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PREPRINT UCRL- 81240

Lawrence Livermore Laboratory

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August 15, 1978

This paper was prepared for submission to the XVII Annual Enrico Fermi Summer School on Plasma Physics, September 4-16, 1978, Varenna, Italy.

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DIAGNOSTICS FOR MIRROR MACHINES*

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ABSTRACT

This paper is subdivided into three chapters to match three corresponding lectures. The goals of the first chapter are to define the neutral-beam-heated, quasi-d.c. mirror confinement systems under discussion here and to give a general example of mirror diagnostics by listing and very briefly discussing the diagnostics used on the 2XIB experiment at the Lawrence Livermore Laboratory. The second chapter develops mirror machine diagnostics in more detail, and adds background for a few selected diagnostics of particular importance to mirror machine studies. The third chapter discusses the special diagnostic needs of future mirror machines, with emphasis on diagnostics involving the higher-power neutral beams used with them.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7495-ENG-48.

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CHAPTER 1. INTRODUCTION TO MIRROR CONFINEMENT DIAGNOSTICS

1.1 Introduction

The practical use of the fusion reaction requires some type of hot-plasma confinement to attain the $n\tau \sim 10^{14}$ required by the Lawson Criterion. Magnetic and inertial confinement are the two main approaches now under study. Magnetic confinement can be subdivided into closed-magnetic field confinement (e.g. toroidal tokamaks) or open-ended (mirror) confinement. This paper is specifically directed toward diagnostics for d.c. or quasi-d.c. mirror confinement systems.

First, a brief physics orientation: Because the magnetic moment $\mu = W_\perp/B$ of a charged particle orbiting in a magnetic field is conserved, a particle with total energy W and a magnetic moment μ is reflected (or mirrored) when it encounters a higher magnetic field B_m such that $W = \mu B_m$. Particles with $W > \mu B_m$, however, would either continue to penetrate to even higher fields or if the B_m represented the peak mirror barrier, would be lost. This criterion for reflection is responsible for a "loss-cone" group of particles in phase space being missing from the distribution function for particles trapped in a mirror confinement system (i.e., between two mirror barriers). The ratio of the barrier field B_m to the weaker central field B_0 is referred to as the vacuum mirror ratio R . Another constant of motion for a mirror-trapped particle is the action or longitudinal invariant $J = \oint p_{\parallel} dv_{\parallel}$. A third somewhat weaker invariant is the conservation of the magnetic flux bundle encircled by a particle orbit. These three invariants are very useful for theory and diagnostics, since the orbital extent and bounce time can change only slowly and the charged particle losses from the confinement interior map out to end-wall surfaces with $W \propto W_\perp$ as $B \rightarrow 0$.

However, the conservation of μ for charged particles entering from outside such a mirror confinement system introduces the problem of how to trap the desired hot plasma within the central confinement region. The best solution to this problem appears to be using the recently available high-power neutral beams to inject the hot particles into the confinement region as neutrals and then attaining trapping through ionization either on an initial target plasma or ultimately on the buildup hot plasma.

The fundamental loss process from open-ended confinement results from Coulomb scattering of particles into the loss cone with

$$\pi_{i,e} = \frac{1}{2} \frac{W_{i,e}^{3/2}}{B_{i,e}} \quad (1)$$

For plasma confinement systems of interest here with $T_e \ll T_i$ (with $W_{i,e} = 3/2 kT_{i,e}$) electron losses would dominate except that the buildup of a positive ambipolar plasma potential ϕ over a sheath region reduces the electron loss rate and increases the ion loss rate until there is no net change flow. Thus, from a simplified view typical mirror systems involve confinement of a hot-ion (loss-cone depleted) distribution with

$$v_{\perp}^2 > \left(\frac{2e\phi}{m} + v_{\parallel}^2 \right) / (R_{\text{eff}} - 1) \quad (2)$$

and electrostatic confinement of a nearly Maxwellian electron population. Two further mirror loss processes also affect present mirror research. First, a simple (azimuthally

symmetric) mirror system is magnetohydrodynamically flute or interchange unstable (i.e. $\beta_1/B > 0$). These instabilities have led to the development of minimum [8] magnetic wells formed by coils of the baseball seam or yin-yang type. Second, the missing loss-cone in the confined ion distribution theoretically makes the plasma susceptible to microinstabilities. Predictions by Post [1] and Baldwin et al. [2] and recent experiments by Coensgen et al. [3] show that the drift-cyclotron loss-cone (DCLC) instability can be effectively stabilized by use of a warm plasma stream flowing through the system and filling part of the missing ion population in the loss cone.

The warm-ion to hot-ion density fraction n_w/n_h that Baldwin et al. [2] predict is necessary to stabilize the DCLC instability in the 2XIIIB experiment at Lawrence Livermore Laboratory (LLL) with $v_h/v_H < a_i/r_p$ is

$$\frac{n_w}{n_h} > \left(\frac{v_h}{v_H}\right)^2 \left(\frac{a_i}{r_p}\right)^{4/3} \quad (3)$$

In Eq. (3), v_h is the ion velocity appropriate to the ambipolar loss-cone hole e.g., v_h from Eq. (2) with $v_{||} = 0$, a_i is the hot ion gyroradius, r_p is the plasma radius, and the a_i/r_p dependence is scaled by Correll et al. [4] to fit recent 2XIIIB data. Unconfined warm plasma of this density implies a minimum stabilizing stream current density for the warm plasma of

$$j_{st} \sim \frac{1 \times 10^{-11} n_h T_h^{3/2}}{(R_{eff}-1) (M_i)^{1/2} M_i} \left(\frac{a_i}{r_p}\right)^{4/3} \text{ A-cm}^2, \quad (4)$$

where T_h and M_i are in keV, M is in a.u., n_h is the hot density/cm³, and $R_{eff} = R_{eff}(1 - \Delta B/B)^{-1}$.

Thus, this discussion of diagnostics is directed primarily at studies of stream-stabilized, hot-plasma confinement in neutral-beam-injected, minimum [8] mirror configurations. Compared with tokomaks, mirror machines generally have higher ion temperatures and a higher plasma $\beta = n(kT_i + kT_e)/B_{vac}^2/8\pi$, and thus higher energy fluxes at the walls.

