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A MULTIPLE TRACK DOPPLER-SHIFT SPECTROSCOPY SYSTEM
FOR TFTR NEUTRAL BEAM INJECTORS

By

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A MULTIPLE TRACK DOPPLER-SHIFT SPECTROSCOPY SYSTEM FOR TFTR
NEUTRAL BEAM INJECTORS

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ABSTRACT

A Doppler-shift spectroscopy system has been installed on the TFTR neutral beam injection system to measure species composition during both conditioning and injection pulses. Two intensified vidicon detectors and two spectrometers are utilized in a system capable of resolving data from up to twelve ion sources simultaneously. By imaging the light from six ion sources onto one detector, a cost-effective system has been achieved. Fiber optics are used to locate the diagnostic in an area remote from the hazards of the tokamak test cell allowing continuous access, and eliminating the need for radiation shielding of electronic components. Automatic hardware arming and interactive data analysis allow beam composition to be computed between tokamak shots for use in analyzing plasma heating experiments. Measurements have been made using lines of sight into both the neutralizer and the drift duct. Analysis of the data from the drift duct is both simpler and more accurate since only neutral particles are present in the beam at this location. Comparison of the data taken at these two locations reveals the presence of partially accelerated particles possessing an estimated $1/e$ half-angle divergence of 15° and accounting for up to 30% of the extracted power.

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INTRODUCTION

To date, neutral beam injectors have successfully served as auxiliary heating systems on many different magnetic fusion devices, including tokamaks,¹⁻⁵ mirror machines,⁶ and stellarators.⁷ The present generation of large tokamaks, the Tokamak Fusion Test Reactor (TFTR), the Joint European Torus (JET), and JT-60, all employ neutral beam injectors as part of their auxiliary heating systems. In addition, the Mirror Fusion Test Facility (MFTF) is designed to employ neutral beams to both heat and fuel the mirror plasma. Design parameters from these impressive systems vary from 10 to 20 MW in power and 2 to 10 seconds in pulse length.⁸⁻¹¹ At the power levels present within these systems, it is imperative to quantify accurately the properties of the beam within the injectors, both to preclude any damage to internal components and to optimize performance. In order to characterize the energy confinement of beam-heated tokamak plasmas,¹² it is important to diagnose the injected neutral beams as well as possible. Those parameters considered most important for confinement studies are the total injected power and the beam composition. The latter quantity, beam composition, is important because hydrogen isotope neutral beam systems, based on extraction of positive ions, are not monoenergetic. Plasma sources in these systems produce three ionic components D^+ , D_2^+ , and D_3^+ (or similar ions for hydrogen or tritium). During the neutralization process the molecular ions dissociate, and upon equipartition of energy among the constituents produce half-energy and third-energy atoms in addition to the full-energy atoms. The relative proportions of the beam in the three energy levels are important since they penetrate and heat the plasma differently.

Optical diagnosis of neutral beams has become popular both because it is difficult to probe high power beams, due to their high power density, and because many other techniques, such as calorimetry and momentum analysis, require stopping most or all of the beam and cannot be utilized on actual injection pulses. Nonperturbing optical techniques avoid both of these problems. Foremost among these is Doppler-shift spectroscopy. Developed at the Lawrence Berkeley Laboratory (LBL),¹³ similar systems have been constructed and utilized at Fontenay-aux-Roses,¹⁴ Culham Laboratory,¹⁵ Lawrence Livermore National Laboratory,¹⁶ GA Technologies,¹⁷ and the Japan Atomic Energy Research Institute (JAERI).¹⁸ Measurements of the beam composition,^{14-16,19-21} transverse velocity distribution,^{13,14,16,20,21} and spatial emissivity variation^{14,22,23} have been made using this technique. In the case of the former measurement, knowledge of excitation cross sections and the evolution of the many charged and neutral components of the beam is required.^{20,24} Measurement of the velocity distribution requires quantitative information for all phenomena that can cause broadening of the Doppler-shifted lines.²⁵ The system described in this paper has been developed for, and employed on, the injectors for TFTR. Preliminary results of beam composition measured at different locations within the injectors are presented. Use of this diagnostic to determine beam divergence from the transverse velocity distribution of our system is still under development.

