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A two-dimensional scanning neutral particle analyzer has been installed on the Advanced Toroidal Facility (ATF). This TFTR-type $E\|B$ spectrometer provides an extended energy range, mass resolution, and flexibility in viewing orientation. Characteristics of the $E\|B$ analyzer and the associated data acquisition and control systems are discussed. Data representative of those taken during neutral beam injection and ion cyclotron heating on ATF are presented to illustrate the analyzer capabilities.

I. INTRODUCTION

The confinement of ions in stellarators during auxiliary heating has received considerable attention in recent years. The complex magnetic geometry in such systems makes theoretical computations of the confinement difficult and time consuming. To investigate this subject experimentally, a neutral particle analyzer (NPA) with horizontal and vertical scanning capability has been installed on the Advanced Toroidal Facility (ATF). The two-dimensional scanning capability of this system makes it a powerful diagnostic tool for understanding ion confinement in stellarators. Measurements have been made during both neutral beam injection (NBI) and ion cyclotron heating (ICH) to study the effects of these heating methods on ion confinement.

The NPA and its control system are discussed. Also, a selection of data taken on ATF is presented to demonstrate the capabilities of the NPA.

II. ANALYZER DESCRIPTION

The main component of the neutral particle analysis system on ATF is an $E\|B$ mass- and energy-analyzing spectrometer developed at Princeton Plasma Physics Laboratory and similar to analyzers used on the Tokamak Fusion Test Reactor. The schematic in Fig. 1 shows the main components of this spectrometer, which is described in detail in Ref. 1.

To provide horizontal and vertical scanning capability, the analyzer is mounted on the carriage as shown in Fig. 2. The carriage is then moved horizontally on a rail supported about 2 m above floor level. For vertical movement, two 2-m drive screws mounted on each side of the analyzer drive the analyzer along the vertical track shown in Fig. 2. When the analyzer is scanned horizontally, its viewing angle can be changed from perpendicular to tangential (in both directions) to the axial magnetic field. When the analyzer is scanned vertically, it can view from below to above the plasma column of ATF.

The location of the pivot point was chosen so as to provide maximum viewing capabilities for the analyzer. Finding the optimum location for this pivot point proved to be fairly difficult. Because of the complex orbit topology of ions in ATF and the corresponding loss regions (see Fig. 3), the analyzer must be able to scan from tangential to the magnetic field (in both directions) to perpendicular to the magnetic field. This allows the analyzer to view all classes of orbits in ATF and to detect the tangentially injected beam ions before they enter a loss region. To avoid having the sightline blocked by the outer wall of the ATF vacuum vessel, the pivot point had to be close to the vacuum vessel.

Because of the limited access to this pivot point, the carriage was designed so that the pivot point remained fixed while being unsupported (i.e., the pivot point is not held mechanically rigid). The final design, as shown in Fig. 2, fixes the horizontal pivot point by providing a rigid pivot

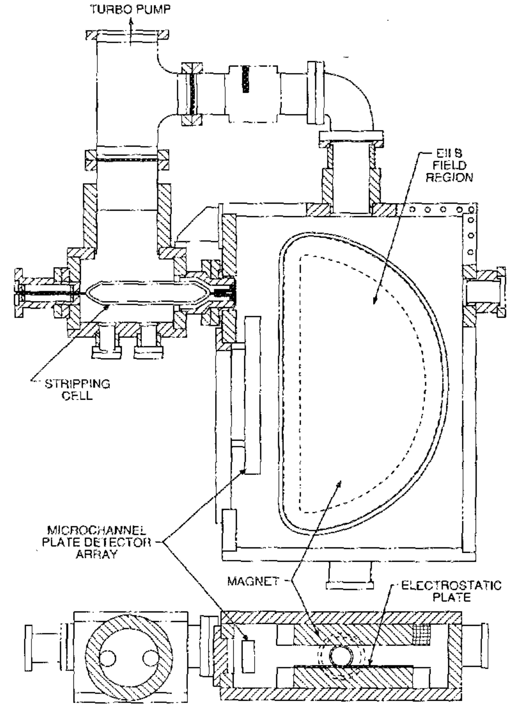

FIG. 1. Schematic of the $E\|B$ neutral particle analyzer.

