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Neutral-Beam Performance Analysis Using a CCD Camera

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We have developed an optical diagnostic system suitable for characterizing the performance of energetic neutral beams. An absolutely calibrated CCD video camera is used to view the neutral beam as it passes through a relatively high pressure (10^{-5}Torr) region outside the neutralizer: collisional excitation of the fast deuterium atoms produces H_α emission (λ=6561Å) that is proportional to the local atomic current density, independent of the species mix of accelerated ions over the energy range 5 to 20keV. Digital processing of the video signal provides profile and aiming information for beam optimization.

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INTRODUCTION

Present generation fusion experiments rely extensively on energetic neutral beams for plasma heating and fueling. In thermal-barrier tandem-mirror devices[1], neutral beams are also used to form sloshing-ion distributions in the end cells, and to remove electrostatically-confined cold ions from the barrier region. In these experiments it is important to determine the operating characteristics of the neutral-beams, preferably after their installation on the experiment. In this paper, we present a simple optical diagnostic technique useful for in-situ measurements of the total atomic current, beam aiming, and current-density profiles of neutral beam sources. Unlike calorimetry, the species mix of accelerated ions need not be known in order to determine the total atomic current. Also, it is not necessary to insert a target into the beam line to obtain the data.

The basic principles of the diagnostic are outlined as follows. The deuterium neutral beam is injected into a region filled to moderate pressure (10^{-5}Torr) with deuterium gas. Collisional excitation of the fast neutrals produces H_α emission (λ=6561Å) within the beam at a rate given by

$$I\left(\frac{\text{photons}}{\text{cm}^3 - \text{sec}} \right) = n_{D_2} \left[j_f\sigma_f + j_h\sigma_h + j_t\sigma_t \right] , \qquad (1)$$

where the subscripts refer to the full, half, and third energy components, respectively, and σ is the excitation cross section, v the velocity of the fast neutrals, and j(x,y,z) is the local neutral current density. The density of target molecules, n_{D_2}, is determined from pressure measurements, and must be sufficiently high (above $5\text{x}10^{-6}$Torr) to ensure that the H_α emission produced by collisional excitation exceeds that produced by the decay of long-lived residual high-n states produced in the source.

Unfolding the atomic current density from the H_α emission requires knowledge of the excitation cross sections, which have been measured[2,3] in the energy range of 100eV to 100keV. For energies appropriate to the TMX-U neutral beams (5 to 20keV) σ is nearly constant, and so the sum of terms in Eq. (1) may be replaced by the single value $\langle\sigma\rangle j_{total}$, with $\langle\sigma\rangle = 9\times10^{-18}\text{cm}^2$. Thus, the emission rate is proportional to the total atom current density, independent of the species mix of accelerated ions.

Using Eq. (1) to determine the atomic current density from the H_α emission requires that the photodetector be absolutely calibrated. Rather than use a photomultiplier tube, which provides information along a single line of sight only, we have calibrated a high-sensitivity CCD (charge-coupled device) TV camera and used it to image a short section of the beam line. When viewing normal to the beam axis, the value of each pixel of the resulting image corresponds to the surface brightness (B) given by

$$B\left(\frac{\text{photons}}{\text{cm}^2\text{-sr-sec}}\right) = n_{D_2}\int d\ell\, j(x,y,z)\langle\sigma\rangle, \qquad (2)$$

where $d\ell$ is along the particular line-of-sight determined by the camera optics and the pixel location within the image. Assuming a bi-gaussian current distribution (parallel and perpendicular to the camera line-of-sight) we may derive the current-density profile from the measured surface-brightness profile.

In the remaining two sections of this paper, we describe how this technique was used to characterize a 20keV Berkeley-type[4] source. In Section II, we give details of the experimental set up, including the electronics required for video image processing. In Section III, sample results are shown, together with a comparison with data obtained from other, independently calibrated, diagnostics.

III. DESCRIPTION OF EXPERIMENT

Initial experiments using a CCD camera to characterize a neutral beam were carried out on a test stand vacuum tank, shown to scale in Fig. 1. The source and neutralizer cell were mounted on one end of the tank, and a stainless steel (type 304) target was mounted at the opposite end, 330cm from the source grid. Pumping was provided by two cryo pumps mounted on the bottom, as shown. The base pressure before a beam shot was below 2×10^{-6} Torr, but deuterium gas from the neutralizer cell would raise the pressure during the shot to $1-4\times10^{-4}$ Torr.