Figure 1 is a schematic diagram of the TFTR neutral beam Doppler-shift spectroscopy system. Long optical fibers are employed, allowing the spectrometer and detector to be placed in an area away from the electromagnetic and neutron radiation hazards of the tokamak. Decoupling from the environment of the tokamak eliminates the need for neutron shielding, thus providing access to the instrument, and reducing the magnetic shielding

problem to manageable proportions. This decoupling is attained at the price of a tolerable loss of signal. A novel feature of the TFTR system is that one detector, a two-dimensional intensified vidicon, is used to gather simultaneous data from up to six different ion sources. As a result, two such systems can monitor all eleven ion sources presently installed on TFTR and the one ion source on the neutral beam test stand.

The TFTR CICADA²⁶ computer system is employed to communicate with this instrument, to analyze the data, and to present the data to the operator.

I. SYSTEM DESCRIPTION

A. FIBER OPTICS

Figures 2 and 3 are schematic representations of elevation and plan views, respectively, of a TFTR neutral beam injector. There are four neutral beam injectors on TFTR, each capable of accommodating up to three 10 cm x 40 cm LBL ion sources.²⁷ Beamlines are numbered 2, 3, 4, and 5 proceeding counterclockwise around the tokamak, with beamline 2 being in a normally counter-injecting direction and beamlines 3, 4, and 5 being co-injectors. Ion sources on a beamline are referred to as A, B, and C from left to right viewed toward the tokamak from behind the ion sources. (Ion source 4A is source A of beamline 4.) Source 5B has not been installed, in place of it, one beamline has been reserved for a test facility with its one ion source connected to the power system for 5B.

The arrangement of the ion sources is such that the 10 cm dimension is horizontal and the 40 cm dimension vertical. This results in the grid rails being oriented horizontally. Viewing ports are installed on the top of each optical diagnostic box located between the ion source enclosure and the source isolation valve. A direct line of sight, shown in Fig. 2, allows the velocity

distribution perpendicular to the grid rails to be observed. Use of a mirror (not shown), internal to the box, accommodates a line of sight, shown in Fig. 3, parallel to the rails. The included angle between the beam and viewing lines of sight is 60° with the beam coming toward the observation point, yielding blue-shifted D_α (or H_α) light. Also shown in Fig. 2 is a 60° line of sight into the drift duct at the end of the beam box. While this view exists on both the heating beams in the tokamak test cell and on the neutral beam test stand, it has been used so far only on the test stand.

A lens-coupled fiber optic system is used to deliver collimated light to the spectrometer. Accurate collimation is required if the transverse velocity distribution is to be determined from the line broadening. Light is collected by a Canon Model FD, 135 mm, f/2 photographic lens. By placing a 600 μ fiber at the focus of the lens, light collimated to within a half-angle of 0.13° is collected.

As part of the light collection system, it is important to determine that portion of phase space being sampled by this diagnostic since it differs from other diagnostics measuring the same parameters. In general, many of the different diagnostics measuring the same parameters are complementary, rather than redundant, since they usually are sampling different portions of the beam's phase space. In this case, the line of sight encompasses the entire vertical extent of the ion source, hence all of the y-, y'-phase space is sampled. (Y is defined to be the vertical coordinate, x the horizontal coordinate, with x' and y' defined as the angles between the trajectory and the x- or y-coordinate, respectively.) The same is not true in the horizontal plane. Here, the ion source is 10 cm wide and the collimation cylinder is 6.4 cm in diameter, crossing the beam axis at a point 60 cm downstream from the ion source. Figure 4 shows that portion of x-phase space, at the ion

source, from which particles are emitted into the field of view. Those particles emitted from the source within the phase space enclosed by the two diagonal lines and $x = \pm 5$ cm have trajectories that lie within the field of view. Assuming a divergence parallel to the grid rails of 0.4° , uniform extraction across the ion source, and Gaussian weighting of emission angles, 65% of the extracted beam passes through the field of view.