1.2 Example of Mirror Machine Diagnostics: 2XIIIB Arrangement

The 2XIIIB experiment at LLL is at the forefront of mirror machine research in the United States, with operation by (Simonen et al. [5]) including buildup of 9 to 13-keV D⁺ plasmas at densities up to $\sim 10^{24}/\text{cm}^3$.

A cutaway view of the neutral-beam injection arrangement for 2XIIIB is shown in Fig. 1; together with some early plasma-buildup curves taken with and without gas-box stabilization. Each of the 12 neutral beams shown includes a Lawrence Berkeley Laboratory (LBL) 20-kV ion source capable of up to 50-A equivalent output of D⁰ after charge exchange in the neutralizer cell. The plasma used for startup came from a D₂-loaded Ti washer gun and the stabilizing gas was injected from a gas box located just outside the end of one mirror.

An artist's sketch of the diagnostic arrangement for the 2XIIIB experiment is shown in Fig. 2; a plasma with a central diameter of ~ 20 cm is included for relative scale. Many of the diagnostics shown are common to other controlled fusion approaches and are covered by other lecturers. Here, we present a brief description of typical diagnostics and associated machine conditions; a more detailed discussion of selected mirror/particle-oriented diagnostic techniques is deferred until Chapters 2 and 3.

Figure 3 shows computer listing of the machine condition and diagnostics available for a recent 2XIIIB data shot. The upper set of output refers to the magnetic field configuration, the plasma gun array used for startup, the status of the gas box or streaming-plasma guns used for stabilization, and associated timing. Typical plasma input shown conceptually in Fig. 4 includes

- Use of one or more plasma guns for startup. Typically, $\sim 10^{18}$ ions/gun are supplied in a ~ 1 -ms pulse with $W_{H_1} \sim 200$ to 400 eV.
- Injection from 12 neutral-beam sources of up to ~ 500 -A equiv. D^0 in a pulse of up to 10-ms duration and with a mean energy $\bar{W}_i \sim 13$ keV. Trapping is $\approx n_i$; in 2XIIIB, typical total beam attenuation is $\sim 80\%$, of which $\sim 25\%$ is ionized and trapped and the remainder attenuated by charge exchange on hot ions (thus contributing only through minor heating).
- Stabilization through use of a gas box with 100-to-600 A D^0 available. Only a small fraction heated by rf can penetrate the mirror and ambipolar barrier.

The lower computer listing of diagnostics shown in Fig. 3 is too extensive for discussion as part of this example; details are therefore left to Ch. 2. However, to round out the diagnostic picture Table 1 lists a few selected parameters with their associated diagnostic techniques and compares typical values measured for 2XIIIB, predicted for the Tandem Mirror Experiment (TMX), or predicted for the Mirror Fusion Test Facility (MFTF). Brief operational details of these machine are included for reference. Note the very high plasma β and high ion temperature achieved in 2XIIIB. Such high β operation reduces classical end losses, since $R_{eff} = R_{vac}/(1-\beta)^{1/2}$, and suggests that mirror confinement is compatible with a compact high power density fusion reactor. The physics modeling of the energy balance implied by the parameters of Table 1 requires an energy-flow model such as shown in Fig. 5 and discussed further in Ch. 3. Briefly, an analysis of the nT_e achieved in 2XIIIB indicates that τ_E is the limiting factor, and that it is dominated by drag on the cold electrons for lower-beam, relatively impure shots and by rf turbulent diffusion for the best high-beam shots. In general, the higher the T_e the less the electron drag loss, but since the ambipolar potential $\phi \approx T_e$ this widens the loss-cone, causing increased instability problems. The need for both higher T_e and increased stability leads to consideration of new machines discussed below.

1.3. Examples of Future Mirror Machines and Associated Special Diagnostics

The goal of warm-stream-stabilized mirror confinement is a relatively compact and economical fusion reactor. Progress toward this goal can be seen from the 2XIIIB results. Thus, a next step is the large experiment called MFTF that is now under construction at LLNL;

startup is planned 1981. MFTF uses a superconducting yin-yang coil set for confinement and an array of 24 new 80-keV ion sources to inject an expected 750-A D^0 equivalent at a mean energy of 50 kV (because the ion source beam includes a mixture D^+ , D_2^+ , and D_3^+). Parameters scaled up from 2XII B operation are shown in Table I, with a predicted $n_{Te} \sim 10^{12}$.

A general problem for the mirror confinement approach to a fusion reactor has been the predicted low $Q \leq 1$, where Q is defined as the ratio of fusion power yield to the equilibrium power input. One approach to accommodate a somewhat low Q is use of high-efficiency direct (ion) energy recovery (Barr et al. [6]) for the ions lost out the ends of the reactor or for neutral-beam-related ion dumps. Another recent very promising approach proposed by Fowler and Logan [7] at LLL and independently by Dimov [8] at Novosibirsk is the tandem mirror concept in which end cells (plugs) electrostatically confine low-energy ions in a central cell, the result being to increase n_i and make $Q \sim 5$ feasible.

Thus, the 2XII B experiment has recently been shut down (except for very limited tests), to make way for the TMX planned for startup in late fall of 1978 at LLL. TMX utilizes a pair of yin-yang confinement coil sets as end plugs for a long connecting central cell. The goal here is to arrange neutral-beam injection so as to allow the end cells to have a higher ambipolar potential than the central cell. In TMX, the long central volume should electrostatically trap enough cold ions for the plasma to be stable and attain the desired classical n_i . The higher-energy ions scattered out over the electrostatic barrier would serve as stabilizing plasma streams for the end plugs. The neutral-beam requirements for this are (a) relatively high neutral-beam energies injected at the end plugs, and (b) either gas or higher-current low-energy neutral beams injected into the central cell. The physics and geometry for these new experiments will be described in much more detail in Dr. Condit's seminars.

CHAPTER 2: BASIC MIRROR MACHINE AND PARTICLE DIAGNOSTICS

2.1 Introduction

This chapter is directed toward filling in the details of mirror-machine-oriented diagnostics. Many plasma diagnostics are similar whether used on mirror machines or tokomaks. Here, I shall try to minimize overlap with other lectures by accentuating several particle techniques particularly appropriate to mirror machines for example, gridded electrostatic detector/analyzers useful for measuring the ion flux escaping from the loss cone.

