle spectrometer and the optical monochromator sample data from a chord of plasma. Thus, to obtain an ion temperature, a mathematical unfolding technique was needed to account for energy dependent processes and spatial nonuniformities. Unfortunately, in a plasma where the azimuthal drift energy is comparable to the random kinetic temperature, unique solutions to Abel-type inversions are not possible. An alternate approach is to use a mathematical plasma model to calculate the expected response of the diagnostic instrument. By adjusting the mathematical model to make the calculated response fit the measured response, an ion temperature and other plasma parameters can be inferred. This approach is referred to as a forward-type calculation as contrasted to the inverse-type calculation which is more commonly attempted. The forward-type calculations used to obtain ion temperatures in SUMMA are discussed later.

To measure ion density, a laser Thomson scattering experiment is being installed in SUMMA. This system is also described briefly below.

Charge-Exchange Neutral Particle Spectrometer. - The charge-exchange neutral particle spectrometer (NPS) is described elsewhere.[2] A schematic of the NPS is shown in Fig. 6. A fraction of those charge-exchanged neutrals which enter the apertures of the collimator are reionized in a nitrogen-gas-stripping cell. By adjusting the voltage on the 90° electrostatic deflection plates, those ions within a narrow band of energies, $\mathscr{E}$ to $\mathscr{E} + \Delta\mathscr{E}$, are allowed to pass into the bending magnet. By adjusting the magnetic field in the bending magnet, the ions are further sorted according to mass. The ions emerging from the exit slits of the bending magnet are detected by a commercial electron multiplier operated in the analog mode. Use of the complete analyzer allows one to determine particle current as a function of energy for a given mass. By employing electronic feedback techniques, a complete energy spectrum, such as shown in Fig. 7, can be obtained in a second or so.

For the results presented in ref. 2, the NPS was not experimentally calibrated, and thus published cross-section data and gas-cell stripping data were used to obtain the overall NPS calibration.[7] Since then, a gas cell similar to that used in ref. 8 was installed in the NPS. The NPS was then shipped to Oak Ridge National Laboratory where it was calibrated by C. F. Barnett and J. A. Ray.

Fig. 8 shows an NPS calibration for helium. At lower beam energies the fraction of the entering helium beam that reached the ion detector decreased rapidly with decreasing energy. This result, which is due to the fall-off in the nitrogen gas cell stripping efficiency at lower energies, was not available in the literature. This appears to be the first experiment to reveal this result. Some other gas may be better suited to ionize helium atoms at low energies, but it is not readily apparent what gas should be used. Unless a better stripping gas can be found, the NPS will be very difficult to apply to helium plasmas with low ion temperatures.

When energetic charge-exchange molecular hydrogen neutrals enter the gas stripping cell they can be dissociated as well as stripped of an electron. Thus, protons (at half the molecular beam energy) and molecular ions will be produced. Hence, the molecular ion distribution will be depleted of those particles that were dissociated, and the atomic ion distribution will contain a contribution from the charge-exchange molecular neutrals. The fraction dissociated is also energy dependent. In the calibration procedure, the equivalent neutral-beam current entering the NPS must be measured. Here, a further complication arises because the gas neutralization cell also causes dissociation which results in a neutral beam composed of both atoms and molecules. Therefore, some means must be found to measure the molecular current in this mixed-particle beam before a meaningful NPS calibration can be made for charge-exchange neutral molecules. In SUMMA, and probably in many other plasmas, molecular ions are present. Thus, the effect of the molecular beam on the proton energy distribution will have to be resolved before the atomic and molecular hydrogen ion temperature can be reliably quoted.

If more than one ion species is present in the plasma, the use of just the electrostatic plates (see Fig. 6) to measure the ion energy distribution of a steady-state plasma can lead to serious misinterpretations of the plasma ion temperature. For example, in SUMMA where the ion temperature is very dependent on the ion mass, the tail of the distribution measured with detector no. one is dominated by the higher mass components, especially an impurity such as carbon.[2] The distribution function measured at detector no. one can possess a single peak and have a smooth tail and still be made up of contributions from several mass species.

A plasma model was devised to interpret the NPS results.[7] This model gave results which agree with experimental data from four different $\underline{E} \times \underline{B}$ type plasma heating devices. The model included the following phenomena: a guiding center description of the particle motion with a kinetic temperature associated with the Maxwellian distribution of cyclotron velocities and axial velocities and a plasma rotation associated with the guiding center motion; radial variation in ion density; energy dependent charge-exchange cross-sections; and a partially-ionized plasma where the energetic ions charge-exchange on a uniformly distributed neutral background gas. The detailed particle motions within the plasma were included to determine those particles that would pass through the collimating apertures of the NPS. From this forward-type calculation, graphs were plotted in which the half-width and most probable energy of the NPS energy spectrum were related to the ion temperature and the plasma drift energy.

Optical Monochromator. - Ion temperature, electron temperature, and relative ion density estimates can be obtained from optical emission measurements on steady-state plasmas such as SUMMA and HIP-1.