The fiber used is plastic clad silica with a numerical aperture of 0.22, matching the $f/\#$ of the collection lens. A continuous length of fiber was pulled from the lens to the spectrometer and field-terminated at both ends, in a concerted effort to reduce connection loss. An SMA connector was used to position the fiber at the focal point of the collection lens and a linear array of six fibers was constructed at the spectrometer end. Overall length of the fiber is 130 m yielding a 1 db attenuation of the red D_α light. Light from the linear array is coupled directly into the slit of a spectrometer.

B. DISPERSION AND DETECTION

The use of a spectrometer and Optical Multichannel Analyzer²⁸ provides a system which gives complete spectral resolution of the Doppler-shift spectrum in a single pulse. While other systems used in neutral beam optical analysis also provide spectral resolution, this is the first that combines spectral resolution with multiple spectra capability on one detector.

Two Czerny-Turner spectrometers are in use as the dispersing elements in the instrument. One spectrometer, manufactured by SPEX Industries, has a one meter focal length and $f/9$ optics, the other, manufactured by Instruments SA, has a 64 cm focal length and $f/5.6$ optics. Both are operated with dispersion on the order of $5 \text{ \AA/mm}$, giving a spectral range of $60 \text{ \AA}$ on the detector. This is enough to accommodate the $40 \text{ \AA}$ Doppler-shift of full-energy 120 keV deuterons from the unshifted D_α line.

An EG&G Princeton Applied Research Corporation (PARC) model 1254E red enhanced SIT vidicon serves as the detector. It has the advantage of offering off-the-shelf two-dimensional resolving capability. The array of pixel elements is 512 x 512 over an active area of 12.5 mm wide by 12.2 mm high. Detector resolution of ± 2 channels is the limiting factor in the resolution of the dispersion/detection system. Each fiber is imaged onto a 50 to 70 pixel high horizontal track across the face of the detector. Each of these tracks represents the spectral data of an ion source; the horizontal direction being wavelength and the vertical being proportional to the spacing between fibers. A track-to-track separation of 50 to 70 pixels is obtained by stacking the fibers, with core, cladding, and buffer, in a linear array at the entrance slit with core-to-core spacing of 1.7 mm.

The gain control of the detector controller was modified to decode the two-bit control logic into four independent high voltage settings. With intensifier voltage settings of 9 kV, 6.8 kV, 5.6 kV, and 4.5 kV, gains approximating full, half, fourth, and eighth are attained. Reduced gain settings are convenient as the number of tracks is increased. Scanning more tracks causes any given pixel to be read less frequently, resulting in increased signal accumulation, and possible saturation or nonlinear behavior.

Even though located 40 m from the center of the tokamak, transient magnetic fields, on the order of 1 G, affected the detector causing variations in the output when the tokamak pulsed. Magnetic shielding consisting of several layers each of Netic²⁹ and Co-netic²⁹ materials reduced the transient field levels to less than 0.1 G and nonvarying operation was achieved.

C. DETECTOR INTERFACE ELECTRONICS

An electronics module, referred to as the data stream controller (DSC), was developed to perform interface functions between the PARC 1216 detector controller (hereafter referred to PARC 1216) and the TFTR CICADA computer system. This module resides in a CAMAC crate and obtains its power from the crate. It receives timing information from CICADA through CAMAC digital timed gate modules, and control information from a standard CAMAC first in, first out module (FIFO).

The DSC performs two functions in its interface role. It handles handshake control when command data are passed from the FIFO to the PARC 1216. More importantly, it supports data acquisition from the PARC 1216, acting as a buffer to two 24-bit CAMAC dual port memory modules.