2.2 End Flux Measurements with Gridded Detector/Energy Analyzers

Individual detectors or large area arrays of gridded detectors are in common use at the vacuum walls by the plasma end fans (where $B \ll B_m$) to measure the current density and distribution of escaping ions as a function of time. A typical gridded detector used by

Cham et al. [9] is shown in Fig. 6. Note the segmented collector plates arranged for spatial analysis of the loss-cone flux at the far wall. In some applications, grid biases are varied to determine the ion currents above some selected minimum energy, e.g., to determine the minimum ion energy cutoff and thus the ambipolar potential.

Gridded detectors are certainly not new, so for a general reference see Stephanakis and Bennett [10]. Here, discussion will center on features particularly relevant to higher energy and higher current density use. Clearly, details of a specific experiment will determine much of the design, for example, the size and shape of the aperture to intercept the desired sample, and the distance to the detector adjusted for field expansion to limit the flux current densities to a value less than or equal to the space-charge-limited current density. Items of fundamental concern are discussed in the following paragraphs.

2.2.1 The Grid Mesh Size

Most precision, gridded, electrostatic analyzers are very careful to use grid aperture dimensions $\leq \lambda_{\text{Debye}}$ where

$$\lambda_{\text{Debye}} = (kT_e/4\pi n_e e^2)^{1/2} \approx 7.4 \times 10^2 \left(\frac{T_e(\text{eV})}{n/\text{cm}^3} \right)^{1/2} \quad (5)$$

If this restriction is satisfied, there will not be significant plasma sheath formation around the grid wires, and the detector or analyzer behaves in the single-test ion/electron mode. However, the potential barrier in the single grid plane can still be appreciably below that of the wire grid. Spengenberg [11] provides a good discussion of the vacuum potentials for a variety of grid configurations. Here, as an example, the vacuum field midway between two typical grid wires of radius r and separation a has been evaluated by Barr [12] as

$$V_{(a/2)}/V_g = [\pi d/a - \ln 2] / [\pi d/a - \ln(2\pi r/c)] \quad (6)$$

for $(2\pi r/a) \ll 1$ and where d is the grid spacing to either adjacent wall. This tendency for potential holes between grid wires can be largely reduced by using a double grid.

The restriction of a mesh aperture size $\leq \lambda_{\text{Debye}}$ is not really necessary, providing care is taken of plasma effects. In particular, the electrostatic field must be applied so that the space-charge-limited current is not exceeded during electron separation; otherwise, a plasma-induced breakdown is probable. Ion sources operate in this mode successfully over long pulses, though for carefully limited conditions of the plasma meniscus surface.

2.2.2 The Number of Grids and Their Potential Distribution.

No fixed rule for the grid number appears warranted. In general, the first grid is always at wall potential to keep the diagnostic from interfering with the plasma to be measured. For ion detection and energy analysis, the second grid has classically been biased negative to suppress electrons and the third grid biased positive to enable ion energy analysis before the final collector plate. However, a "filter" connection with the second grid biased positive for retarding ion energy analysis and the third grid negative for electron removal appears to be subject to less error or secondary emission problems (Stephanakis and Bennett [10]). This filter type of detector bias was used by Molvik [13] on 2X1B. In general, people try to make the grids as transparent as possible, with the possible exception

of the first-wall grid, where low transparency can be used to reduce the ion current density if it is near space-charge limits. The material for these large-area detector grids is another consideration; stretched Mo or W wire or mesh are most frequently used, though etched Ni is most available commercially. Some references [10] suggest coatings of dispersed carbon on grids and collector plates to avoid the variable impurity layer problem and to generally reduce secondary emission.

2.2.3 Space-Charge Limited Currents.

For an ion current of density j , mass m , charge q , and kinetic energy W incident upon a electron-suppressing grid of negative potential V spaced a distance L from the $V = 0$ reference entrance grid one can show [Osher and Porter [14]] that

$$j_{s.c.l.} = \frac{2}{9\pi} \left(\frac{2e}{m/q} \right)^{1/2} \frac{V^{3/2}}{L^2} \left[\left(\frac{W}{V} + 1 \right)^{3/4} + \left(\frac{W}{V} \right)^{3/4} \right]^2$$

$$= \frac{1.72 V (kV)^{3/2}}{(M/q)^{1/2} L^2 (cm)} \left[\left(\frac{W}{V} + 1 \right)^{3/4} + \left(\frac{W}{V} \right)^{3/4} \right]^2 \text{ mA/cm}^2. \quad (7)$$

2.2.4 Secondary Emission and Surface Effects.

Some combination of measures is usually taken to reduce secondary emission, since loss of an electron from the collector is indistinguishable from the collection of a positive ion; if other effects are neglected, $I(\text{meas}) = I_0(1 + \gamma_e)$. A common measure to prevent electron escape is either use of a fourth negatively biased grid just in front of the collector plate or use of a locally strong B_z field at the collector surface. A common technique to reduce secondary emission is use of Mo, W, or C collector plates. The "filter" mode grid biasing discussed in Sec. 2.2.2 suppresses secondary emission directly. Figure 7(a) shows a typical γ_e vs H^+ energy curve for 90° incidence on Cu (e.g. See Osher [15]). If the detector is exposed to an appreciable source of impurity ions having a high charge state, metastable or energetic neutrals, or vacuum ultraviolet (VUV) photons, the requirement for γ_e suppression for meaningful analysis is that much more severe.

A second surface effect that should also be considered both during use and during calibration is the probability that low-energy ions back scatter from the collector with a fraction of their incident energy. Den and Robinson [16] give theoretical and predicted curves for many materials; $\gamma(\text{Ref.})$ and $\gamma(\text{energy refl.})$ for $90^\circ H^+$ incidence on Cu are given in Fig. 7(b). Most back-scattered particles should be neutral, although equilibrium target fractions of positive and negative ions are also expected for the appropriate energy.

2.2.5 Calibration/Transparency

If carefully designed, gridded detectors yield simple absolute measurements of the incident ion flux over a known area. One way to measure the effective transparency for a gridded detector stack is to simply measure light attenuation through the grid assembly

(with the collector removed) with a collimated light beam incident on a photo cell. Here, internal reflections could be a problem unless grid surfaces are matte black (generally, the method is satisfactory with Mo or W wire and good when surfaces are covered with C or dispersed carbon [10]). A second more elaborate technique is use of a known ion beam to calibrate the detector signal against a similar area (preferably deep cup) calorimeter (e.g., Osher and Porter [14]).