Fig. 9 is a typical optical monochromator trace for the Balmer-α spectral line in a hydrogen plasma. The narrow central peak was caused by Franck-Condon neutrals and electron excitation of background neutrals. The wide component is due to the Doppler-broadened charge-exchange component from which the ion temperature can be obtained. The main advantages that the optical monochromator has over the NPS is the fact that there are no strong energy dependent processes in the monochromator apparatus, and the monochromator system is easier to operate. But a plasma model is still required to interpret the results. Two different models have been developed to interpret the optical emission measurements. For the first model[9] a chordal average of the ion temperature was uniquely related to the second moment of the Doppler-broadened line profiles. Corrections for magnetic splitting, fine structure, monochromator slit function, and energy dependent cross-sections were derived and included. It was assumed that the ions charge exchanged on a uniformly distributed neutral background gas. Transit times and high density effects were not included.

Azimuthal drift motion was also verified by scanning the plasma at various distances from the axis. When the guiding centers of the ions drift with a velocity component parallel to the line of sight, the entire charge-exchange component of a neutral atomic line will be shifted relative to the narrow central component because of the Doppler effect (see Fig. 9). The central component is due principally to electron-collision excitation of neutral atoms which are not expected to drift appreciably. Hence the shift of the charge-exchange component gave a measure of the drift velocity of the ions.

A second plasma model for the interpretation of optical emission data has recently been developed.[10] The plasma model, previously developed to interpret the NPS measurements,[7] has been adapted to analyze shapes of the Doppler-broadened charge-exchange neutral lines. The NPS model was modified to include energy-dependent excitation charge-exchange cross sections, and particle transit during the time lag between the excitation event and the light emission. It was shown that if the ions possess finite cyclotron radii, the azimuthal drift contributes to the Doppler-broadening when sighting through the plasma axis. Thus the ion temperatures obtained from the second model were as much as 30 percent lower than those obtained from the first model. When the assumptions of spatial uniformity, zero time lag, and zero cyclotron radius are used in the second model, the results reduce to those of the first model.

<u>LaserThomson Scattering Experiment</u>. - A laser Thomson scattering experiment is being installed in SUMMA to measure electron density and temperature (see Fig. 10). Measurements can be made with either a 10-joule Q-switched ruby laser with a one shot per minute repetition rate, or a 1-joule Q-switched ruby laser with a 60 shot per minute repetition rate. The use of an 0.12 steradian lens provides for sufficient photon collection to allow the light to be split into four beams for electron temperature measurement. To measure the electron density, the total collected light is passed through a notch filter (to minimize background plasma light) and detected on a single photomultiplier tube (PMT).

The laser output intensity is monitored on a separate channel employing an integrating sphere and a PMT. The scattering measurements are then normalized to the light collected by the monitor PMT to eliminate data scatter due to shot-to-shot variations in laser output. The stray light level, determined from Rayleigh scattering measurements on argon gas, was equivalent to the Thomson scattered light from a plasma with an electron density of 2×10^{12} electrons per cm^3.

Plasma Heating Results

<u>Ion Temperature</u>. - Fig. 7 shows the raw NPS energy distribution data for a helium plasma at several electrode voltages with the magnetic field held fixed.[2] These curves are <u>not</u> typical of a simple Maxwellian energy distribution. To obtain a good theoretical fit to these data using the forward-type calculation[7], it was necessary to superimpose an azimuthal drift motion on a randomized energy distribution. The drift velocity needed to fit the type of data shown in Fig. 7 was in agreement with the $\underline{E} \times \underline{B}$ drift velocity calculated using the measured radial electric fields[7] (from Langmuir probes) and magnetic fields. Note that the tail of the energy distribution shown in Fig. 7 extends smoothly beyond the value of the cathode voltage. Other data have been obtained for helium in which the tail of the distribution extends beyond 34 keV when the cathode voltage is less than 20 kV. Thus the NPS revealed that the plasma ion energy distribution is randomized rather than cut off at an energy equivalent to the cathode potential.

Fig. 11 is a plot of ion temperature obtained from the NPS against the ratio of power input, P, to the magnetic flux density, B, for a helium plasma. The power input, P, is the product of cathode voltage and total current to the two cathodes. The trend in Fig. 11 illustrates the need for higher voltage and current levels to achieve high ion temperatures at the higher magnetic fields. Thus, water-cooled electrodes were developed to accommodate the higher power levels. A trend similar to that shown in Fig. 11 was also obtained for a hydrogen plasma, but the maximum ion temperatures reached were about 1 keV for protons and 1.2 keV for molecular ions. These results, which indicate that the higher mass particles are heated to higher temperatures, were expected since the $\underline{E} \times \underline{B}$ drift energy is proportional to the ion mass.

Ion temperatures obtained from the optical monochromator had the same trends as the NPS results in Fig. 11. But the optical results, which were obtained using the first plasma model (see section on "Optical Monochromator"), were up to about 20 percent higher than the NPS results. This is to be expected since the first plasma model did not include the contribution to Doppler broadening caused by rotating plasmas with finite ion gyroradii. The second model was not yet available when these data were reduced.

<u>Electron Temperatures</u>. - Electron temperatures were obtained from optical line intensity ratios in helium. Electron temperatures ranged from about 17 to 31 eV. The large value of T_i/T_e, as well as the high ion temperatures and predicted high ion density, make the SUMMA plasma very attractive for the development of the submillimeter laser Thomson scattering method to measure ion temperatures.

ORIGINAL PAGE IS
OF POOR QUALITY

Advanced Plasma Diagnostics Systems Development in SUMMA

The development of plasma diagnostics is central to the controlled thermonuclear program. Plasma properties must be reliably measured to document progress, to further the understanding of the physical processes, and to develop scaling laws. Local measurements of electron temperature, electron density, ion temperature, and plasma space potential are needed for this understanding. Systems to detect plasma instabilities and characteristic frequencies are also needed. Ultimately, such diagnostics systems will be incorporated into the thermonuclear reactor control systems. SUMMA's steady-state hot-ion plasma and its combination of large volume and high magnetic flux density offer ideal conditions to develop the needed diagnostics systems.

