GA–A24021

IMPROVED CCD DETECTORS FOR HIGH SPEED, CHARGE EXCHANGE SPECTROSCOPY STUDIES ON THE DIII–D TOKAMAK

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This is a preprint of a paper to be presented at the Workshop on Scientific Detectors for Astronomy, Waimea, Hawaii, June 16–22, 2002 and to be published in the *Proceedings*.

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Work supported by
the U.S. Department of Energy under
Contract Nos. DE-AC03-99ER54463 and W-7405-ENG-48

GENERAL ATOMICS PROJECT 30033
JUNE 2002

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The tokamak plasmas utilized in magnetic fusion research provide access to some of the longest duration, highest temperature plasmas on earth. For example, on the DIII-D tokamak, plasmas lasting up to 10 seconds have been produced with ion temperatures up to 27 keV and electron temperatures up to 15 keV in toroidal plasmas with 1.7 m major radius, 0.65 m half width and 2.5 m vertical height. Typical particle densities in these plasmas are in the range of 2.0×10^{19} m^{-3} through 2.0×10^{20} m^{-3}. Spectroscopic measurements of line radiation from highly ionized atoms provide one of the key techniques for determining the plasma parameters in tokamak discharges.

Charge exchange spectroscopy [1] allows determination of ion temperature, poloidal and toroidal velocity, ion density and radial electric field E_r in high temperature tokamak plasmas. This technique is based on excitation of visible and near UV radiation from hydrogen-like and lithium-like ions via charge exchange with high energy (80 keV) neutral deuterium beams injected into the plasma. Spectroscopic lines used to date for these measurements include He II (468.6 nm), C IV (465.83 nm, 772.62 nm), B V (494.47 nm), C VI (343.37, 529.05, 771.68 nm), O VIII (297.57,434.04 nm), F IX (342.9, 479.4 nm), Ne X (524.90 nm), Ar XVI (346.3 nm), Ar XVIII (344.9 nm), Ca XXVIII (344.9 nm) and Ca XX (346.3 nm). Charge exchange spectroscopy has been one of the workhorse diagnostics on the Doublet III and DIII-D tokamaks since 1983 [2]. The ability to determine E_r, for example, has been essential in testing the model of $E\times B$ shear suppression of turbulence [3], which has revolutionized our understanding of turbulence in magnetized plasmas.

Key issues for charge exchange spectroscopy are the need for multiple spatial views, which demands detecting multiple spectra, while simultaneously obtaining millisecond time resolution. Our present system acquires spectra simultaneously from 40 different spatial locations across the plasma at 750 different times during the discharge. Our initial spectroscopic system utilized intensified linear photodiode array detectors [4,5]. For the year 2000 experimental campaign on DIII-D, we replaced the intensified photodiode array detectors on a portion of our system with advanced CCD cameras [6] mounted on faster (f/4.7) spectrometers [7]. The 16 spatial locations in this portion of the system are concentrated the edge of the tokamak plasma, which exhibits some of steepest spatial gradients and the most rapid changes in temperature, rotation speed and E_r. These cameras utilize the 652×488 pixel Pluto chip from SITe [8]. We are now in the midst of a similar upgrade on the portion of the system which views the plasma core. Relative to the intensified diode system, the new spectroscopic system has improved the photoelectron signal level by about a factor of 20 and the signal to noise by a factor of 2 to 8, depending on the absolute signal level. A major portion of the signal level improvement comes from the improved quantum efficiency of the back-illuminated, thinned CCD detector (70% to 85 % for the CCD versus 10%–20% for the image intensifier) with the remainder coming from the faster spectrometer. The CCD cameras also allow shorter minimum integration times: 320 microseconds while archiving to personal computer (PC) memory and 150 microseconds using temporary storage on the CCD chip. The PC memory option allows up to 8192 spectra per camera per tokamak shot, limited only by available memory, while the faster on-chip storage is limited to 254 spectra.

A detailed description of the design of the spectroscopic system and the detectors developed for the 2000 campaign has been published previously [9]. A key design feature is use of the split frame architecture of the CCD chip to measure two spectra per chip while maintaining high speed readout. A simple optical coupling system utilizing two planar mirrors allows use of two CCD cameras per spectrometer, thus reducing the number of spectrometers required by a factor of two.

An example of the high-speed spectroscopic results produced by the upgraded CCD system is shown in Figure 1. This shows the line brightness, Doppler temperature and toroidal velocity for several points near the plasma edge while the plasma is undergoing repetitive bursts of magneto-hydrodynamic (MHD) oscillations called edge localized modes (ELM). These MHD modes periodically reduce the confinement in the edge plasma, causing the reductions in temperature and rotation shown in the figure. One of these ELM bursts is shown in the figure. Also shown in the figure is the D_α brightness from another diagnostic; the D_α change is used as a marker for the onset of the ELM. The CCD data for this figure was taken at 0.332 ms integration time as part of a detailed study of the ELM dynamics. The distinct changes seen in rotation and temperature in 0.332 ms demonstrate the excellent time resolution of the CCD cameras.

