Beam emission imaging system for 2D plasma turbulence measurements

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A two-dimensional analog to the beam emission spectroscopy (BES) diagnostic has been designed to acquire vorticity and plasma flow-field information by resolving the spatial and temporal intermittency of plasma turbulent structures. The beam emission imaging diagnostic measures collisionally induced neutral beam fluorescence to infer local plasma density variations. It consists of a high-throughput, interline-transfer CCD camera viewing, with narrow spectral bandwidth, a 10 cm high diagnostic neutral beam as it traverses the plasma. The camera is coupled to a gated image intensifier that provides for two images with exposure times up to a few ms to be separated by as little as 10 μs. Sensitivity to density fluctuations of $\tilde{n}/n > 1.0\%$ is expected using the Phaedrus-T beam operating at 20–25 keV in He^0 or D^0.

I. INTRODUCTION

The beam emission spectroscopy (BES) diagnostic on TFTR has provided a great deal of information about plasma turbulence inside the confinement region in tokamaks, and, in particular, radial and poloidal correlation coefficients, $\rho(\Delta_{r,\theta})$, and wave-number spectra, $S(k_r)$ and $S(k_\theta)$, have been determined.[1] The current BES system on TFTR is not, however, able to measure accurately the phase relationship between $S(k_r)$ and $S(k_\theta)$ to derive the two-dimensional wave-number spectrum, $S(k_r,k_\theta)$.

The beam emission imaging (BEI) diagnostic discussed herein will be able to determine directly the $S(k_r,k_\theta)$ spectrum by acquiring two-dimensional images of the density variations. The degree of spatial intermittency of the turbulent structures can also be resolved by analyzing these variations in a given image. If two successive pictures are taken within a decorrelation time τ_c, temporal intermittency of density structures and bulk plasma flow-field information can be resolved. The flow-field measurements can then be used to ascertain the local vorticity of the plasma.

II. DIAGNOSTIC SYSTEM CONCEPT

In analogy to the temporal intensity fluctuations measured at a single spatial point with BES, BEI measures spatial intensity fluctuations at a fixed time. To accomplish this, a BEI system employs a high resolution 2D imaging array with maximum sensitivity (to minimize photon statistical noise) to view fluorescence from a diagnostic neutral beam (DNB) as it traverses the plasma. As in BES, high-throughput collection optics are employed on the tokamak, and achievement of photon-statistical-noise-limited signals is required.

Both BEI and BES measure the photon emission from collisionally excited neutral particles in the DNB. First, the fast neutral has a collision with either an electron, ion, or impurity ion that excites the neutral. As the atom relaxes, it will decay either back to the ground state or to an intermediate excited level and emit a photon of a particular frequency indicative of the transition. By employing spectral filters, BEI and BES measure only photons from a particular transition, and because the DNB has an energy much higher than the background plasma, light due to the beam neutrals will be Doppler shifted away from that due to the background plasma edge component.[2]

A 2D image of the local density field via BEI will exhibit plasma turbulence through local small-amplitude variations in intensity on scale lengths of order 1–3 cm. As such, BEI measurements will be much less sensitive to global beam density variations arising from beam source fluctuations and fluctuating beam attenuation induced by strong modulations in the edge plasma.

The spatial resolution, and hence the accessible ranges in k_r and k_θ, are determined by the viewing optics, the finite width of the beam, and the finite lifetime of the measured excited state. This lifetime gives the excited atom time to move to a different location in the plasma before photon emission, and thus the local density measurement will be smeared out over that distance.[2]

The finite lifetime, if long compared to the mean collision time, can also provide enough time for the excited atom to collide with another plasma particle which could either ionize the particle from its excited state, or force the particle to relax (collisional de-excitation). The rate of excitation increases with plasma density, but the probability of further collisions is also enhanced, and the population of excited atoms saturates as a result.[2] Because of this, the relative intensity fluctuation level $\tilde{I}/I$ is not necessarily equal to the density fluctuation level $\tilde{n}/n$; in Phaedrus, $\tilde{I}/I \approx (1/3)(\tilde{n}/n)$ for H_α while $\tilde{I}/I \approx (2/3)(\tilde{n}/n)$ for He (the lifetime of the transition of interest is much shorter for He than D).[2,3]

Thus the requirements for a BEI system is that it provide a spatial resolution of <1 cm (for $k \leqslant 3\ \mathrm{cm}^{-1}$) and a sensitivity to variations in intensity of 0.5% or less to allow observations of turbulence with $\tilde{n}/n \approx 1\%$. In addition, at least 8–10 resolution elements in the plasma image plane are desired to allow derivations of the shape of the turbulent structures, and hence $S(k_r,k_\theta)$.