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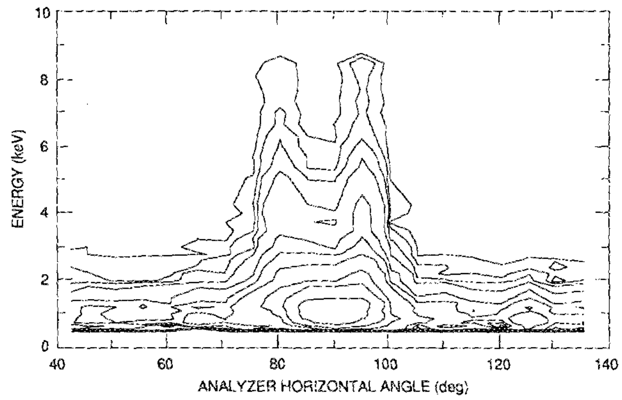

FIG. 6. Contours of constant proton charge-exchange flux obtained during hydrogen minority ICH at $f = 14.4$ MHz and $B_0 = 0.95$ T. The vertical viewing angle of the analyzer is maintained at $\theta = 0°$.

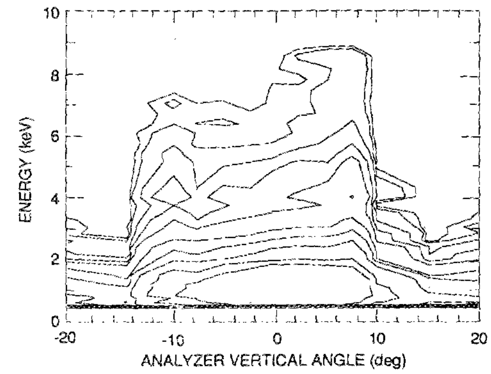

FIG. 7. Contours of constant proton charge-exchange flux at a horizontal angle of 95° obtained during hydrogen minority ICH at $f = 14.4$ MHz and $B_0 = 0.95$ T.

analyzer components. This program continuously monitors all of the available signals from the NPA and displays them on a computer terminal. The user can modify certain analyzer settings (magnetic and electric fields, cell pressure, etc.) to values required by the experiment.

At the end of each discharge, the signals of the 78 energy channels along with all information pertaining to the status of the analyzer are read through a serial highway driver to a VAX 8700.[11] The data are stored in the ATF Data Management System[12] for later recall. A data analysis package then reads the raw data and displays plots of the analyzed data between ATF shots. This analysis package is menu driven (full-screen menus) and provides the user a large degree of flexibility in both data analysis and data display.

IV. APPLICATIONS

The spectra measured by the NPA during NBI for three horizontal angles nearly tangent to the magnetic field are shown in Fig. 5. Note that the tangency radius of the analyzer angle $\phi = 45°$ roughly corresponds to the beam tangency radius. The three peaks in the spectra correspond to the full, one-half, and one-third energy components of the injected beam. As expected, the detected flux diminishes as the analyzer is moved away from the beam tangency radius.

The NPA has been used to measure the fast ion distribution during hydrogen minority ICH. A high-energy tail up to 50 keV has been observed by the NPA. Furthermore, this high-energy tail was found to vary as the analyzer viewing orientation was changed. The flux measured as the analyzer was scanned horizontally at $\theta = 0°$ is shown in Fig. 6. These data were taken over approximately 20 fairly reproducible discharges, with the NPA viewing orientation changed between shots. The analyzer was also scanned vertically at a horizontal angle corresponding to one of the peaks of Fig. 6. The variation associated with changing the vertical viewing angle is shown in Fig. 7.

ACKNOWLEDGMENT

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[8] Jorway Corp. Model 321, Westbury, NY 11590.
[9] Joerger Enterprises, Inc., Model 320, East Northport, NY 11731.
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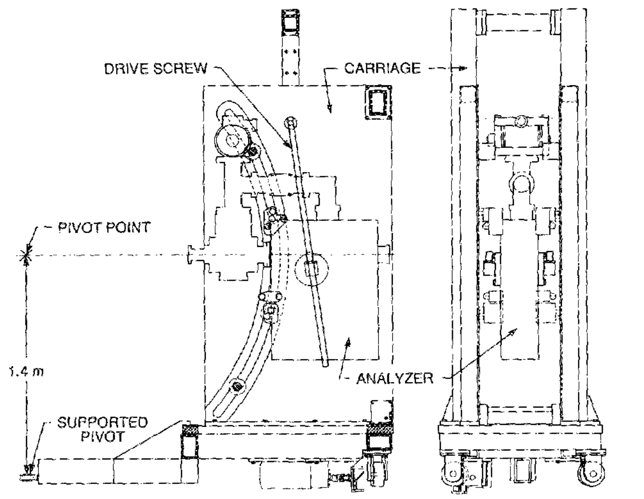

FIG. 2. Plan views of the analyzer in the moving carriage. The analyzer is designed with an unsupported pivot point in the sightline and rotates horizontally about a fixed point located directly below the real pivot point. The analyzer moves horizontally on the wheels shown at the bottom. The vertical motion is produced by a pair of 2-m drive screws that move the analyzer on the curved vertical track.

point 1.4 m directly below the nominal pivot point of the analyzer. In the vertical direction, the arc of the curved track on the carriage (see Fig. 2) was chosen so that the sightline of the analyzer passes through the pivot point at all vertical angles. Alignment tests confirm that the analyzer does in fact rotate about this pivot point with the sightline passing within $\simeq 2$ mm of the pivot point at all angles.