2.2.6 Use As An Energy Analyzer

Use of gridded detectors is generally limited to less than a few keV ions by corona and breakdown problems. Electrons accelerated to only 50 eV can ionize the background gas efficiently and possibly set up a Penning discharge region if sufficient background gas and a magnetic guide field ($B \gg 10^{-2}$ T) are present. Similarly, ions of a few hundred eV can backscatter and/or create electrons through secondary emission.

An ion cutoff energy $e\phi \sim 160$ eV was measured by Foote [9] for low-density, quiescent plasma confinement in Baseball II. For plasmas with higher rf fluctuation levels, the cutoff is not clear, making ϕ measurements subject to large error.

2.3 Higher Energy End Flux Measurements

Present measurements of the hot ion density and energy distribution function tend to be based on radially located neutral particle analyzer data. This is appropriate to present confinement experiments where the hot confined ion velocity is peaked near 90° and the neutral beam is available for a charge exchange target. However, as confinement becomes more classical, and the machines of sufficient nl to limit neutral particle analysis to boundary regions, the detailed measurement of the energetic end flux will become more important. For this purpose the whole array of higher energy electrostatic analyzers and magnetic analyzers are available for small sample measurements with a suitable collimated nonadiabatic transition between the confinement end field and the analyzer field.

For example, high momenta impurity ions naturally expelled out the open-end by the ambipolar potential can be analyzed with a simple magnetic analyzer (Osher[17]). Use with an array of solid state detectors in the counting mode would allow measure of mv/q and $1/2 mv^2$ (for sufficiently energetic ions). In the current mode with either Faraday cups or high gain detectors only mv/q signals would be available as a function of time, thus requiring additional information for unique identification. In any case use of such a magnetic analyzer requires that the B (analyzer) $\gg B$ (shielded confinement fringe field).

2.4 End Flux Calorimetry Measurements

A set of simple, integrating end-loss calorimeters has proven useful for 2XIIIB. The calorimeters used by Milen et al. [18] were chosen with a sensitivity to match the expected power flow (total ~ 1.5 MW deposited in 2XIIIB during an ~ 10 -ms pulse). The segmented calorimeters were located outside the mirrors to examine the energy flux mapping from the loss

cones. The deposited energy data obtained is subject to appreciable uncertainty from the large area integration with only a few samples but appears to show that end losses can approximately account for the total energy loss for 2XIIIB operation with $T_e \leq 60$ eV. However, for higher T_e operation an increasing portion ($\sim 1/2$) of the input energy cannot be accounted for by the end calorimeters. In either case the data also appears somewhat anomalous since the measured current flux times the expected energy integrated over the pulse is appreciably less than the measured total energy. This brings up questions about thermal conduction and secondary emission discussed in Ch. 3. It would be very desirable to develop an array of fast response end and radial calorimeters to allow full accounting of the energy flow.

2.5 Neutral Particle and Analyzer

Indirect measurement of the hot ion density and energy distribution is commonly done through hot plasma charge exchange with the neutral beam and analysis with a fast atom analyzer. With the ion velocity peaked by confinement toward high V_1/V_0 ratios, the analyzer is normally located radially near the midplane of the machine. Application of this technique to large machines will ultimately be limited by reionization of the exiting neutral and.

Here the 15-channel analyzer designed by Moxsen et al. [19] for 2XIIIB is shown in Fig. 8. This instrument uses a N_2 cell for stripping the neutral to an ion, a magnetic analyzer for mv/q separation, and finally electrostatic analysis for $mv^2/2q$ followed by a Daly-type photomultiplier-scintillator detector. (The incident ion is accelerated to a high-voltage negative terminal, where secondary electrons are produced and accelerated to finally impinge upon a scintillator photomultiplier detector.) This instrument was calibrated with a known ion/neutral beam. The 2XIIIB computer data acquisition system developed by Cummins et al. [20] is used to process the data between shots to yield a curve of dN/dW versus W as is shown in Fig. 9. The effective low-energy limit for this analyzer is ~ 200 eV.

2.6 Low-Energy Neutral Particle Analyzer

At energies less than a few hundred eV, the re-ionization process used in the stripping cell of the analyzer just described becomes inefficient and also the magnetic analyzer of limited use. Thus, a new neutral-particle analyzer is under development by Hunt and Turner [21] for use on TMX where central-cell ions down to < 100 eV are of interest. In their instrument, velocity is measured by mechanically chopping the particle-detection channel, and a Daly-type detector is used to detect neutrals through secondary emission. The low-energy neutrals of interest will be produced by an energetic neutral probe beam undergoing charge exchange with the warm confined plasma.

2.7 Alternate Hot Ion Density Measurements

Direct measurement of the local hot ion density n_H has proven to be difficult. Thus several corroborative measurements supporting the fast atom analyzer data are included here, with the intent of allowing comparison with the generally more accurate measurements of the electron density n_e ($n_e = n_p = n_H + n_w$ for $Z = 1$) and from the difference setting an upper limit on the warm or impure plasma fraction.

2.7.1 Diamagnetic Signal

The high β confinement achieved with mirror confinement makes local and global measurements of $\Delta B/B$ an important measure of performance. Correll et al. [22] used the large diamagnetic loop shown in Fig. 2 (a baseball seam shaped loop located just outside the ceramic vacuum chamber liner) to measure the volume plasma dipole moment

$$M = 1/r_p^2 \sim 10^7 \text{ A-cm}^2. \quad (8)$$

The magnetic field energy difference after reduction by ΔB is proportional to:

$$\int n_i k(T_i + T_e) dV. \quad (9)$$

2.7.2 Neutron Yield

A relatively standard scintillator photomultiplier detector has been used by Hunt et al. [23] for time-resolved neutron yield measurements. Absolute yield measurements were made with a calibrated silver activation-delayed β^- counter. The quantity measured in this case is the neutron yield from

$$\int n_D^2(dv) dV. \quad (10)$$

Direct wall D_2 -neutral beam neutron production is measured to be $\leq 10\%$ of the volume yield.