Finally, successive images can be differenced to observe the time evolution of these structures and hence provide information on the turbulent flow fields. Of course, each image must be acquired with a total exposure time much less that

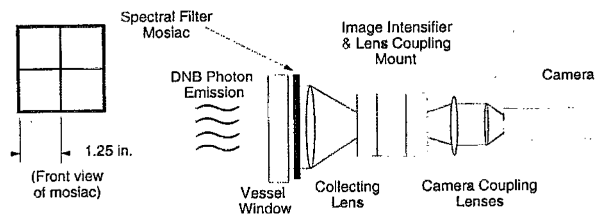

FIG. 1. Optical layout for the beam emission imaging detection system.

the local turbulence decorrelation time, which typically is found to be 10–100 μs.

III. PROTOTYPE DESIGN

A prototype experiment has been constructed on the Phaedrus-T tokamak to test the feasibility of making BEI measurements. The beam sightline geometry is optimized on Phaedrus-T, and the DNB energies are in the range of 20–25 keV.[4] The spatial resolution, considering the effects discussed above, is approximately 1.0 cm for a D^0 beam and 0.3 cm for a He^0 beam.[2]

Figure 1 illustrates the optical system for the prototype experiment. The spectrally filtered (1 nm bandpass) DNB emission ($\lambda=656$ nm for D^0, $3\rightarrow2$ transition, $\lambda=587$ nm for the He^0 $3\rightarrow2$ transition) is collected and focused onto a Varo Inc. GEN-II type image intensifier. The intensifier acts as a light amplifier and as a very fast shutter (effective gate times can be <1 μs). The output of the intensifier is then 2:1 reduced onto a Pulnix model TM-745 camera employing an interline-transfer CCD detector. A Dipix Technologies P360F frame grabber board installed in a local PC digitizes the RS-170 (standard video) signals from the camera.

The present video digitizer samples data at 8-bits per pixel, and summing of adjacent pixels is employed to reduce the bit noise to values well less than the desired intensity fluctuation sensitivity. For example, a 4×4 square binning of the digitized data gives a bit noise of 0.1%, while reducing the effective array of pixels in the image from 628×237 (camera resolution in a single field) to 157×59, which still provides more than enough spatial sampling in the image.

The camera has been configured to read out the CCD chip in "field" mode (noninterlaced video) as opposed to "frame" mode or interlaced video. Two independent images can be acquired using field mode at the cost of half the vertical spatial resolution. The entire active part of the detector is moved into the masked (dark) readout buffer every 16.7 ms, and the process of moving the image to the masked area takes only 10 μs.

The vertical sync signal (derived from the RS-170 video signal) indicates (every 16.7 ms) when the camera is shifting the pixels into the readout buffer. By gating on the image intensifier just before and just after a vertical sync transition, two independent, time resolved images which are separated by as little as 10 μs (see Fig. 2) can be acquired. This should be fast enough to acquire flow-field information from the turbulence ($\tau_c\approx10$–100 μs).

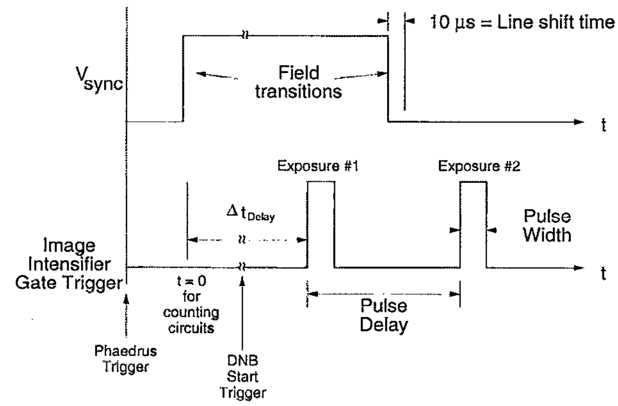

FIG. 2. Vertical sync trace (derived from RS-170 signal) and image intensifier gate trigger timing diagram.