Presently, two advanced plasma diagnostics systems are being examined under NASA University Grants. NASA Grant No. NSG-3057 was established at Rensselaer Polytechnic Institute with R. L. Hickok, Jr. and K. A. Connor as co-principal investigators. The purpose of this Grant was to carry out the evaluation and preliminary design of an ion beam probe diagnostic system for the SUMMA hot-ion plasma facility. The design is directed to SUMMA, but the concepts involved will represent a significant advance in the technology of plasma diagnostics, and will have general applicability to controlled thermonuclear fusion systems and other large-scale plasma devices. A NASA Grant is being negotiated with Massachusetts Institute of Technology with B. Lax and D. R. Cohn as co-principal investigators. The goal of this program is to perform a detailed study and specification of the laser, detector, and optical system requirements for performing a Thomson scattering determination of ion temperatures in SUMMA. The results of the RPI study, and the proposed MIT study are summarized below.

Heavy Ion Beam Probe (RPI)

The only known way to measure the plasma space potential without disturbing the plasma is heavy ion beam probing.[11] The heavy ion beam probe technique has been well established, but its application to large controlled thermonuclear reactors presents significant new problems. These problems were identified and potential solutions were devised as part of NASA Grant NSG-3057 at RPI.

The specific objective was the detailed design of a beam probe system for the NASA LeRC SUMMA plasma device. The design for this system incorporated new concepts for guiding the beam across the confining magnetic field and through the plasma and in detecting the secondary ions created in the plasma. If successful, these concepts will provide the solution to many of the problems that must be overcome in order to carry out beam probe diagnostics on reactor size plasma systems.

For all beam probe systems used to date, beam detection and energy analysis is performed outside the magnetic field. This requires that the average Larmor radius of the primary beam be about twice the effective radius of the magnetic field. Direct scaling of this technique to large plasma systems would require prohibitively high beam energies. For conceptual reactor designs, however, the plasma diameter is much less than the magnetic field diameter. In principle ion beam probing only requires that the Larmor radius of the beam be greater than the plasma radius. This criterion reduces the necessary beam energy to reasonable values but it presents some new problems in directing the lower energy beam across the strong magnetic confining field and analyzing and detecting the secondary ions inside the fields. Such an analysis technique may offer some advantages as well since it will be possible to make use of the magnetic field to evaluate the energy of the secondary ion beam.

It still appears that reactor size systems will require MeV beams, even if the proposed techniques for reducing the required beam energy are used. The problems associated with using MeV probing beams, the transport of low energy beams across the magnetic field and energy analysis of the secondary ions inside the magnetic field can all be addressed on SUMMA. Brute-force extrapolation of existing techniques would require the use of 1-2 MeV beams. Lower energy beams can be used by developing appropriate transport systems for guiding the beam across the field and by carrying out the energy analysis inside the field. The relatively long, small diameter entrance ports on SUMMA are similar to those expected on reactor size systems and consequently provide a realistic restriction on the design of the beam transport system.

Primary and secondary ion orbits were determined for ion beam energies ranging from 50 keV to 5 MeV in the SUMMA magnetic fields. These orbits revealed that energy analysis inside the magnetic field region required 150 to 500 keV beam energies while external energy analysis required 1.4-1.6 MeV beam energies. The lower energy technique is being pursued for the present because it represents the more significant advance in beam probing, i.e., the use of the confining B field in the energy analysis and the design of the beam transport system.

The two system constraints of port access and the lower beam energy were not compatible with existing beam probe designs; the long ports in the SUMMA magnet spacer and highly curved low energy orbits made it impossible to directly inject the beam across the magnetic field. In concept this difficulty can be overcome by the development of an electrostatic charged particle guidance system that permits the beam to originate outside the magnetic field and be guided to the plasma. This is a variation on a Wein velocity filter in which the kinetic energy of the beam is allowed to vary along the trajectory. While trajectory calculations have been carried out with specific reference to SUMMA, the concept appears applicable to any large, high magnetic field device. This system should provide considerable flexibility in directing probing ion beams through complex physical support structures as well as assisting in the penetration of large magnetic volumes.

Various techniques were considered for sweeping the beam to produce a detector line with adequate spatial resolution. A variation in beam angle of $\pm 0.2^{\circ}$, using sweep plates near the gun, was calculated to produce a sweep of approximately ∓2 cm in the plasma region. Use of the potential distribution in the electrostatic guidance system for this purpose did not seem feasible because the orbits are too sensitive to changes in the higher (positive) potential and not sensitive enough to changes in the lower (sometimes negative potential).

An energy analyzer has been designed for use in inside the cylindrical vacuum chamber of SUMMA. It is similar to electrostatic energy analyzers used previously with ion beam probe systems, but the non-negligible B field in the analyzer is used to provide a zero order momentum analysis and the electric field is used only to correct for the variation in the beam energy due to the space potential. This reduces the required analyzer voltage but complicates the extraction of the space potential from the applied field.

