Neutral Beam Emission Spectroscopy Diagnostic for Measurement of Density Fluctuations on the TFTR Tokamak

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Abstract

A multi-channel diagnostic for measuring low amplitude, long wavelength ($k_{\perp}\rho_i < 0.5$) density fluctuations along the outer half of the plasma has been installed on TFTR. It is based on observing fluctuations in the H_{α} fluorescence of a neutral heating beam due to collisional excitation from the plasma and impurity ions. Both radial and poloidal correlation lengths as short as 2-3 cm can be determined, with the spatial resolution limited primarily by the width and geometry of the three neutral beam sources. Optical fibers transmit the light from a 20-cm diameter vacuum window, re-entrant mirror, and lens assembly to sixteen interference filter/photomultiplier combinations located outside the radiation area. Initially, the fibers comprise a fixed 55-channel radial array and readily movable 10-channel vertical arrays which can be positioned at 27 radial locations. The filters are designed to accept the Doppler-shifted H_{α} emission from primary energy component of the neutral beam, and reject background lines and unshifted edge H_{α} . The measurable fluctuation amplitude (@ $S/N = 1$) is limited to 0.5% over a 100 kHz bandwidth by the photon noise associated with the DC level of the beam emission. The contribution of impurities to the total beam fluorescence will be determined directly by measuring impurity density fluctuations using charge exchange recombination emission from the $n = 8-7$ CVI line at 5292 Å.

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Introduction

Beam emission spectroscopy (BES) is a powerful non-invasive technique for measuring turbulence in a high temperature tokamak plasma, through the observation of fluctuations in the fluorescence of an energetic neutral beam as it strikes the background plasma and impurity ions. Localized variations in the collisional excitation and radiative decay of the fast beam neutrals results in fluctuations in light emission, giving a direct measure of the plasma density oscillations. After a series of feasibility studies were carried out on a 4-channel prototype diagnostic on the PBX-M tokamak,¹ a versatile multi-channel system has been installed on TFTR, where observations are made on fluctuations in the D_{α} recombination ($n = 3 \rightarrow 2$) emission @ 6561 Å from a 5 MW, 100 keV deuterium neutral heating beam. Operation in the visible spectrum permits the use of high-throughput optical systems and because fiber optics are used to transfer the light outside the radiation area, the diagnostic design can be simplified considerably.

Atomic physics plays an important role in determining the achievable resolution and sensitivity of the measurement.² The lifetime of the $n = 3$ excited state is long enough for emission to occur over 1.5-2 cm (assuming 100 keV deuterium beams). However, in the density regime of TFTR, multi-step processes collisionally excite or ionize the atom prior to radiative recombination, depleting the excited state. Thus the excited-state lifetime is considerably shortened, resulting in emission averaged over 0.5 cm. In addition, the depletion of the excited state decreases the intensity fluctuations relative to the density fluctuations, and the beam fluorescence becomes less sensitive to changes in plasma density at higher densities. The resulting saturation of the excited level population at high densities also depends on the plasma temperature and the neutral beam energy. For conditions in TFTR, useful sensitivity for D_{α} fluorescence is projected for densities up to $8.0 \times 10^{13} \text{ cm}^{-3}$.

One of the principal advantages of BES is the spatial localization of the measurement. Much like charge-exchange spectroscopy, the collected light is emitted

in a region only where the line-of-sight intersects the neutral beam. Because the density fluctuation correlation lengths are longest along the field lines, the greatest spatial resolution is achieved where the viewing sightlines are tangent to the field lines at the point of intersection with the neutral beam. To provide such a geometry, a new optical configuration was designed for TFTR, where the outer and central sightlines are illustrated in Fig. 1. In this design, light detection is localized within a relatively small volume ($\approx 2 \times 2$ cm across by 20 cm along the field lines) and the spatial resolution is limited by the radial extent covered by the line-of-sight as it traverses the width of the neutral beam. In each TFTR neutral beam line there are three ion sources with an angular separation of $\approx 4^\circ$ with the beams intersecting at the outer edge of the plasma. The spatial resolution is limited to about 1.0 cm where the beams cross at the edge, however, in the interior ($R = 265$ cm), the beams are separated by almost 15 cm, and the spatial resolution is only 5.5 cm. The interior resolution improves to about 2.5 cm if one of the ion sources (4c) is not used.