In addition to the CCD TV camera (hereafter referred to as simply the H_α camera), several other diagnostics of beam performance were available. Both thermistors and a Faraday Cup (FC) were mounted on the target plate at a position corresponding to the center of the beam footprint. The thermistors were used to measure the total energy deposited on the plate during the shot; because the plate was thin (0.32cm) in relation to the beam footprint (8x40cm), thermal conduction across the plate was negligible and so the thermistors actually provided a measure of the peak energy deposition per unit area. The FC was used to collect the residual ion current in the beam, from which the peak neutral-current density as a function of time was obtained, assuming a 95% equilibrium fraction of neutrals.[5]

For comparison with the spatial profiles obtained with the H_α camera, an absolutely calibrated infrared (IR) camera was set up to view the front surface of the target. From these measurements we not only obtained the beam divergence, but the total power delivered to the plate. Given an independent measurement of the species mix from Doppler-shift spectroscopy[6] (the line of sight for these measurements is also indicated in Fig. 1), we could thus arrive at yet another estimate of the atomic current delivered by the beam.

A Sony XC-38 CCD TV camera was used in these experiments. The small size (1"x2"x5"), high sensitivity (3 lux), and insensitivity to magnetic fields make this an ideal camera for fusion research applications. It was mounted on top of the vacuum vessel, as shown in Fig. 1, and viewed a short segment (~50cm long) of the beam at 176cm from the source grid, normal to both the beam axis and the major axis of the elliptical beam footprint. The vacuum window was made from clear plexiglass, and introduced a 10% loss. A Bayard-Alpert ionization gauge calibrated for D_2 was mounted at the same port and used to record the background pressure during the beam pulse.

The camera optics consisted of a 16mm focal length, f/1.8 variable aperture lens. A narrow- band (λ_o=6561Å, 30Å bandpass) interference filter was mounted in front of the lens, making the camera sensitive to H_α emission only. The range of acceptance angles of the filter was such that there was some attenuation of the light emitted from the edge of the beam. In future measurements, a 100Å filter will be used to avoid the problem.

The camera and its associated optics were calibrated using a tungsten-ribbon lamp of known brightness, traceable to NBS. In addition to the absolute calibration, the limits of linearity of the camera and the signal processing electronics were documented using calibrated neutral density filters. Thereafter, the lens aperture was adjusted in order to always stay within the linear range of the system, which also minimized the effect of the automatic gain control circuitry of the Sony camera.

During a beam pulse, the video output of the camera was sent to a VCR (video cassette recorder, Sony BVU-820) for temporary storage on 3/4" magnetic tape, as shown in Fig. 2, which contains a block diagram of the signal processing system. In order to quantify the brightness recorded by the H_α camera, the video signals were digitized following storage on tape. Because video equipment is AC coupled, the DC baseline (the no signal, or black level) shifts with the average brightness of the scene. Consequently, it was found necessary to add a DC restoring amplifier to the signal path before the digitizer. Overall, the VCR and DC restorer preserved the absolute signal level with an accuracy of better than 1%.

The video data was digitized using a CAMAC compatible "frame grabber" (LeCroy 8857A) with 128kbytes of memory, which was sufficient to acquire one video field of 500x262 8-bit pixels which were then transferred to a computer (HP9920) for further processing. Since each beam pulse lasted 75msec, but a video field represents only a 16.7msec snapshot, it was necessary to use the VCR as a data buffer for the digitizer; after each shot, the data was replayed slowly, field by field, and the data was digitized. We note that this feature (individual field access) is not available on 1/2" format "consumer" recorders.

III. DISCUSSION OF RESULTS

Typical data used for analysis appears in Fig. 3. Here we show both the camera signals and the neutral pressure reading obtained during a 75msec beam pulse. Each trace represents the H_α brightness profile averaged over the previous 16.7msec, with the peak signal corresponding to a surface brightness of 4.5×10^{13} photons/(cm^2-sec-sr). The horizontal scale defines the position along the major axis of the beam footprint, relative to the beam centerline. From these profiles and the known distance to the source grid, a beam divergence of 3.5° is obtained, which is in agreement with the IR camera measurements.

Good agreement between independent diagnostics is also obtained for measurements of the total atomic current produced by the source, although not all of the data could be obtained on a single shot. From the H_α data, the total current is obtained by multiplying Eq. (2) by $a\sqrt{\pi}$, where a is the 1/e half-width as derived from brightness profiles such as those shown in Fig. 3. The right hand side of the equation is determined from the pressure data and the peak H_α brightness. Similarly, the total power delivered to the target may be obtained from the thermistor, FC, and IR camera data. Typically, we find that all three atomic current measurements agree to within 20%, thus establishing confidence in the H_α diagnostic technique.