The physical location and dimensions of the analyzer are chosen such that the secondary beam used to determine the potential in the center of the plasma through the analyzer field is centered on the detector plates with $\underline{E} = 0$. Any other energy beam requires $E \neq 0$ to be so centered. Because the path of the beam through the analyzer depends primarily on $\underline{B}$ field, there is no simple mathematical relationship to provide calibration. However, a calibration curve can be obtained numerically in a straight-forward manner.

Submillimeter Laser Thomson Scattering (MIT)

Since ion temperatures determined from either the NPS or optical monochromator depend on the presence of charge-exchange neutrals, their usefulness will diminish as the plasma improves. For a fully ionized plasma of fusion-like density and temperatures, neutrals will not penetrate very far into the plasma. Hence, charge-exchange dependent phenomena will only yield information about the plasma surface. Submillimeter-wavelength laser Thomson scattering[12] offers the ability to measure local ion temperatures and possibly some plasma instabilities for the fully ionized plasma. This diagnostic method is still in the stages of laser development and scattered signal detector development.[12,13] The system will make use of a megawatt CH_3F laser and a heterodyne detection system employing Schottky-barrier diode detectors. Recent advances[12,13] in the development of both the high power 496 μm CH_3F laser and the Schottky-barrier diode detector now make such a system study feasible.

Requirements for Ion Thomson Scattering. - Spatially resolved direct measurements of ion temperatures in fully ionized, high temperature, clean plasmas may only be obtained by ion Thomson scattering measurements. Until now, these measurements were not possible in plasmas in the 10^{12} to 10^{14} cm^{-3} range because of the absence of high power long wavelength (i.e., submillimeter) laser radiation. Shorter wavelength is not acceptable for ion temperature measurements because it results in prohibitively small scattering angles.

The relative importance of electron and ion scattering is determined by the value of α, where

$$\alpha = \frac{\lambda_o}{4\pi\, \lambda_d \sin(1/2\theta)} \tag{1}$$

and λ_o is the laser wavelength, λ_d is the Debye length, and θ is the scattering angle. If $\alpha \gtrsim 3$ the ion scattering dominates. With $\alpha \geq 3$ and $T_i/T_e \gtrsim 2$ the scattered radiation has a Gaussian spectral distribution. The full width at half maximum of this distribution is $\Delta\omega = kV_T$ where V_T is the ion thermal velocity, and $k = 2\pi/\lambda_o \sin(1/2\theta)$ is the scattering vector. In the SUMMA plasma, $T_i/T_e > 10$. Only the larger Tokamaks, which will not be available for several years, will satisfy the criteria $T_i/T_e \gtrsim 2$. According to experiments in SUMMA[2] and to scaling laws developed at ORNL,[3] the SUMMA plasma will provide a high T_i, a low $T_e (T_i/T_e > 10)$ and high ion density (10^{13} to 10^{14}/cm^3). Hence, the SUMMA plasma is ideally suited to establish the proof of principle for this diagnostic in a short time. For $\lambda_o = 496\ \mu$m, $n_e = 10^{13}$ cm^{-3}, and $T_e = 50$ eV; T_i is readily determined if $\theta \lesssim 135^o$. Thus, the existing ports in SUMMA which allow for 90^o scattering experiments are suitable for this experiment. For $T_i = 2$ keV, $\Delta\omega$ will be about 1 GHz.

The power scattered from a thermal plasma and received by a detector at angle θ is

$$P_s(\theta) = P_o n_e \sigma \ell\, d\Omega \tag{2}$$

where P_o and P_s are the incident and scattered powers, $\sigma = 4\times10^{-26}$ cm^2 is the Thomson scatter cross section per solid angle, ℓ is the length of the scattering region in the field of view of the detector aperture, and $d\Omega$ is the solid angle subtended by the detector aperture at the scattering region. For $P_o = 1$ MW, $n_e = 10^{13}$ cm^{-3}, $\ell = 5$ cm and $d\Omega = 10^{-3}$, $P_s = 2\times10^{-9}$ watt. This level of scattered power should be detectable with the Schottky-barrier diode heterodyne detection system under development.

Laser Development Program. - Inversion in the 496 μm CH_3F laser is obtained by irradiation with a 9.55 μm P(20) CO_2 laser pump in a zig-zag fashion.[13] Theoretical considerations and experiments[13,14,15] indicate the power levels obtained from CH_3F will scale at least linearly with CO_2 pump power. CH_3F radiation in the megawatt range will require the use of gigawatt level CO_2 pump radiation. The development of a 200 kW CH_3F laser system is under way at the MIT National Magnet Laboratory under ERDA sponsorship.

Heterodyne Detection System. - Based on the present experimentally determined minimum detectable power of a nitrogen-cooled Schottky-barrier diode in the heterodyne mode,[16,17] a signal-to-noise ratio of 2.2 should be attainable at a plasma density of 3×10^{13} cm^{-3}. This is based on scattering a 1 megawatt laser beam and sampling 10 frequency intervals in the 1 GHz bandwidth. Detector development at the MIT Lincoln Laboratory is aimed at improving the signal-to-noise ratio by a factor of 100. The detector development work is being supported by ERDA.

Optical System. - The optical system for the CH_3F laser Thomson scattering diagnostic will involve lenses or mirrors to focus the radiation from laser onto plasma. The diameter of the beam which emerges from the laser will be on the order of 15-20 cm. A lens or mirror system will be needed to focus the scattered laser radiation on the detectors. The trade off between increasing solid angle of detection and decreasing resolution will be investigated. Beam dump geometry will be studied and an appropriate absorber of submillimeter radiation will be chosen. Detailed studies of the appropriate optical system for SUMMA will be made in close collaboration with the SUMMA group at LeRC.