Detector set-up parameters are passed from the FIFO to the PARC 1216 vidicon controller via the DSC. In this capacity, the DSC performs the necessary handshake and monitors the word stream to filter out and insert command words. It holds the RUN command, sent by CICADA, until it receives an initializing timing pulse. When this command is issued, the PARC 1216 commences sending data; after one minute, the DSC issues a STOP command causing data transmission to cease.

Data are acquired by the DSC in one of two modes: transparent mode or integration mode. In the transparent mode it merely performs handshake buffering between the PARC 1216 and the dual port memory. A frame (one scan of all tracks) worth of data is passed to the dual port memory after each frame. In the integration mode, it performs a sum of the data for each channel on a frame-by-frame basis. In this mode, the data sent to the dual port memory are the time integral of the signal over the programmed acquisition time.

The 16-bit-wide data stream from the 1216 contains 14 bits of spectral channel intensity data and two bits of synchronization information. The last bit specifies the end of frame, and is used by the DSC in its data buffering. In the integration mode, the dynamic range of the system is increased to 23 bits through the summation technique.

The DSC has four lines for receiving timing pulse information. These are start foreground acquisition, stop foreground acquisition, start background acquisition, and stop background acquisition. Until receipt of a start pulse on one of these input lines, the DSC ignores the data being sent by the PARC 1216. Upon receiving the start pulse, the DSC starts accumulating data after the next end-of-frame synchronization bit it finds. Data are accumulated until the end of frame following the receipt of the stop pulse. The data are then transferred to the background or foreground dual port memory (depending on which set of input lines the data stream controller received the timing information).

After transmitting the data to the dual port memory, the DSC enters a playback mode in which the data are replayed through a digital-to-analog converter. This signal is presented on a front panel BNC as an analog output.

D. COMPUTER CONTROL

System set up, arming, data acquisition, and data analysis are all accomplished via the TFTR CICADA real time computer system. Four software tasks are utilized. An interactive task allows an operator to define the detector scanning configuration; an event-driven task initializes the hardware each shot; an event-driven archival task creates archived raw data files on the central computer facility; and an interactive data analysis and display task can be used to fit and display the data to an operator at a terminal operating station (TOS).

The interactive set-up task functionally replaces the PARC 1215 console. Through this menu controlled task, the operator defines the x- and y-locations of the tracks on the detector, the detector gain, and the scan rate. This information is processed into a command string that is sent to the FIFO. This program also allows the operator to select those ion sources for which data are to be acquired and/or fit.

An event-driven task is run every shot to initialize the hardware. It obtains power system timing and detector set-up parameters from the data base. It computes a timing envelope to encompass all sources for which data are to be acquired. Background acquisition commences with the first filament power supply to turn on. Beam data acquisition commences one scan prior to the first beam extraction. After computing the timing envelopes, the task loads the timing modules and initializes the other hardware components. Beam firing and software sequencing are initiated by a hardwired clock and timing system.

An interactive analysis and display task can be executed from a TOS once raw data disc files have been created. This program is a modified version of a program developed at LBL.³⁰ It executes a nonlinear multiple regression fit to the data to determine the Doppler-shifted line positions, widths, and amplitudes, and hence the amount of light associated with each peak. When performing the measurement in the neutralizer, knowledge of the amount of gas through which the beam has passed is necessary since the beam is in a transitory state at the point of observation. With estimates of the line-integrated gas density and measurements of the line shapes and magnitudes, it is possible to determine the beam composition at the point of extraction. An event-driven task capable of automatically performing the same function each pulse is under development. Processed data from this latter analysis task will be stored in a processed data base on an off-line VAX cluster.