IV. PRELIMINARY TESTS AND FUTURE PLANS

Using the low quantum efficiency (QE$\approx$4% at 587 nm) GEN-II type image intensifier, initial observations of the Phaedrus DNB were made. Figure 3 shows a schematic of the experiment, where the camera views a 10 cm wide region near the plasma edge. The He^0 beam is roughly 10 cm high and 5 cm wide, and effectively acts as a sheet beam since the optical sightlines are tangent to the local flux surface in the beam–sightline intersection volume. Though the system was able to see the beam, it was not sensitive enough to confidently observe fluctuations.

Several improvements to the prototype are presently being installed, including larger collection optics, a more quan-

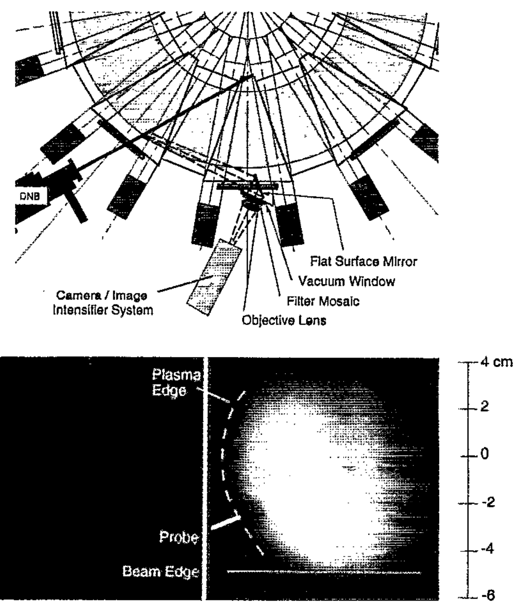

FIG. 3. Viewing geometry of the BEI diagnostic on Phaedrus-T (top) and images of the edge neutral helium beam fluorescence observed just before (bottom left) and during (bottom right) the beam pulse. The bottom edge of the beam can be made out at −5 cm, and the feature on the left at a midplane height of −3 cm is a probe that is out of focus. Also, the vertical line feature seen just right of center is an artifact of the image intensifier. ($t_{exp}=500$ μs; $\Delta t=16.7$ ms between left and right frames.)

tum efficient GEN-III type intensifier (QE≈15% at 587 nm), and a more sensitive CCD camera. With these advances, the system should be capable of detecting local turbulence of order $\tilde{n}/n \approx 1\%$. Initial experiments will concentrate on the large amplitude edge fluctuations, which have been measured using BES and other fluctuation diagnostics to be much larger than the core fluctuations;[1,4,5] hence, they should be easier to see. The edge is also a good place to compare results from Langmuir probe studies and BES experiments on Phaedrus-T [4,6] and with previous edge imaging work done on other tokamaks.[7–9] Afterward, the system will be focused inside the edge to make core fluctuation measurements.

Also, an area-scan CCD camera with high frame readout rate, but lower spatial resolution, is under consideration as a means of acquiring better statistical measurements of vorticity and the turbulence spectrum. This new camera is a 64×64 slow-scan camera that can read out 2700 frames per s. Instead of acquiring only one pair of frames separated by 10 μs per DNB pulse, this new camera will be able to capture 20 pairs of frames separated by at least 17 μs. Both cameras have their signals digitized to eight bits, but the new slow-scan camera can be upgraded in the future to 12-bit digitization.

V. SUMMARY

The goals of the BEI diagnostic are to complement the BES and other fluctuation diagnostic results by determining the $S(k_r, k_\theta)$ spectrum, to resolve the spatial and temporal intermittency of any plasma turbulent structures, and to acquire information on flow field and vorticity in the plasma. A $\tilde{n}/n$ sensitivity of about 1.0% is expected in the confinement region of Phaedrus-T despite complications due to beam attenuation and other beam physics. The prototype experiment described above should provide a deeper insight into the nature of plasma turbulence and a better understanding of the diagnostic itself which would facilitate refinements in an improved future system for deployment on large fusion facilities.

ACKNOWLEDGMENT

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