2.7.3 Fusion Ion Reaction Product Detector

Another diagnostic, shown schematically in Fig. 10, has been developed by Fonte [24] to detect the energetic ion reaction product from fusion reactions, i.e., from the 3-MW proton branch (instead of the 2.5-MW neutron branch) of the D-D reaction. This detector allows quantitative measurement of the reaction rate in a selected volume determined by collimation and by a detailed mapping of ion trajectory. Accurate measurement ($\leq 1\%$ error) of the energy spread of the reaction product can also yield the temperature of the reacting ions.

2.8 Plasma Density Measurements

Various standard techniques are available for measuring n_e and T_e . Thus this topic is only briefly noted here for completeness. A third more novel approach to measurement of

n_p through neutral beam attenuation $\propto (n_i \sigma_{cx} + n_e \sigma_{ion} v_e) / v_i$ is included here in more detail.

2.8.1 Thomson Scattering

The arrangement for Thomson scattering with a Ruby laser is shown in Fig. 2. The measurements of the local n_e for several discrete locations and times by Clauser and Goodman [25] is in excellent agreement with corroborative microwave and neutral beam profile measurements as shown in Fig. 11. The limitation of Thomson scattering as far as n_e and T_e measurements are concerned are its cost and relative inflexibility. Thus it appears desirable to use other techniques for wider spatial scans or n_e and T_e as a continuous function of time, with specific points in space and time calibrated with Thomson scattering.

2.8.2 Microwave Interferometry

The arrangement for stationary and movable 2-mm and 4-mm microwave systems is shown in Fig. 2, and the radial profile data shown in Fig. 11. The item of specific interest here is the development of simple counting circuit by Futch et al. [26] to allow direct readout of $\sin \delta$ with an indicator for lost fringes if fringes are missed during bursts of rf turbulence. The movable 4 mm microwave interferometer was used to measure the longitudinal density profile shown in Fig. 12, but here the cold stream plasma contributes a large fraction of the density near the gas box end and the hot central plasma density must be inferred from symmetry.

2.8.3 Neutral-Beam Plasma Measurements

Neutral-beam injection brings in a useful new auxiliary diagnostic developed by Turner et al. [27]; namely, neutral-beam attenuation along carefully collimated chords passing through the confined plasma can be used to determine the effective plasma thickness. One neutral-beam source was specifically arranged and monitored for this function on 2X118. The details of one of the carefully collimated detector channels are shown in Fig. 13. The relative position of the array of 13 such detectors is shown in Fig. 2. A typical example of the radial plasma profile after Abel inversion is shown in Fig. 11.

2.9 Neutral Beam Diagnostics

Neutral-beam diagnostics includes a wide variety of support measurements including:

- Ion source - Power supply related controls.
- Ion source operation (with suitable automatic power supply protective circuits.
- Computer overall control and data logging.
- Neutral beam - Gas control for optimum charge exchange.
- Aiming adjustment available with readout and means of calibration.
- Wide dynamic range fast sensors for aiming and divergence monitors.
- Pop up machine center segmented calorimeters for test aiming and trapping optimization.

Beam dump calorimeters for standard beam output measurement (with and without plasma buildup).

In addition, many measurements are made on the test stand to yield operating parameter for minimum divergence (e.g. with use of a 10 cm x 40 cm array of 45 secondary emission cups as described by Waugh [28]), and also for species analysis using either a magnetic analyzer or through Doppler shifted D^0 light. An example of the neutral beam profile and aiming capability is shown in Fig. 14.

CHAPTER 3. DIAGNOSTIC NEEDS FOR FUTURE MIRROR MACHINES

3.1 Introduction

This chapter will be oriented toward areas of needed diagnostic development including:

- Improved measurements from present diagnostics,
- Special needs of new mirror machines,
- High power flow related diagnostics for a better detailed energy balance, and
- Adapting techniques to a wider plasma parameter range in an increasingly hostile plasma environment.

3.2 Better Local Measurements of Hot Ion $n(r,v,t)$

The present techniques for measuring hot ion $n(r,v,t)$ include 1) measurement of dn/dv via the escaping neutral flux produced by charge exchange on the neutral beams, 2) Thompson scattering on the ion feature, and 3) fusion reaction product analysis.

The present technique using charge exchange utilizes the type of neutral beam analyzers described in 2.5 and 2.6 above. This requires a multichannel instrument such as shown in Fig. 8, and yields the unfolded ion energy distribution shown in Fig. 9. Ultimately this technique is limited to the plasma boundary through reionization = no!, particularly for lower energy particles, thus this is an area of increasing need for large confinement systems.

The use of Thompson scattering arranged for $\alpha > 1$ [$\alpha = \lambda/4\pi\lambda_D \sin \theta/2$] to look for the ion feature, has not been satisfactory so far for fusion studies due to general domination by collective turbulent scattering.

The third approach shows better promise, but requires less than $\leq 1\%$ error in measurement of neutron or reaction ion energies for useful information as to the ion temperature. The yield of neutrons (or other reaction product) yields a measure of $\int n^2(v)v dv$ and any possible neutral beam wall related production. The arrangement of the charged reaction product analyzer is discussed in Section 2.7 and the instrumentation shown in Fig. 10. In principle it should allow very accurate measurement of the reacting ion spread. Suitable collimation can be used to limit contributions to selected volume regions. However, portions of the interior of larger high-field confinement systems may not be accessible to this charged-particle reaction product technique because of the limited ion gyroradius. Clearly we need some new approach adaptable to the new larger and hotter confinement

systems, though the neutron yield will become an increasingly important index of overall performance.

3.3 Local Measurement of Magnetic Field

The best present technique for measurement of the magnetic field involves use of the diamagnetic loop shown in Fig. 2 and discussed in Sec. 2.6 to measure the volume averaged $(n_i k T_i)_i$ through the diamagnetic signal $\Delta B/B$. The measurement of plasma β is very important, but present volume averaged measurements of $\Delta B/B \approx 1 - (1 - \beta)^{1/2}$ restricts its application largely to a self-consistent check on hot ion confinement. The diamagnetic loop diagnostic signal is relatively large since the magnetic moment for 2XIIIB is measured to be $\sim 10^7$ A-cm², but also subject to appreciable systematic error due to the significant background subtraction signal from flux change in a pulsed system. Use of magnetic probes or diamagnetic loops in locations exposing insulating jacket surfaces to very intense plasma bombardment should be avoided. Use of a superconducting d.c. magnet coil in future machines such as MTF should reduce the background flux pickup problem.