References

1. J. J. Reinmann, et al., Proc. Fifth Symp. Eng. Problems of Fusion Research, Inst. Electrical and Electronics Engs., 1973, pp. 587-591.
2. J. J. Reinmann, et al., IEEE Trans. on Plasma Sci. PS-3, 6 (1975).
3. ORNL-4688, Oak Ridge National Lab. (1971).
4. D. R. Sigman, and J. J. Reinmann, NASA TM X-2783 (1973).
5. D. R. Sigman, J. J. Reinmann, and M. R. Lauver, NASA TM X-3033 (1974).
6. J. J. Reinmann, M. R. Lauver, R. W. Patch, R. W. Layman, and A. Snyder, NASA TM X to be published.
7. G. W. Englert, J. J. Reinmann, and M. R. Lauver, Plas. Phys. 17, 609 (1975).
8. C. F. Barnett, and J. A. Ray, Nuc. Fusion 12, (1972).
9. R. W. Patch, D. E. Voss, and J. J. Reinmann, NASA TM X-71635 (1974).
10. G. W. Englert, R. W. Patch, and J. J. Reinmann, NASA TM X to be published.
11. F. C. Jobes, and R. L. Hickok, Jr., Nuc. Fusion 10, 195 (1972).
12. B Lax, and D. R. Cohn, IEEE Trans. on Microwave Theory and Techniques MIT-22, 1049 (1974).
13. D. R. Cohn, private communication.
14. F. Brown, et al., Optics Comm. 9, 28 (1973).
15. F. Brown, S. Kronheim, and E. Silver, Appl. Phys. Lett. 25, 394 (1974).
16. H. R. Fetterman, et al., Appl. Phys. Lett. 24, 70 (1974).
17. H. R. Fetterman, et al., Intern. Conf. on Submillimeter Waves and Their Applications, Inst. Electrical and Electronics Engrs. Soc. on Microwave Theory and Techniques, 1974, pp. 93-94.

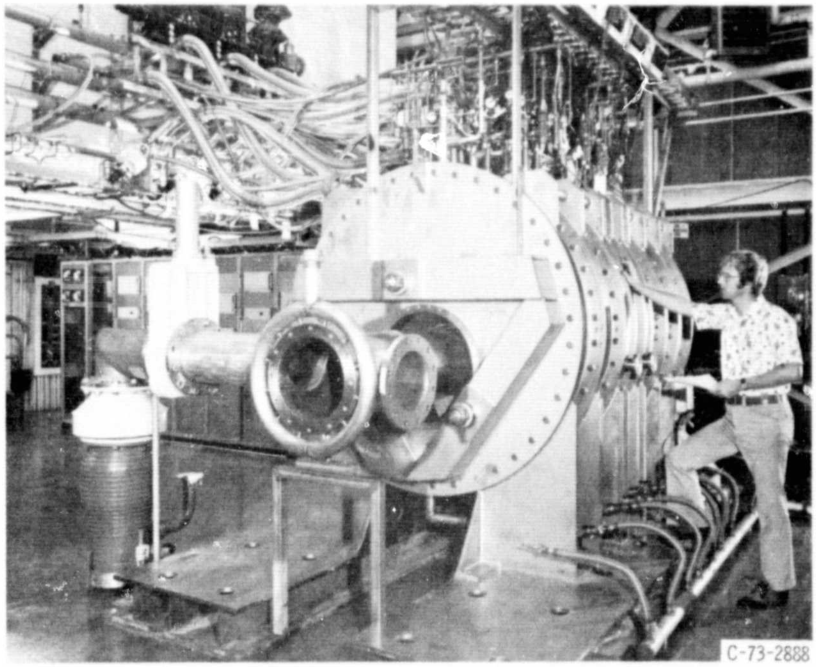

Figure 1. - SUMMA facility.