Because photon statistical noise ultimately limits the measurable amplitude of the density fluctuations, a new high-throughput optical port assembly was installed on TFTR. The collection optics are located in a diagnostic bay adjacent to the neutral heating beam duct, as close as possible to the beam, thereby providing the greatest light collection efficiency for a given lens aperture. The average distance from the lens to the beam is ≈ 250 cm. Viewing along the beam at an angle from 31° to 57° to the beam, the emitted light is Doppler-shifted red between 20 and 60 Å from D_α at 6561 Å (assuming 100-keV deuterium beams). The Doppler shift is essential to distinguish between the beam fluorescence and background D_α from the cold plasma edge and D_α fluorescence from other neutral beams.

In this paper the initial configuration of the BES diagnostic on TFTR is described. Also discussed are some of the considerations which influenced the design include maximizing light collection efficiency and spatial resolution, eliminating interfering light signals, providing adequate protection in a high radiation

environment, and allowing for potential expansion in the number of channels.

Experimental Apparatus

To provide a tangential view across the outer half of the plasma while utilizing a radially-oriented port, the design utilizes a re-entrant vacuum window and a mirror positioned on a 1/4" stainless steel support inside the vacuum vessel (see Fig. 2). The extent of the mirror and associated hardware is limited to 25 cm in front of the port flange to keep it 1.7 cm behind the vessel bellows cover plates so that there is no heat conduction directly from the plasma. In addition, the mirror is housed in a 1/16" thick stainless steel housing which acts as a thermal shield from the 30 W/cm^2 radiative heat flux. There is no direct mechanical coupling to the mirror, so any warping of the shield under the heat load does not affect the mirror position. The box is designed to withstand a maximum temperature of 380°C , which is anticipated for a duty cycle of 5-second maximum power RF heating pulses separated by a 5-minute cooling interval. The heat shield is blackened on both sides with a carbon coating to increase the emissivity of the stainless steel from 0.8 to 1.0 and enhance radiative cooling. The blackening agent is "TV Tube Koat" a carbon powder in a toluene vehicle.³ The toluene evaporates during drying, resulting in a smooth, flat black, vacuum compatible, uniform conducting coating, which is found to be resistant to arcing and peeling.

The 20×28 cm rectangular Vycor mirror (flat to 8λ) is supported on a 1/4" stainless plate which is electrically and thermally isolated from the housing to minimize eddy current stresses and heat loading on the mirror. The support is mounted on a gimbal to reduce thermal stresses transferred to the mirror and is adjustable to provide for *in situ* alignment. There is an observation slot to minimize the redeposition of carbon and metals on the mirror and window. A stainless steel gear-driven air-actuated shutter covers the slot during glow discharge cleaning and Ohmic discharges. The 8"-diameter fused silica vacuum window is located on a 10" copper-gasket vacuum flange, the largest bakable viewport readily obtainable. The mating flange welded to a 14" copper-gasket flange to provide access for mirror

removal and adjustment without requiring physical entry into the vacuum vessel.

To measure fluctuations at the 1% level, the optics are optimized for optical throughput while maintaining good spatial resolution. The large-aperture lens is 20 cm in diameter to match the size of the vacuum window, resulting in a $f/12$ collection angle. Utilizing the full numeric aperture of the fibers ($f/2$), requires a $6\times$ demagnification. The imaging objective is a 34 cm focal-length three-element compound lens with the fiber bundles placed 38 cm behind the lens. Each fiber optic bundle consists of four 1-mm core fused silica fibers in a 2×2 pattern. Fifty-five such bundles constitute the 14-cm long radial fiber array, which runs along an arc to compensate for curvature of the image field, and is tilted about the optical axis to bring the array into focus along the center of beam source 4b. The throughput of the collection optics is $6.2 \times 10^{-3} \text{ cm}^2 \text{ sr}$ for the central fiber bundle.

The lens is composed of three BK-7 glass convex elements and is similar to, but 14 times larger than, a common 1" focal-length eyepiece. Because the system is designed to operate only in the deep red portion of the visible spectrum, chromatic aberration is not corrected, and all surfaces are anti-reflection coated at 660 nm. Due to the limited permitted protrusion of the heat shield into the vacuum vessel, the size of the mirror is restricted. This design locates the aperture stop of the lens system 32 cm in front of the lens coincident with the front edge of the mirror. This maximizes the field-of-view for a given mirror size and avoids overfilling the mirror, preventing collection of light from the inner wall plasma limiter and from the bellows cover plate on the outer wall. While this design does not reduce the strong vignetting caused by these obstructions (up to 30% at the edge channels), it shifts it to a more benign location. In addition, this design minimizes the size of the mechanical aperture at the front of the mirror, thus minimizing deposition of foreign material during operation when the shutter is opened. Another advantage of this lens design is that the chief rays from all object points are parallel to the optic axis at the point of incidence on the fiber optic bundles, so that all the fibers are stacked parallel to each other.