Another approach to measurement of the magnetic field is to measure the line integral Faraday rotation $\chi = 2.6 \times 10^{-14} \lambda^2(\text{cm}) \int n_B(\text{G}) \cdot d\mathbf{l}$ of a polarized Far Infrared laser beam as it passes through the plasma region of interest. This technique was applied by Stallard et al. [29] to 2XIIIB with a 337 μm HCN laser using a two pass signal system with a corner reflector mounted off the 2XIIIB wall as shown in Fig. 15. This diagnostic approach shows promise but was too sensitive to vibrations to provide the needed few degree accuracy during first tests. However, as an interferometer it verified the μ -wave find.

A third approach to this problem is a local B measurement diagnostic based upon the Zeeman effect. Clauser [30] proposed use of a dye tuned laser beam to pump a selected He^0 state in the $\sim 1 \text{ cm}^3 \sim 90^\circ$ intersection of diagnostic energetic He^0 with the laser beam, to generate a locally Zeeman split fluorescent radiation signal. The dye tuned laser was procured and the diagnostic $\sim 1 \text{ cm}^2$ 20 keV He^0 beam developed. However Drake et al. [31] found that Ti impurity light in 2XIIIB was too intense to allow clean measurement of the selected He line. This diagnostic will likely prove very useful in future machines having the much lower impurity levels.

A fourth approach to local B measurement is based upon cyclotron modulation of laser light scattered from electrons. This approach is under study by Forrest et al. [32], at Culham.

A really good measure of local B appears essential to very high β and to field reversed mirror studies described in the seminars given by Bill Condit. Use of heavy ion beam probes to measure line integrals of B is also possible, but requires extensive instrumentation and involves unfolding uncertainties.

3.4 Plasma Potential ϕ (and E) Measurements

A technique being used to measure the total effective ambipolar potential is cutoff in the low energy ion spectrum. Such observations gave a ~ 160 volts for a quiescent plasma

in Baseball II; the instrument is described in Section 2.2. When appreciable turbulent losses are present this method has been unsatisfactory.

A much more refined method has been developed by Hickok et al. [33] using local striping of an energetic heavy ion beam and a precision measurement of emergent particle energy relative to the input beam energy. The difference energy then represents the potential difference between site of ionization (charge state change) and the confinement chamber wall (instrument ground). Determining the trajectories for the incident and emergent beams is a definite complication, but the measurement is relatively precise. Such a heavy ion beam system is being designed by Hornady et al. [34] for the new T1X experiment planned for startup this fall at LLL. The need here is for a simplified diagnostic, because local measurements of ϕ and E are needed throughout the mirror barrier plasma interface region to assess the operation of the electrostatic end plugs.

3.5 Local Instability Measurements

The general approaches to detecting the onset of instabilities are 1) rf measurements through various standard probes, 2) detection of end loss bursts, 3) microwave scattering bursts, or 4) ultimately through gross energy spectrum and confinement time changes. The detection of rf near ω_{ci} is useful for onset information and frequency correlation with theory, but it generally lacks spatial information (Grubb et al. [35]) due to plasma shielding and other effects. However, in large future machines the major density and magnetic field gradients are expected to be limited to a boundary region. Theory predicts this boundary region will need stabilization by a warm plasma stream if

$$a_i \left(\frac{1}{n} \frac{dn}{dr} \right) > \frac{1}{30} \quad (11)$$

Thus the end-stream fluctuations appear to provide the best local boundary-zone measure of instability. This feature becomes more important with a hotter T_e machine; e.g., in MFTF about 1250 A-0° at 3-4 keV is expected necessary (Osher [36]) to stabilize its 10^{14} density $\bar{W}_i \sim 50$ keV plasma with $T_e \sim 800$ eV. Clearly, it is important that the cold stream input be kept to a minimum current density over the minimum area. Careful placement of a segmented high frequency version of a gridded probe such as described in Section 2.2 should be considered.

3.6 End-Wall Diagnostics

The energy flux density at the end wall in future machines such as MFTF becomes a formidable problem. To limit the expected energy flux to ≤ 100 W/cm², it was found essential in that machine to use field expansion and energy flux dilution by moving the end walls back 9 m from the machine midplane. Thus, simple structural cooling is an engineering problem, at least without use of direct energy recovery to reduce the energy flux. Similarly, any reflux of secondary electrons, recycled gas or impurities can influence confinement performance, as discussed by Post [37]. Present diagnostics has been limited to incident ion flux and energy measurements. The problems of thermal conduction and secondary emission are

under study by Hall [38] and Porter [39]. Special large biased grid structures are being constructed to test secondary electron suppression. Modulated ion and electron probe beams of known energy could be used as a diagnostic to study the surface secondary emission and sheath problem, but this can only be done in conjunction with the end loss flow of a confinement experiment, where non-interactive installation of the beams and associated probes would be difficult. Some compromise solution between the small test sample and the attempt to eliminate the problem by single large changes would appear desirable. The segmented calorimeter described in Section 2.4 may shed information on the end surface problem through better understanding of the overall energy balance.

3.7 Neutral Beam and Stabilizing Stream Related Diagnostics for a Better Detailed Energy Balance

The use of large arrays of high-power neutral beams with mirror machines makes $\geq$ MW input power available. A detailed correlation of the net power input and the attained plasma parameters such as done by Simonen et al. [40] for 2XIIIB requires an analysis of energy balance processes. Thus, accurate diagnostics are required to measure the total net input power to the plasma by the neutral beams, the net power input (or loss) by the stabilizing stream technique, and an inventory of all the loss processes (with sufficient spatial measurement to allow global integration). Such a plasma input arrangement is shown conceptually in Fig. 4, with the expected main ion energy flow to the electrons shown in Fig. 5. Accurate continuous measurements of n_e and T_e thus become fundamental to understanding the overall confinement physics. The net energy flow and the measured plasma parameters are also necessary to allow evaluation of the overall figure of merit for the confinement system

$$\eta_E = \frac{(\text{Total plasma energy present})}{(\text{Total power into plasma/ion present})} \quad (12)$$

Present experiments tend to have only a very limited array of calorimeters installed for the neutral-beam input and end-loss measurements with charge-exchange losses and vacuum ultraviolet treated as corrections. An extensive array of end-and side-wall fast response calorimeters, would seem very valuable as a double check of the present physics modeling.