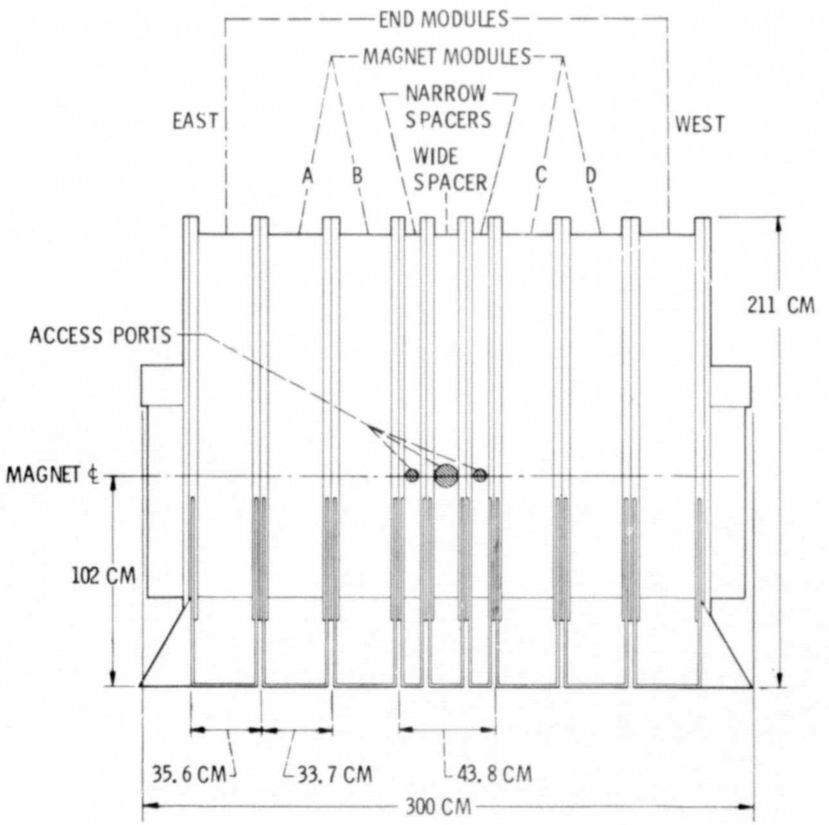

Figure 2. - Side view of SUMMA in simple mirror arrangement.

CS-68539

PRECEDING PAGE BLANK NOT FILMED

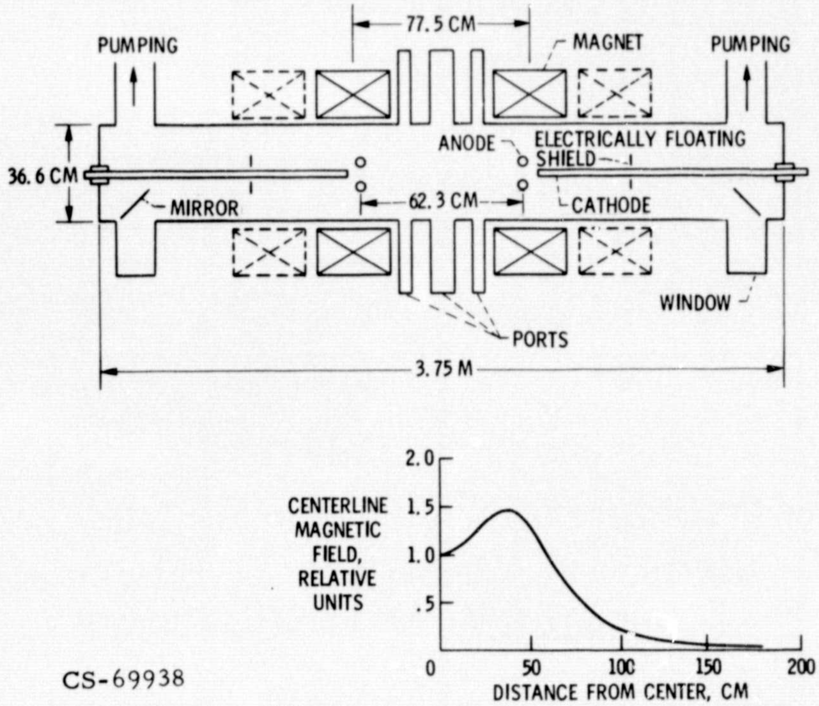

Figure 3. - SUMMA test section and magnetic field.

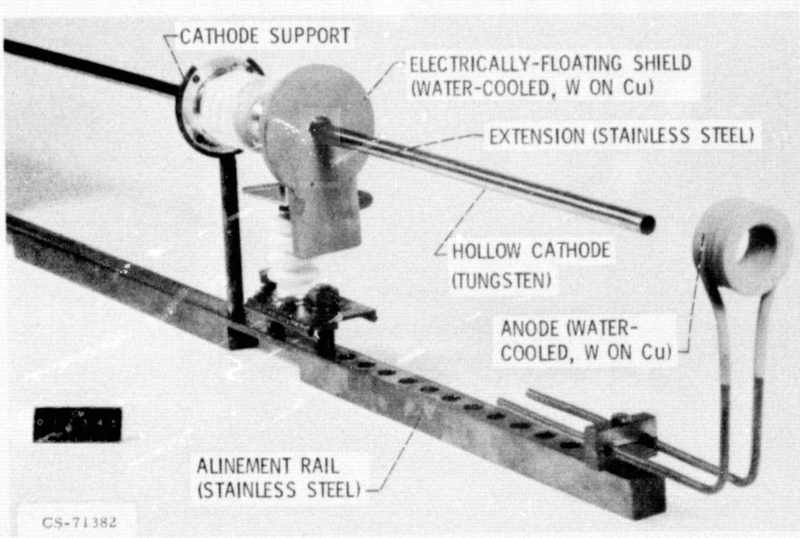

Figure 4. - SUMMA electrode assembly.

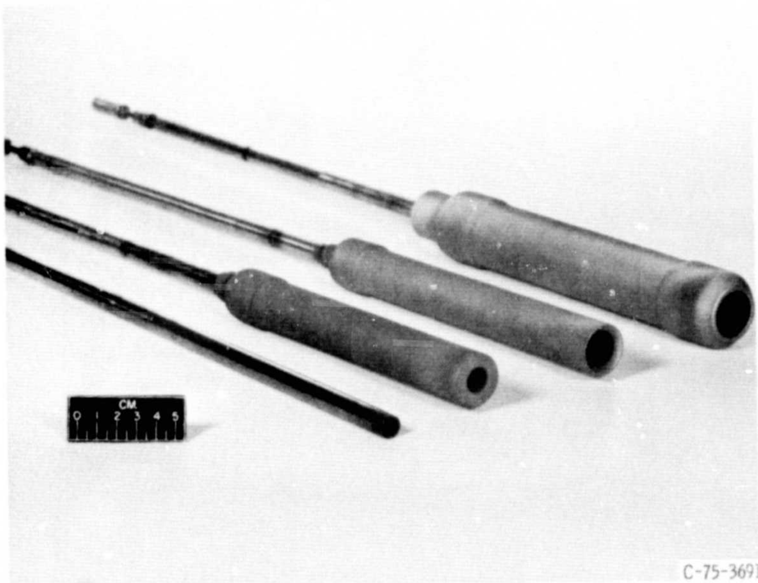

Figure 5. - Tungsten cathode and three water-cooled cathodes.