II. RESULTS

A. MULTITRACK DATA

Of the two instruments, the one based on the 64 cm spectrometer is operational on TFTR beamlines 4 and 5, with the position of the central ion source on beamline 5 (source 5B) dedicated to the neutral beam test facility. Simultaneous data have been collected on up to four ion sources as shown in Fig. 5. During this pulse the beams were injecting into a TFTR plasma. A Polaroid of an x, y, z monitor of the real time output of the detector controller is shown for sources 4A, 4B, 4C, and 5A, top to bottom. The z output is a function of the signal intensity and wavelength increases left to right. Beam energies for this pulse were 85 kV for all beamline 4 sources and 87 kV for 5A. The tracks corresponding to the test facility and to ion source 5C lie below these four and were not activated during this particular pulse, since those sources were not operating.

Four spectrally resolved lines are evident for each track, the rightmost being the unshifted D_α line and the other three the Doppler-shifted beam component lines. Right to left the blue-shifted lines correspond to third-energy, half-energy, and full-energy atoms (arising from extracted D_3^+ , D_2^+ , and D^+ , respectively). The white band of light overlaying these lines on some of the tracks represents ions that are only partially accelerated. These ions charge exchange with gas in the grid structure and do not fall through the entire accelerating potential. As will be shown below, these atoms are highly divergent and can comprise a significant fraction of the extracted beam power.

The species corresponding to fractions of D^+ , D_2^+ , and D_3^+ at the extraction plane for this pulse are 0.56, 0.32, and 0.12, respectively, with little variation from source to source. Assuming equilibrium neutral

fractions (a good assumption for the TFTR beamlines), these fractions correspond to injected neutral particle fractions of 0.29, 0.44, and 0.27. Error bars are approximately $\pm 5\%$ for each species, and are dominated by uncertainties in the line density of gas between the extraction plane and field of view of the instrument. This uncertainty in the line density is due primarily to uncertainties in the temperature of the gas in the neutralizer.³¹ Agreement with typical values attained on test stands at LBL³² is within the error bars for the full-energy fraction but shows somewhat more D_2^+ and less D_3^+ than LBL, indicating slightly different gas efficiency.

B. COMPARISON OF DRIFT DUCT AND NEUTRALIZER MEASUREMENTS

Data were also acquired at the drift duct location indicated in Fig. 2. There are several significant advantages to using this location to measure the beam species. First, ions have been magnetically removed by the time the beam reaches this location. A small fraction (on the order of one percent) of the neutral particles reionize in the drift duct, but are quickly removed by the magnetic fields of the tokamak and do not affect the measurement. Ions are therefore not present to capture electrons into excited states. The only particles present of any significance are atoms at full-, half-, and third-energy. Therefore, the only cross sections required are for the excitation of these atoms into $n = 3$ states via collision with background gas molecules

(underlining implies a beam particle) and this cross section is well known.³³ Second, the measurement is independent of the line-integrated gas density

through which the beam has passed, and hence independent of any gas temperature effects taking place in the ion source or neutralizer. This is much simpler than the neutralizer case where 14 different types of particles and their excited states must be followed as a function of line-integrated gas density because the beam composition evolves from 100% charged particles toward equilibrium fractions of ions and neutrals. Any uncertainty due to errors in the estimation of the integrated line density are eliminated. Third, the charge exchange background has disappeared and any uncertainties in how to subtract it are gone. Last, the measurement is performed close to the point of injection where one would ideally like to measure it.

Figure 6 shows data taken at the drift duct location on the test facility. Concomitant with the significant advantages described above are several drawbacks. The gas pressure at this position is several orders of magnitude smaller than that in the neutralizer, yielding a signal that is several orders of magnitude smaller. Part of the reduced signal magnitude was recovered by opening the slits on the spectrometer to 700μ , from 25μ for the neutralizer measurement. The penalty for opening the slit is that instrument broadening swamps velocity distribution broadening and deconvolving the divergence becomes difficult. Another drawback of the drift duct location is that the fraction of the beam being observed decreases, but only slightly from the 65% mentioned earlier to approximately 50%.