The spatial resolution of the optical system due to various contributions are summarized in Table 1, for interior, middle, and edge views of the plasma. The resolution limit is approximately two channels wide and is dominated at the plasma's center by the finite beam width. The size of the fiber bundles are chosen so as to contribute only half as much resolution loss as that from the beam width. However, at the outer edge where the beams cross, the contributions are comparable, and some improvement in resolution may be realized by dividing the fiber array into 1×2 bundles and stopping down the collection lens if adequate light intensity permits. The additional loss of resolution due to the lens design is $\approx 10\%$ as determined from the point spread function. The contrast for adjacent fibers bundles is good as characterized by the MTF which is 0.88 at 2 lp/cm. These figures apply to both the sagittal and tangential directions and to both axial and off-axis points. For an ion gyro-radius ≈ 3 mm, this resolution is suited for studying long-wavelength ion modes and other moderate-to-large scale phenomena with $k_{\perp} \rho_i < 0.3 - 0.5$ depending on radial location. This diagnostic complements microwave scattering density fluctuation diagnostics which observe short wavelength modes with $k_{\perp} \rho_i > 2.0$.

In addition to the 55-channel radial array, 10-channel bundles are packed vertically in movable brass ferrules and positioned in a slotted mount immediately below the radial array. This allows a vertical scan while viewing along the magnetic field lines. These ferrules may be placed in any of 27 radial locations, and switched manually from slot to slot in a few minutes. In total, there are 325 locations available with a radial extent from the plasma center to the edge ($\Delta R = 80$ cm) and vertically from the mid-plane to 20 cm above. Initially, 220 fibers are allocated for the 55-channel radial array and 80 fibers in two 10-channel vertical arrays.

Spectrometers and Signal Level

The wavelength filters need to pass the Doppler-shifted light over a $40\text{-}\text{\AA}$ range, while excluding edge D_{α} , D_{α} fluorescence from other beams intersecting the line of sight, continuum radiation, molecular radiation and neighboring impurity

lines. The line-of-sight/beam (source 4b) crossing angles range from 34.2° at the center of the plasma ($R = 265$) to 56.0° at the outside edge ($R = 350$). Furthermore, the beam energy varies from 90 to 105 keV, and the angular separation between the ion sources is 4° . The resulting Doppler shifted wavelengths range from $6621.7 \text{ \AA}$ ($R = 265 \text{ cm}$; $E_{\text{beam}} = 110 \text{ keV}$; source 4a; first energy component) to $6579.3 \text{ \AA}$ ($R = 350 \text{ cm}$; $E_{\text{beam}} = 90 \text{ keV}$; source 4c; third energy component). The major interfering impurity lines are due to CII collisional excitation (6583 and $6578 \text{ \AA}$) emitted at the cold plasma periphery. Since the CII emission interferes with the second and third energy components two-thirds the way into the plasma, and the plasma attenuates these more than the primary component beyond this point, light from only the primary energy component is utilized. This allows the bandwidth of the filter be much narrower, reducing the transmitted continuum radiation, and simplifies analysis because the fluorescence is emitted from a beam with a single measurable energy. It is possible to tune the ion sources to different energies, so as to make the Doppler shifted light from the two beam nearly coincident, however the filters are designed to accept arbitrary beam energies ranging from 90 to 110 keV. Considering the angular spread of two ion sources and the additional angular width of $\pm 2.7^\circ$ due to the acceptance cone of the collection optics, an $8 \text{ \AA}$ -wide passband wide is required.

The narrowest readily available interference filters with this passband are 3-cavity filters, which have a 90% transmission passband inside 0.7 times the width of the filter. The filters employed are $12\text{-\AA}$ wide (FWHM) and are centered at $6621 \text{ \AA}$ to accommodate the farthest red shift. They are tilt-tuned up to 9° to center the filters down to $6597 \text{ \AA}$ and accept light as low as $6593 \text{ \AA}$, $2 \text{ \AA}$ lower than required. These filters attenuate to $< 1\%$ of the peak transmission beyond twice the width of the filter, so that $6583 \text{ \AA}$ is blocked. The filters are AR coated at 660 nm and the peak transmission is 70-80%. Blocking is $< 10^{-4}$ outside the passband for wavelengths up to $1.2 \text{ }\mu\text{m}$, necessary if silicon photodiode detectors are used. The 2"-diameter filters are housed in a telescope assembly with 2" f/2 optics consisting of simple plano-convex AR

coated elements and are tuned manually by tilting a rotatable stage.