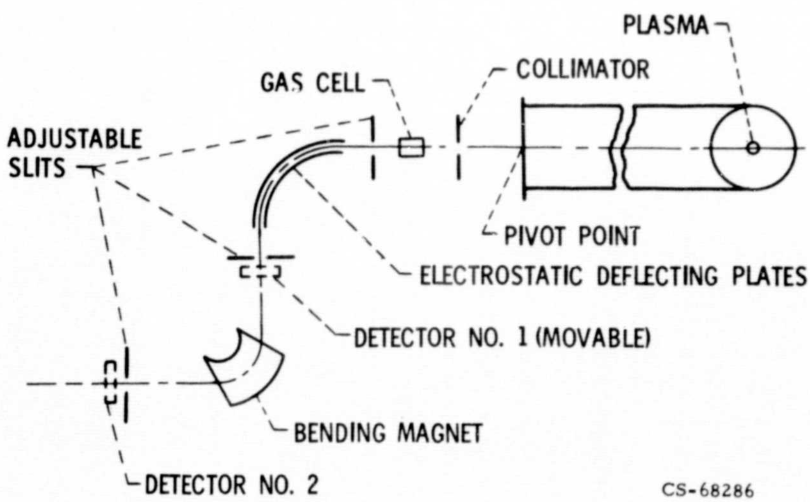

Figure 6. - Change exchange neutral particle analyzer.

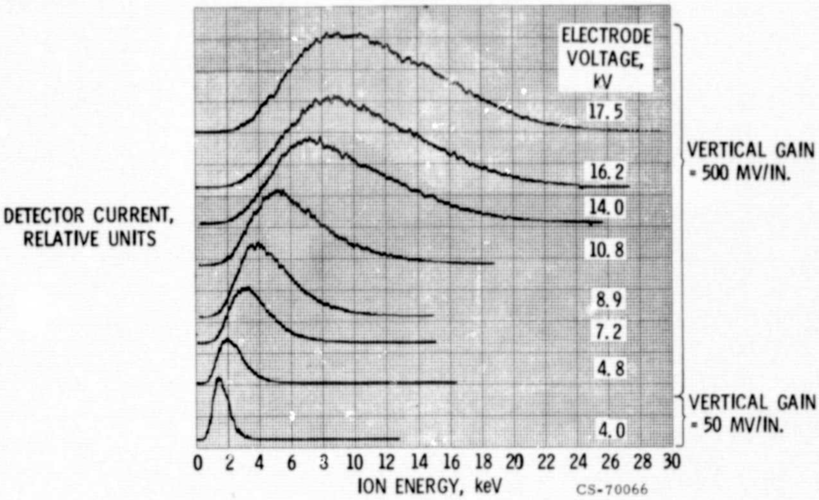

Figure 7. - He^+ energy distributions for eight electrode voltages.

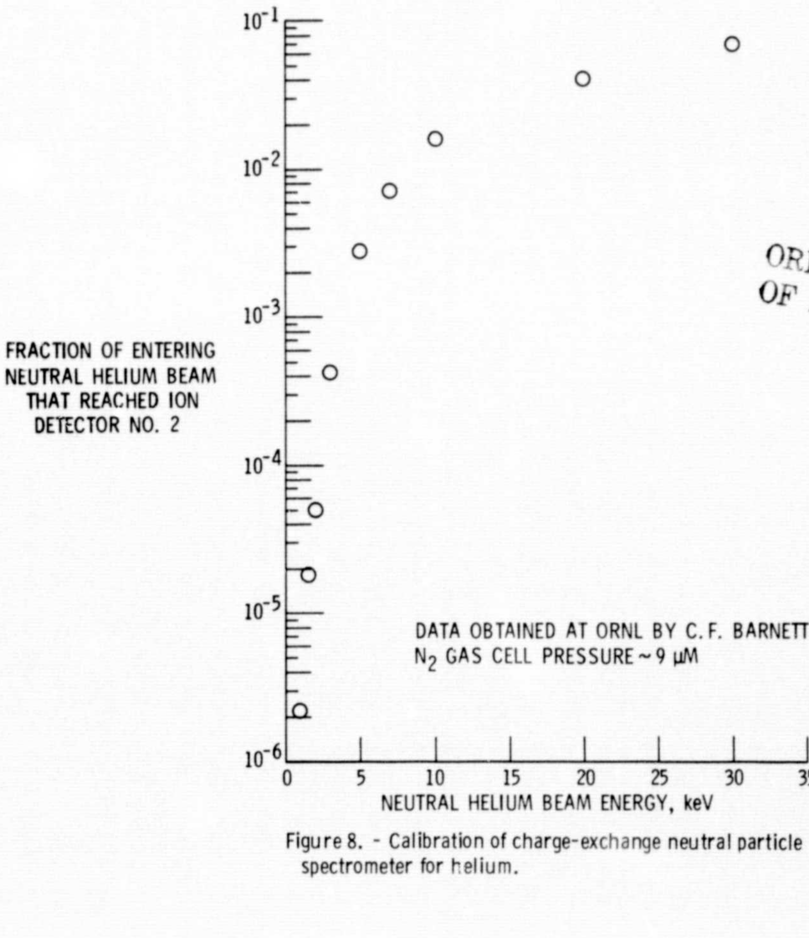

Figure 8. - Calibration of charge-exchange neutral particle spectrometer for helium.