By comparison, Fig. 7 shows data collected at the neutralizer location. Here the signal-to-noise ratio is improved, due to reasons just mentioned. One also notices that the background under the Doppler-shifted peaks is reduced when the measurement is carried out in the drift duct. The relative amount of background to Doppler-shifted peak is reduced by approximately a factor of three compared to the neutralizer measurement.

Based on a threefold reduction in signal over a distance of 7 m, assuming a beam divergence of 1.45° ($1/e$ half-angle) perpendicular to the grid rails, as measured via least squares fit to thermocouple data, and assuming that the divergence parallel to the grid rails of the partially accelerated particles is the same as the beam, one deduces that the divergence of these background particles is on the order of 15° ($1/e$ half-angle). Most of these particles never reach the end of the neutralizer. These partially accelerated particles would give rise to the non-Gaussian beam profiles seen by others.³⁴

III. SUMMARY

A Doppler-shift spectroscopy system installed on the TFTR neutral beam injectors has shown that simultaneous collection of data from several ion sources can be achieved. Large (600 μ) core fibers were used because of their large cross section and hence large collection area, and because they are, relatively speaking, easy to work with. Care was taken to design the system with no fiber-to-fiber couplings and their inherent loss of light. As a result, signal-to-noise ratios attained indicate that time resolution approaching the millisecond level may be possible for the beam composition measurement. An electronic shutter, controlled by CICADA, has been installed inside the SPEX spectrometer to perform this experiment. Spacing the fibers 1.7 mm center to center at the entrance slit yields excellent vertical separation of the tracks while allowing simultaneous viewing of data from six ion sources.

Experience has shown that the ideal location to monitor the composition of the neutral beam is in the drift duct connecting the beamline to the tokamak, not in the neutralizer. Concern over the exact shape of the background due to the partially accelerated particles is ameliorated by

monitoring the signal in the duct since the background level is reduced threefold. Measuring the beam after the neutralization is complete eliminates the need to know the line density of the neutralizer. Hence the measurement becomes independent of the gas temperature distribution in the neutralizer and of the gas throughput into the ion source. Knowledge of well-known cross sections is all that is necessary to make the measurement.

The background of partially accelerated particles is believed to comprise a significant fraction of power extracted from the ion source. Waterflow measurements produce results which show only 70% of the extracted power delivered to the calorimeter when the deflection magnet is off. We believe that most of this power is in the form of highly divergent, partially accelerated particles, and can be seen in the Doppler-shifted spectroscopic data. Estimates of the divergence of these particles is 15° , and only a small fraction of them actually reach the tokamak. In order to optimize injector performance every effort should be made to minimize this background level.

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FIGURE CAPTIONS

- Fig. 1. Schematic of the TFTR neutral beam injector Doppler-shift spectroscopy system. Shown are the flow of beam, light, and data.
- Fig. 2. Schematic elevation view of a TFTR neutral beam injector showing lines of sight, perpendicular to the ion source grid rails, in the neutralizer and drift duct.
- Fig. 3. Schematic plan view of a TFTR neutral beam injector showing the neutralizer line of sight parallel to the grid rails.
- Fig. 4. Phase space representation, at the ion source, of those particles emitted into the field of view of the collection optics. x is the horizontal coordinate and x' is the angle a trajectory makes to the x axis. Trajectories from the ion source emanating between the two diagonal lines are within the field of view.
- Fig. 5. Polaroid showing the real time display of the image on the detector. The brightness of the trace is a function of the signal intensity falling on the detector. Top ion source is 4A, followed by 4B, 4C, and 5A on the bottom.
- Fig. 6. Doppler-shifted spectrum obtained using the line of sight in the drift duct. Shown are the lines corresponding to the full-, half-, and third-energy atoms as well as the unshifted D_α line.

Fig. 7. Doppler-shifted spectrum obtained using the line of sight in the neutralizer. Shown are the lines corresponding to the full-, half-, and third-energy atoms as well as the unshifted D_{α} line.

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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