ACKNOWLEDGEMENTS

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Fig. 1 Schematic of neutral beam test stand, showing the location of the diagnostics. OMA-optical multichannel analyzer for Doppler shift measurement.

Fig. 2 Block diagram of video signal processing electronics.

Fig. 3 Neutral pressures and H_α camera data obtained during a typical 75msec neutral beam pulse. The shaded region along the left-hand time axis shows the duration of the beam pulse.

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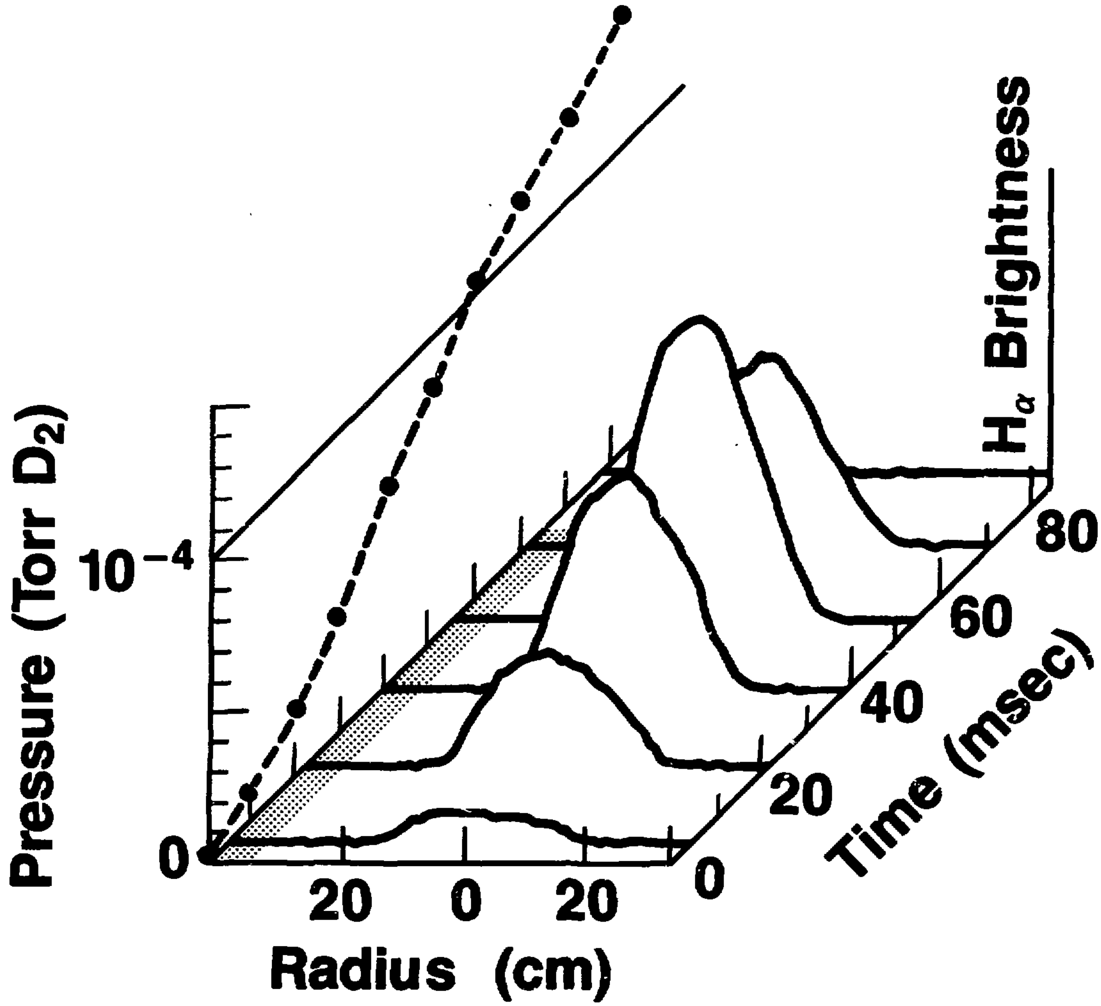
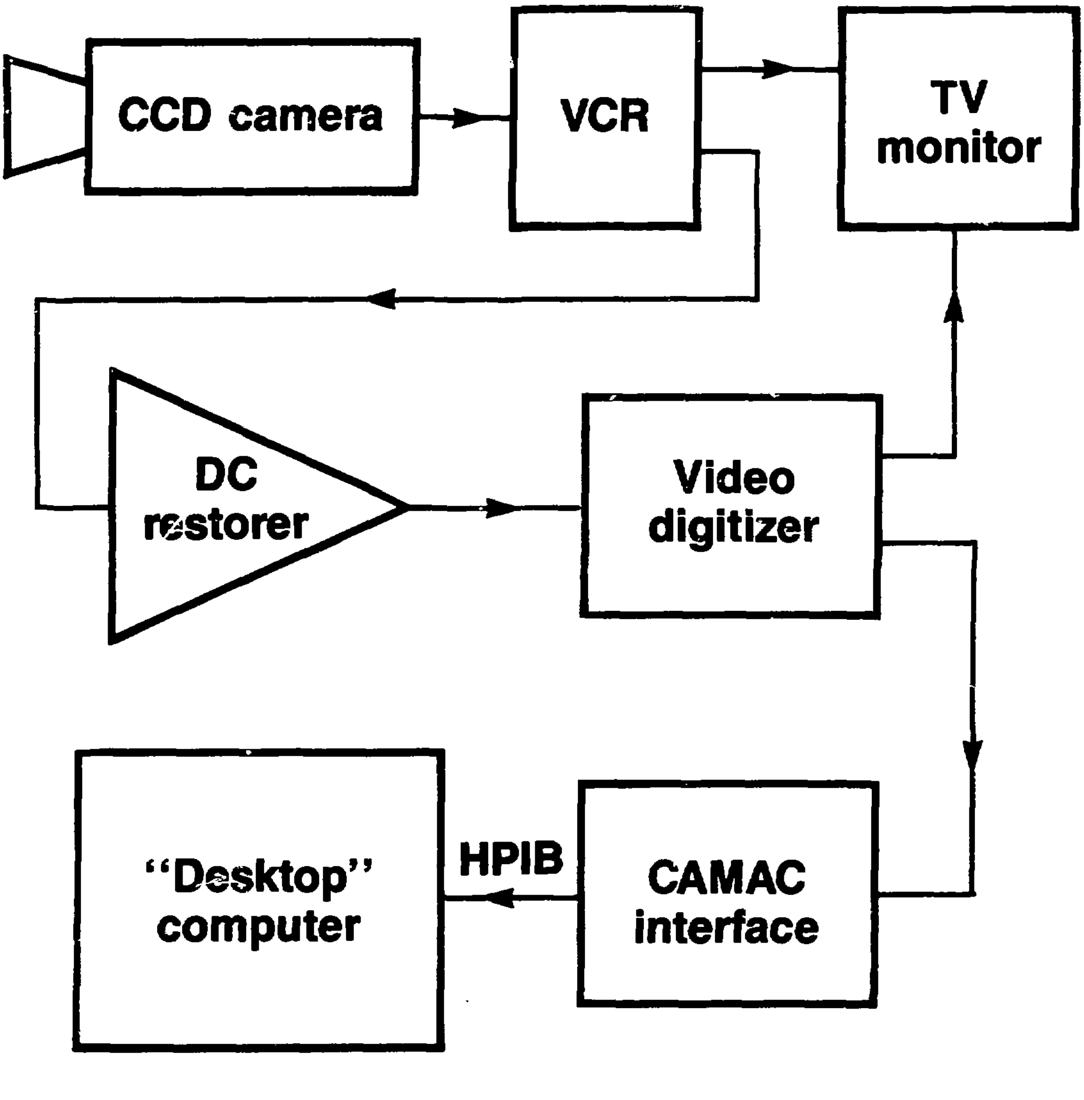