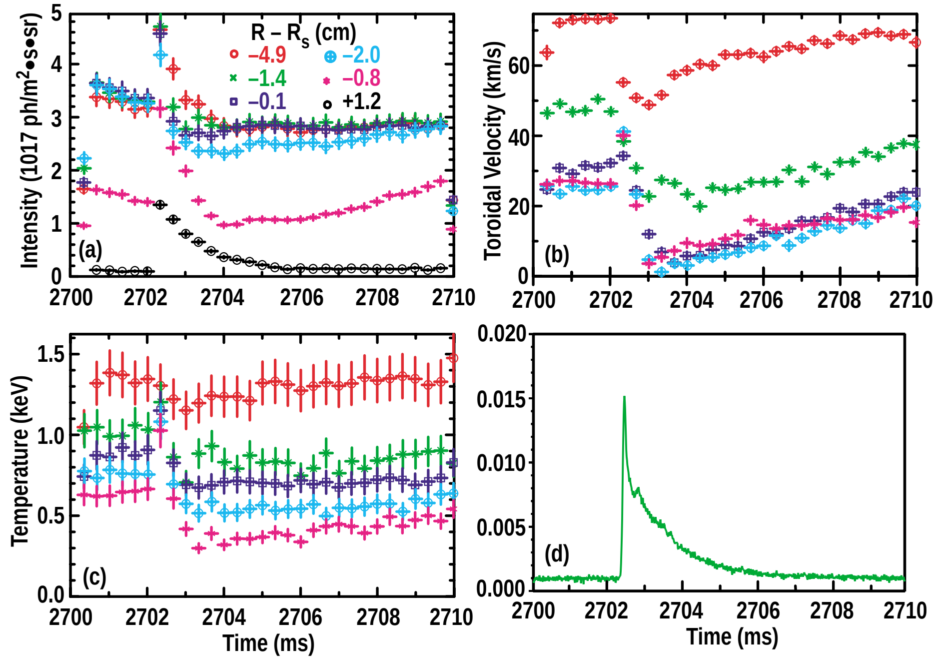

Figure 1. Plot of (a) edge C VI 529.05 nm line brightness, (b) toroidal rotation determined from C VI Doppler shift, (c) ion temperature determined from C VI Doppler line broadening and (d) D_α brightness from the divertor region of the D III-D tokamak. The measurements in (a-c) are made at the locations indicated on the figure. These locations in centimeters are relative to the magnetic separatrix which marks the edge of the plasma as defined by the location of the last closed magnetic flux surface. The time range shown includes the time when an edge MHD instability (edge localized mode) occurs, which rapidly alters the brightness of the C VI and D_α lines and quickly changes the rotation and ion temperature. The measurements in (a-c) are made at 0.332 ms intervals by the CCD cameras discussed in the main text. Note that on the locations closer to the plasma edge, the rotation and ion temperature first increase right after the ELM before decreasing again. The behavior would not have been detectable without the excellent time resolution of the CCD camera and the high quantum efficiency, which allows gathering sufficient photons to make good measurements in these short time intervals.

The use of a CCD chip for high speed spectroscopy demands a different optimization of the chip readout than is used for 2-D images. In our case, with one spectrum on each half of the chip, we bin all 251 rows of the exposure area in each half of the chip onto the serial registers prior to reading out the serial registers. This gives a minimum integration time of $m\tau_p + n\tau_s$, where m=251 is the number of rows, τ_p is the parallel row transfer time, n=340 is the number of serial pixels (including overscan) read out through each of the four readout nodes and τ_s is time to read out one of the serial pixels. For a 2-D image, the minimum integration time is given by $m\,(\tau_p + n\tau_s)$. In order to achieve high-speed, 2-D readout, this latter formula demonstrates that achieving as short a τ_s as possible is the key. τ_p plays little role in the overall readout time for 2-D readout. However, for high-speed spectroscopic use, τ_p and τ_s both need to be as short as possible, since m and n are comparable. Unfortunately, most commercially available CCD chips have τ_p values of 4 μs or longer even when they can achieve sub microsecond τ_s values. The 652 x 488 Pluto chip is exceptional in achieving a minimum τ_p of 600 ns in routine operation. The minimum τ_s value of 450 ns is set by the data acquisition hardware in the PC.

This work was supported by the U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463 and W-7405-ENG-48.

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