Assuming that all unshifted edge D_α , fluorescence from other beams, and CII excitation are blocked, there are still several potential sources of interfering signals which are not associated with localized density fluctuations. The first is fluctuations in continuum emission (bremsstrahlung) through the passband of the filter. Initial checks on the PBX-M prototype have shown no detectable background bremsstrahlung. Even integrated along the entire line-of-sight through the TFTR plasma, the bremsstrahlung is expected to be less than 5% of the signal. Unless Z_{eff} fluctuations are considerably larger than density fluctuations, this is a modest contribution.

Z_{eff} also contributes directly to the fluorescence. The collisional excitation cross sections of the beam-plasma interaction scale with q^2 , where q is the charge of the plasma ion.⁴ Therefore, in a single-step excitation model, the intensity should scale with Z_{eff} . This effect is measured with the same apparatus, but it is not the beam fluorescence which is measured. Recombination emission from charge exchange excitation of the plasma by the beam is measured the CVI line ($n = 8-7$) at 5292 Å, as is done routinely with the CHERS ion-temperature diagnostic. The carbon emission, being the primary impurity, gives a representative indication of the Z_{eff} fluctuations.

Plasma density fluctuations cause variations in neutral beam attenuation, and this may affect the measurements further inside the plasma. However, the beam attenuation cross section does not vary with plasma density⁴, and the effect of the density fluctuations, averaged over the beam trajectory, should be small as long as the line-averaged density does not vary in the frequency range of interest. This contention is supported by observations in PBX-M, where strongly fluctuating modes localized at the edge of the plasma were observed, while the disturbances were not observed in the signals from the plasma interior.

Finally, fluctuations in the neutral beam intensity can give rise to an independent noise spectrum. Therefore, the beam intensity itself is monitored routinely with a high-throughput telescope that has been installed on the TFTR beam duct. The

spectrum of the beam fluorescence, excited by the residual neutral gas in the duct before it strikes the plasma, is compared to the plasma signal. The telescope can observe off the midplane to check spatial uniformity and views towards the beam at 30° so fluctuations in the individual energy components can be distinguished. The filter for the beam duct monitor includes all three energy components because there are no impurity lines near the blue-shifted emission. Preliminary measurements on TFTR using a low-throughput beam monitor indicates that narrow band ($\Delta f = 250$ Hz) beam intensity fluctuations to less than 1% should be detectable.

Ultimately, it is the quantization noise from the individual photons that limit the sensitivity of the measurement. Initially, the detectors are high quantum-efficiency photomultiplier tubes with enough internal gain to overwhelm any thermal and amplifier noise; Hamamatsu R636 Gallium Arsenide (60 mA/W, 12% QE @ 660 nm) side-on photomultiplier tubes. The expected photon flux at the wavelength of the primary energy component of the 100 keV TFTR neutral heating beams with a current density equal to 12.2 mA/cm^2 is $3.25 \times 10^{13} \text{ photons/cm}^2/\text{sr/sec}$ per source. Allowing for two beam sources to cancel a factor of two loss in the optics, fibers, and filters, the source brightness multiplied by the optical throughput gives a incident power of 30 nW on the detector. Multiplied by the cathode response, the photocathode current is 1.80 nA. The challenge of this measurement is detecting wide bandwidth fluctuations with a 100:1 signal-to-noise ratio in the presence of the photon noise⁵ associated with the photocathode current, $(2qI_{\text{cath}})^{1/2}$, which is $2.4 \times 10^{-14} \text{ A}/\sqrt{\text{Hz}}$. Assuming a 20% excess noise factor in the PMT's dynode amplification, and a gain of 550 to keep the anode current below $1 \mu\text{A}$ to prevent anode heating, the amplified photon noise is $1.6 \times 10^{-11} \text{ A}/\sqrt{\text{Hz}}$. The photomultiplier's anode dark current is only 0.1 nA at 800 V, or 0.01% the signal level, and contributes a negligible 1% to the photon noise. Owing to the relatively large input capacitance from the connecting cables, a low input voltage noise (3 nV/ $\sqrt{\text{Hz}}$), wide bandwidth pre-amplifier (Harris HA-5147) is employed and the amplifier noise contributes only about 1.2% to the total noise. For a fluctuation

bandwidth of 100 kHz as was observed in PBX-M, a fluctuation amplitude 0.5% of the DC signal would equal the noise level. RMS averaging of 16 of these spectra allows fluctuations to be detected down to approximately 1/3 of the noise level.