As evidenced by Fig. 3, the analyzer viewing angle must be known quite accurately. The horizontal angle is measured by a mechanical binary encoder[2] (with accuracy of 0.1°) mounted on the tongue of the carriage. The vertical angle is measured by an inclinometer[3] (with accuracy $\simeq 0.2°$) mounted directly on the analyzer.

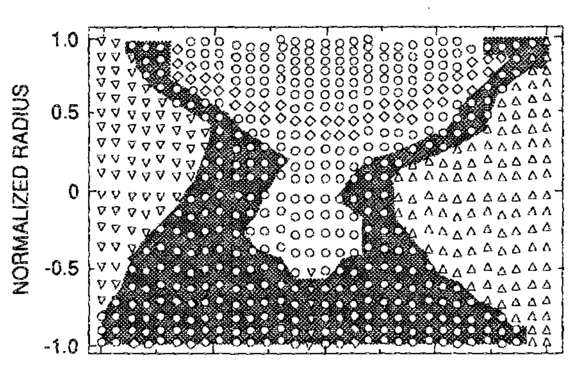

FIG. 3. Confined region (nonshaded area) for 10 keV protons viewed by the NPA at $B_0 = 1$ T in ATF in the equatorial plane ($\theta = 0°$). The symbols indicate the types of orbits observed: co-circulating ($\triangle$), counter-circulating (∇), helically trapped ($\bigcirc$), and transitional ($\Diamond$). A positive normalized radius indicates a position inside the magnetic axis, farther from the NPA, while a negative normalized radius indicates a position outside the magnetic axis, nearer to the NPA. This calculation was obtained by following particles for 1 ms to determine if their orbits carried them outside the last closed flux surface of ATF.

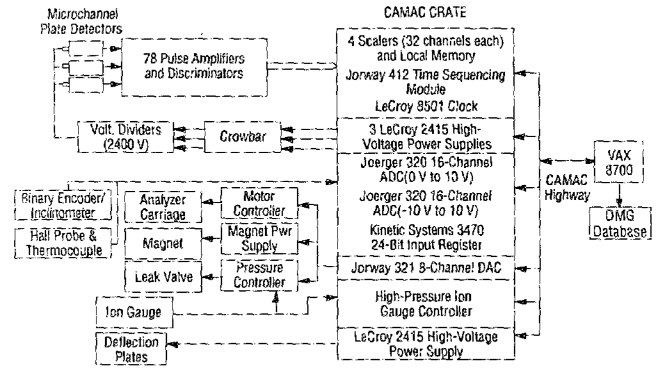

FIG. 4. Schematic of the NPA electronics and their interface with the data acquisition and control systems operated via computer.

III. ANALYZER CONTROL AND DATA ACQUISITION

The signal handling and data acquisition system is depicted in Fig. 4. The detected signals from the microchannel plates are sent into combined pulse amplifier and discriminators which provide TTL level pulses. These TTL pulses are then sent to BiRa scalers with local memory.[4] The scalers are gated at a variety of data acquisition rates by a Jorway time sequencing module[5] driven by a LeCroy clock.[6]

The biasing for the microchannel plate detectors as well as the deflection voltage for the electric field are controlled by LeCroy high-voltage power supplies.[7] The computer-programmed output of a Jorway eight-channel digital-to-analog converter[8] (DAC) controls the position of the analyzer, the current supplied to the magnet, and the stripping cell pressure.

Two Joerger 16-channel analog-to-digital converters[9] (ADCs) monitor the magnetic field, the stripping cell pressure, the vertical angle of the analyzer, and the readouts of various components of the analyzer vacuum system. The output of the binary encoder is monitored by a Kinetic Systems input register.[10] The voltages applied across both the microchannel plates and the electric field deflection plates are monitored by the LeCroy high-voltage power supplies.

To incorporate the available information into a user interface, a control program has been developed for remotely changing and monitoring the settings of the various

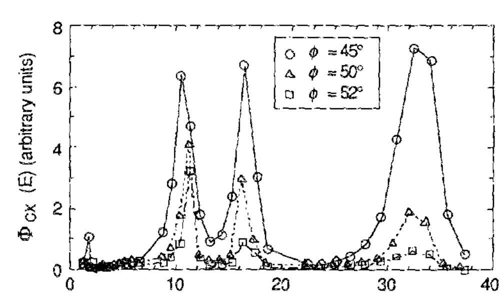

FIG. 5. NPA measured spectra at angles close to tangential. The three peaks in the spectra correspond to the full, one-half, and one-third energy components of the beam.