Pressure (Torr D_2)
10^{-4}
0
20
0
20
Radius (cm)
H_α Brightness
0
20
40
60
80
Time (msec)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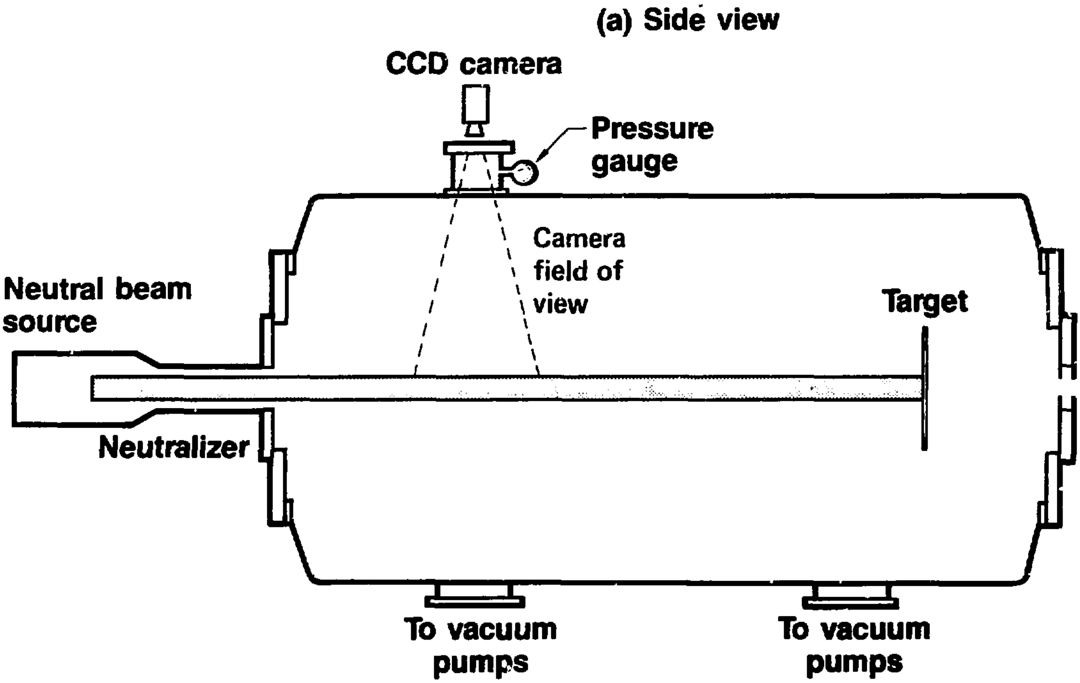
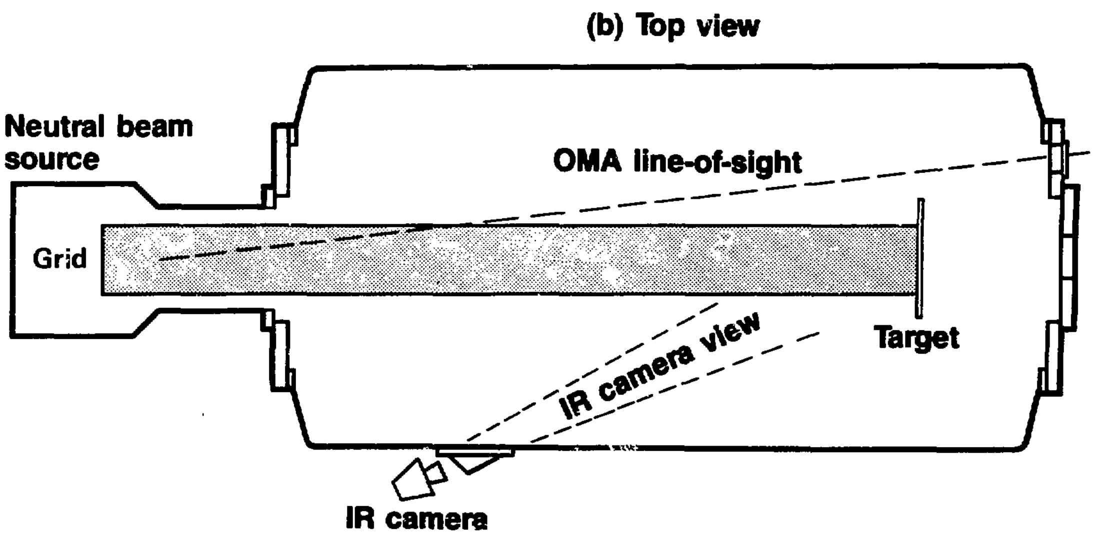
VCR
TV monitor
DC restorer
Video digitizer
"Desktop" computer
HPIB
CAMAC interface


(a) Side view
CCD camera
Pressure
gauge
Camera
field of
view
Neutral beam
source
Target
Neutralizer
To vacuum
pumps
To vacuum
pumps


(b) Top view
Neutral beam
source
OMA line-of-sight
Grid
Target
IR camera view
IR camera