3.8 Diagnostic Environment Constraints

Many of the diagnostic elements in present use have limited tolerance to the intense particle, vacuum ultraviolet, or neutron fluxes as is expected from the new generation of mirror machines now under construction. Table II compares some of the environmental conditions for 2XIIIB, with those predicted for MFTF.

Clearly we must avoid using magnetic field sensitive components or extensive magnetic shielding will be required. Also use of solid state elements such as SCR's must be remotely located beyond neutron shielding or they will have a relatively short life. Use of many

plastics such as Teflon may also be restricted because of cumulative neutron damage. Internally located diagnostics will require either careful location or extensive cooling or both; power at the neutral-beam dumps range up to $\sim 5 \text{ kW/cm}^2$.

3.9 Future Mirror Machines and Their Special Diagnostic Requirements

The first new mirror machine planned to extend the 2XIIIB studies is the TMX now scheduled for initial operation in late 1978. The physics features of this machine were noted in Section 1.3 and described in detail by Bill Condit in his seminars. Briefly here, the special diagnostic needs for this machine include 1) a means of measuring the local plasma potential in each of the three cells, and 2) means of measuring the combined ion energy distribution so as to include the very low-energy ions in the central cell.

The first of these requirements will utilize a heavy ion beam probe for plasma potential measurement as described in Section 3.4. Here we want to clearly measure the plasma potentials of both the end cells and the central cell, to assess electrostatic low energy ion confinement in the central cell by the end plug trap.

The second requirement is for a self-consistent check of the confinement central cell of low energy ions that would normally be lost out the loss cone of a standard, single-cell mirror machine. The approach is development of a new neutral beam analyzer described in Section 2.6. Means of measuring the effective n_{Te} and of detecting sites of incomplete stabilization also have special importance for TMX.

The next scheduled machine is the MFTF planned for operation in 1981. It is intended to check 2XIIIB scaling to large size and eventually to be suitable for use as an end plug for a high energy tandem experiment. For MFTF much of the special diagnostic needs come from its larger size and much higher-energy flux levels. Close-in walls could receive $\sim \text{kW/cm}^2$. Thus care in design and location are needed even for established diagnostic techniques. Other special requirements includes local rf sensing to allow adjusting local stabilization currents to a minimum for effective DCLC stabilization, and a more detailed energy balance to assess progress in scaling n_T toward fusion reactor requirements. The special diagnostics required to sense stabilization are discussed in Section 3.5. The diagnostic problems associated with the end walls and the need for a more detailed set of measurements for a detailed energy balance are described in Section 3.6. Either machine will require a major increase in computer-data acquisition and control, to handle the vast data matrix available to characterize a given pulse.

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Figure Captions

Chapter 1:

- Fig. 1 The upper portion is a cutaway view of the magnetic coil and neutral beam arrangement for 2XIIIB. The lower portion of the figure shows typical plasma buildup curves with and without gas stabilization.
- Fig. 2 An artist's layout of the 2XIIIB plasma diagnostics.
- Fig. 3 Data acquisition center computer printout for a typical 2XIIIB plasma shot, listing the available diagnostics and associated data storage.
- Fig. 4 Conceptual plasma and energy input into a typical mirror confinement experiment.
- Fig. 5 Conceptual equilibrium flow of the expected main hot ion input energy to the colder electrons.

Chapter 2:

- Fig. 6 Schematic view of a typical gridded detector energy analyzer. The potential arrangement shown is of the classical retarding grid type, with a double analyzer grid to assure uniform retarding potential.
- Fig. 7a The upper curve gives a general curve of γ_e vs energy for H^+ incident at 90° on Cu (composite of many references).
- Fig. 7b The lower curve gives 1) typical ion back scattering coefficients γ_R and energy backscattering coefficient γ_{RE} vs energy for H^+ incident at 90° on Cu (from the work of Oem et al. [16]).
- Fig. 8 The 15 channel neutral particle analyzer used on 2XIIIB.
- Fig. 9 Processed neutral particle detector data showing the ion distribution function dn/dE vs ion energy E obtained with the neutral particle analyzer shown in Fig. 8. Data storage allows between shot analysis yielding such an energy distribution at the end of every 500 μsec time step during the shot.
- Fig. 10 A schematic view of the fusion reaction detector arrangement by Foote [24] including details of the solid state detector and a conceptual fusion ion trajectory.

- Fig. 11 Comparison of plasma radial profile measurements made with Thomson scattering, a microwave interferometer, and a neutral-beam plasma profile detector.
- Fig. 12 An axial plasma density profile obtained in 2XIIB by use of movable 4 mm microwave interferometer and Langmuir probe data. The mirror fields and inferred hot and cold plasma components are shown for reference.
- Fig. 13 Drawing of one of the tightly collimated neutral beam profile detectors (used in an L-shaped array of 13 detectors).
- Fig. 14 Horizontal and vertical neutral beam profiles; aimed and measured before machine shots with a central calorimeter probe.
- Fig. 15 Schematic view of the HCN laser beam arrangement for Far lay rotation measurements in 2XIIB.