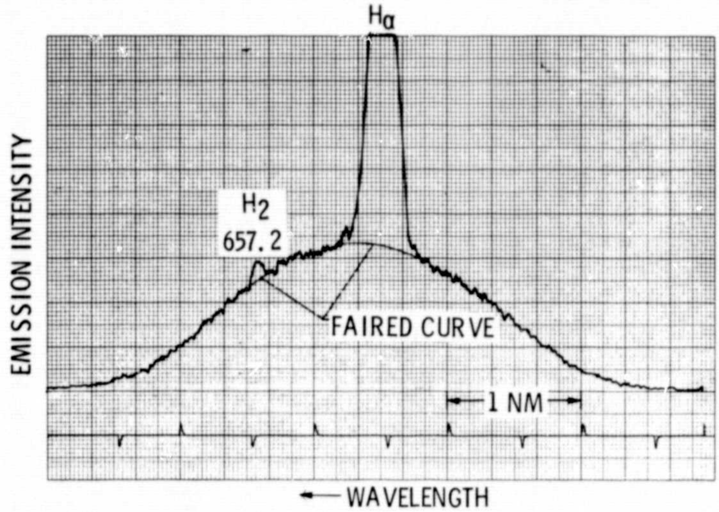

Figure 9. - Typical H_α line exhibiting wide and narrow components.

E-8563

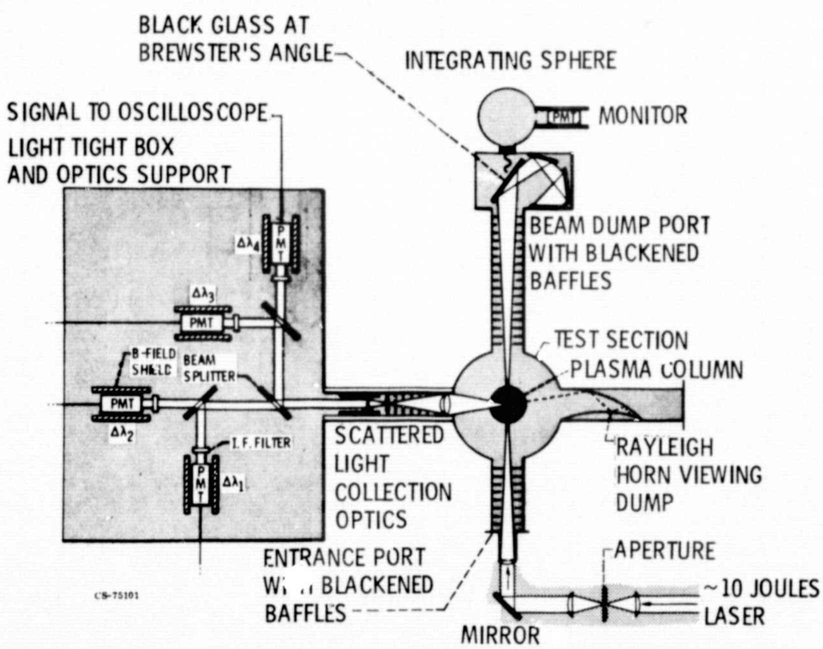

Figure 10. - Laser Thomson scattering apparatus schematic.

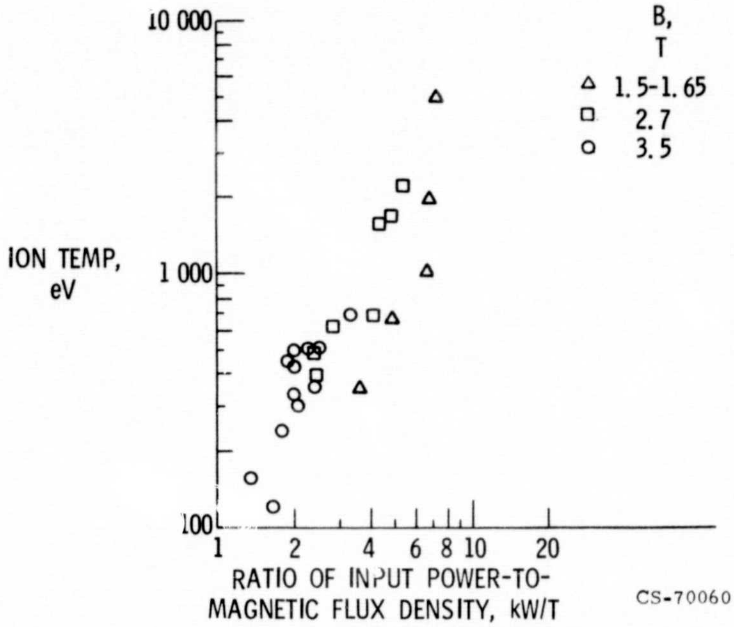

Figure 11. - He^+ ion temperature vs. P/B from NPS.