The signal bandwidth is limited to 300 kHz by a 6-pole Butterworth anti-aliasing filter which cuts off at 450 kHz and has a 300-600 kHz transition band. The bandwidth is designed to be 1/4 of the 1 MHz maximum sampling rate of the LeCroy 6810 waveform digitizer when operating in four-channel mode, allowing a comfortable margin for the width of the anti-aliasing filter transition band beyond the Nyquist criterion. Initially, 16 channels are recorded on four transient recorders over a 256 msec interval. Each channel has a 256 ksample (0.5 MByte) memory for a total data acquisition load of 8 MBytes. The waveforms are typically binned into 256 1-msec intervals, and the FFT calculation provides 256 300-kHz spectra for each channel. A summary of the capabilities of TFTR's BES diagnostic is presented in Table 2.

Significant improvements in signal-to-noise may be achieved by increasing the quantum efficiency (QE) of the detector and reducing the photon noise. Silicon photodetectors are being considered as replacements for the PMT's. With a suitable AR coating, QE's of 90% can be realized at 660 nm, resulting in a factor of 6 increase in signal for a factor of 2.5 improvement in signal-to-noise. At these bandwidths, a 10-20 $\times$ gain of an avalanche photo-diode is adequate to overcome the thermal noise and amplifier noise, however, the avalanche amplification introduces a 50% excess noise factor.⁶

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References

- ¹Fonck, R.J., Duperrex, P., Jaennig, K.P., and Paul, S.F., Bull. Amer. Phys. Soc., 34 (1989) 2049.
- ²Fonck, R.J., Proceedings Eighth Topical Conference on High-Temperature Plasma Diagnostics, Hyannis, MA. May 6-10, 1990.
- ³TFTR vacuum materials committee, material #057.
- ⁴Janev, R.K., Boley, C.D., Post, D.E., Nucl. Fus., 29 (1989) 2125
- ⁵Horowitz, P. and Hill, W., The Art of Electronics, 2nd ed., Cambridge Univ. Press (1989) 431.
- ⁶Webb, P.P., McIntyre, R. J., and Conradi, J., RCA Review, 35 (1974) 234.

List of Figures

Fig. 1. Plan view of the TFTR vacuum vessel illustrating the BES sightlines and the neutral beam lines.

Fig. 2. Detail of the optical configuration of the BES diagnostic on TFTR including collection optics, mirror, shielding box, shutter, and sightlines.

Contribution to Loss of Spatial Resolution

<u>location</u>	<u>beam width</u>	<u>fiber width</u>	<u>f/no. spread</u>	<u>aberrations</u>	<u>resolution</u>
R = 265	2.65 (61%)	1.73 (26%)	0.65 (4%)	1.01 (9%)	3.38
R = 310	2.00 (56%)	1.40 (27%)	0.83 (10%)	0.70 (7%)	2.27
R = 350	1.00 (26%)	1.18 (37%)	0.96 (24%)	0.69 (13%)	1.95

Table 1. Achievable spatial resolution set by various contributions in the optical system at the center, half-way to the edge, and edge of the plasma. Figures are in centimeters. Figures in parentheses are relative contributions assuming that the individual contributions are incoherent. Beam width calculation assumes only 2 of 3 beam sources (4a and 4b).

Summary of Capabilities

fluctuation resolution	0.5% ($\Delta f = 100$ kHz, $S/N = 1.0$)
spatial extent	265 - 350 cm (radially) 0 - 20 cm (vertically from mid-plane)
number of sightlines	55 radially along the mid-plane 10 vertically at any of 27 radii
spatial resolution	1.9 - 3.4 cm
analog bandwidth	300 kHz
number of data channels	16
sampling rate	1 MHz
sampling duration	256 msec
data acquired	8 Mbyte

Table 2. Summary of capabilities of the TFTR BES diagnostic

FIG. 1

FIG. 2