Table 1. Listing of selected parameters measured for 2X11B and predicted for TMX and MFTF

Parameter	Diagnostic	2X11B(meas.)	TMX (pred.)		(pred)
			Plug	Central	
n_p density(cm^{-3})	Microwave fnd Thomson scattering Neutral beam attenuation	10^{14}	5×10^{13}	10^{13}	10^{14}
W_i ion energy(keV)	Fast atom analyzer	13	26	.08	50
T_e electron Temp. (eV)	Thomson scattering	60 - 150	200	-	800
R_p plasma radius (cm)	Neutral beam profile Microwave	8	7	31	30
L_p plasma length (cm)	Interferometry	25	40	550	112
plasma diamag. β	Diamagnetic loop	.5 - .7	.5	.5	.5
Neutron yield/s Total yield	Scintillation counter (silver activation counter)	3×10^{11} 10^9	- -	-	2.6×10^{16}
rf fluctuations ϕ (volts) (near ω_{ci})	Electrostatic probes Microwave scattering Fluctuating end losses	50 V	7	-	7
n_T (cm^{-3})	Combination	10^{11}	3×10^{11} - 10^{11}	-	10^{12}
R_{vac} mirror ratio	--	2:1	2:1	40:1	2:1
B_0 central field(T)	--	.7	1	.05	2
Pulse duration (s)	--	10^{-2}	2.5×10^{-2}	-	.5(to 30)
Neutral beams (A)	--	500	160	125	750
W_i (keV)	--	14	26	Cold	50

Table II. Comparison of 2X11B and NSTF diagnostic environment

Parameter	2X11B	NSTF
Central field $B_0(T)$	.7	2.0
Mirror ratio R_{vac}	2	2
Mirror to mirror distance (m) (characteristic field length)	1.6	3.4
Expected energy flux at end wall (kW/cm ²)	.5 at 3 m	.1 at 9 m
Neutral beams available:		
Plasma target	1-5 plasma guns	50 plasma guns
Startup neutral beams (MW)	-	15.6 (1200 A, 13 kV)
Main neutral beams (MW)	6.5 (500 A, 13 kV)	37.5 (750 A, 50 kV)
Main pulse duration (s)	10 ⁻²	.5 (to 30)
Neutron yield (n/s - total yield)	10 ¹¹ - 10 ⁹	2 x 10 ¹⁶ - 10 ¹⁶

Figure 1: The upper portion is a cutaway view of the magnetic coil and neutral beam arrangement for 2XIIB. The lower portion of the figure shows typical plasma buildup curves with and without gas stabilization.

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2XII-B PLASMA DIAGNOSTICS

Figure 2: The artist's lay out of the 2XII-B plasma diagnostics.

7/ 7/78 SHOT 43
 MAP OF 2X II GUN
 TIME=0C 185AC 185BD 1GUN 2GUN 3GUN 4GUN 5GUN 6GUN10GUN11GAS INEBEAM
 VALUE 12.000 145.0 1370.0 13.000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
 TIME 12354 1.0000 14.0 14.0 1300 1200 1.0000 1.0000 1.0000 200 19.50 1.0000
 DUTY 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000

DIAGNOSTIC	#	1	NEUTRAL ANALYZER	15	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	2	2 MM INT(15 USEC)	2	CHANNELS,	4096	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	3	PIGGY BACK ANALY	1	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	4	STR3456+REC3418	8	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	5	BEAM SUM 1	1	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	6	PARADY ROTATION	2	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	7	RADIAL BEAM ATTN	11	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	8	AXIAL BEAM ATTN	7	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	9	NEUTRONS	1	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	10	DIAP. LOOP	1	CHANNELS,	3072	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	11	WEST END LOSS AN	1	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	12	MICROWAVE SCATTE	1	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	13	2 IN. TRANSMISSION	1	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	14	R F PROBES - BIO	7	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	15	LASER INTERFACE	1	CHANNELS,	816	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	16	13 TIP RF PROBE	6	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	17	2 MM INT(22 CM)	2	CHANNELS,	4096	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	18	PHASE DETECTION	1	CHANNELS,	4096	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	19	X-RAYS	4	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	20	BEAC EMI. BD W#2	2	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	21	U-U SPECT	2	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	22	H-ALF TOT LT=1.2	2	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	23	2 IN SCAT (PD)	1	CHANNELS,	2048	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	24	LANG PROBE 1	1	CHANNELS,	1024	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	25	LANG PROBE 2	2	CHANNELS,	1024	DATA	POINTS/CHANNEL
DIAGNOSTIC	#	27	SECONDARY DETEC	1	CHANNELS,	2048	DATA	POINTS/CHANNEL

Figure 3: Data acquisition center computer printout for a typical 2XII B plasma shot, listing the available diagnostics and associated data storage.

Figure 4: Conceptual plasma and energy input into a typical mirror confinement experiment.

Figure 5: Conceptual equilibrium flow of the expected main hot ion input energy to the colder electrons.

Figure 6: Schematic view of a typical gridded detector energy analyzer. The potential arrangement shown is of the classical retarding grid type, with a double analyzer grid to assure uniform retarding potential.

1) SINGLE PARTICLE EFFECTS:

Figure 7a: The upper curve gives a general curve of γ_e vs energy for H^+ incident at 90° on Cu (composite of many references).

Figure 7b: The lower curve gives 1) typical ion back scattering coefficients γ_B and energy backscattering coefficient γ_E vs energy for H^+ incident at 90° on Cu (from the work of Gen et al. [16]).

2XIIB CHARGE EXCHANGE ANALYZER

Figure 8: The 15 channel neutral particle analyzer used on 2XIIB.

ION ENERGY DISTRIBUTION

Figure 9: Processed neutral particle detector data showing the ion distribution function dn/dE vs ion energy E obtained with the neutral particle analyzer shown in Fig. 8.. Data storage allows between shot analysis yielding such an energy distribution at the end of every 500 μsec time step during the shot.

REACTION ION DETECTOR

Figure 10: A schematic view of the fusion reaction detector arrangement by Foote [24] including details of the solid state detector and a conceptual fusion ion trajectory.

RADIAL DENSITY PROFILE

Conclusions:

- Symmetric in azimuth
- $R_p/a_i = 2$ to 4

Figure 11: Comparison of plasma radial profile measurements made with Thomson scattering, a microwave interferometer, and a neutral-beam plasma profile detector.

STREAM CHARACTERISTIC

Figure 12: An axial plasma density profile obtained in 2XIIB by use of movable 4 mm microwave interferometer and Langmuir probe data. The mirror fields and inferred hot and cold plasma components are shown for reference.

Figure 13: Drawing of one of the tightly collimated neutral beam profile detectors (used in an L-shaped array of 13 detectors).

NEUTRAL BEAM COLORIMETER PROFILES

Vertical

Horizontal

Figure 14: Horizontal and vertical neutral beam profiles; aimed and measured before machine shots with a central calorimeter probe.

Figure 15: Schematic view of the HCN laser beam arrangement for Faraday rotation measurements in 2XIIB.