Beam Emission Spectroscopy for density turbulence measurements on MAST

D. Dunai[1], A.R. Field[2], N. J. Conway[2], A. Thyagaraja[2], S. Zoletnik[1], J. Sárközi[1]

[1]*KFKI-RMKI, Association EURATOM, P.O.Box 49, H-1525, Budapest, Hungary*

[2] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

Introduction

A trial beam emission spectroscopy (BES) system has been installed on the MAST spherical tokamak to characterize the low-amplitude, high-frequency density turbulence. The intensity of the Doppler-shifted, visible D_α emission from the D^0 heating beam is approximately proportional to the local electron density. Although the heating beams are typically 10-20 cm wide (FWHM), by observing along the direction of the field lines, it is still possible to detect fluctuations with perpendicular scale lengths of a few cm, since the flute-like turbulence is elongated along the B-field, i.e. $k_\perp/k_\parallel >> 1$. Competing numerical models of plasma turbulence predict that anomalous transport can arise from fluctuations over a wide range of spatial scales, from the system size down to the electron gyro-radius ($0.01 < k_\perp/\rho_i < 100$). Simulations with the two-fluid, reduced MHD code CUTIE indicate the possible importance of low wave number ($k_\perp\rho_i < 1$), meso-scale fluctuations for the anomalous transport, which are typically at frequencies of 0.1-1 MHz and amplitudes of $\delta n_e/n_e < 1\%$ [1]. An advanced BES system has been implemented on the DIII-D device utilising the heating beams, which is capable of measuring 2D images of the core turbulence, fast particle driven modes and other MHD activity [2]. The trial BES system has been implemented on MAST with the aims of: detecting the presence of meso-scale turbulence at the 1% level, testing electronics developed for the APD detectors and also of benchmarking simulations of the beam emission, which are to be used to predict the performance of a more extensive BES 2D imaging system which is planned for MAST.

Diagnostics

The trial BES system utilises the collection optics of the charge-exchange recombination spectroscopy (CXRS) system [3] and images 8 spatial channels ($\Delta R \sim 4$ cm) over the gradient region of the plasma (1.1 m < R < 1.4 m) onto large area Avalanche Photo-Diode (APD) detectors (5×5 mm^2) with high quantum efficiency (QE < 85%), equipped with custom amplifiers to provide measurements at up to 1 MHz bandwidth. The D_α (656.1 nm) fluorescence of the D^0 heating beam ($E_0 \sim$ 40-50 keV) is Doppler-shifted by 2-3 nm to the red. A single interference filter is used ($T_{max} \sim 55\%$, $\lambda_0 \sim 659.0$ nm, $\Delta\lambda_{FWHM} \sim 1$ nm) to separate the beam emission from the higher intensity edge emission. The main contribution to the background is the CII (657.8, 658.3 nm) doublet. By tilting the filter the contribution from this edge emission to the core channels can be minimised. The system views the SW beam, which is fitted with a duo-pigatron ion source and has a FWHM ($w_{½}$) ~ 20 cm, from a port 0.4 m below the mid-plane to view approximately along the B-field. The other beam at

MAST is fitted with a PINI source producing a more collimated beam ($w_{½}$ ~ 11 cm) and is hence brighter but at present no suitable port is available to view this beam along the field direction.

A numerical simulation of the BES diagnostic has been developed, which models the attenuation and excitation of the beam using atomic data from the ADAS database [4], the étendu of the collection optics, filter transmission, detector characteristics and calculates the noise level, both from the photon statistics and the electronics. The predicted line-integrated intensity is 4×10^{17} $\gamma m^2 s^{-1} sr$ for a typical channel through the beam at 1.4 MW power level, which results in ~ 1×10^3 detected photons in the 0.5 μs integration period. The minimum level of detectable plasma fluctuations is limited by the statistical photon noise, with $\delta n_e/n_e \propto 1/N^{1/2}$ where N is the number of photons detected in the integration period. Hence, this corresponds to a photon noise level of ~ 3% at 1 MHz bandwidth. The APD detectors have an internal gain of ~ 50 at 360 V bias voltage and custom, high-frequency, ultra-low-noise amplifiers are used in a temperature-stabilized housing. At 2 MHz sampling frequency the Poisson noise dominates the electronic noise at detected photon rates above 5×10^9 γs^{-1}. The sensitivity of the APD system to incident photons is measured to be ~ 2×10^7 γ/mV. The data acquisition system utilises an 8 channel, 2 MHz ADC with 14 bit resolution.

The spatial resolution is limited by the de-excitation time τ_D of the excited state, which is much shorter than the spontaneous radiative decay time $\tau_r = 1/A_{ij}$ ~ 15 ns when the effect of collisions is considered. Calculations [5] for a 50 keV H^0 beam at typical tokamak densities result in an estimated de-localisation along the beam of ~ 1 cm, i.e. τ_D ~ 3 ns. As well as this fundamental limit, the spatial resolution is also limited by the line-of-sight integration through the beam emission and the curvature of the B-field. Using the simulation calculations, this spatial delocalisation is estimated to be ~ 3-6 cm, increasing with the observed radius.

Results

The evolution of the beam emission signal from an edge channel is shown in Fig. 1 for a discharge with 1.3 MW NBI heating power. At the beam cut-off time the beam emission intensity is also seen to decrease rapidly, which is the signature of the prompt beam fluorescence. The signal level of 40-80 mV corresponds to an intensity in the range 2-5×10^{17} $\gamma m^2 s^{-1} sr$, which agrees within 20% with the predicted intensity from the simulation. At this photon rate the electrical noise ~ 8 mV dominates over the photon noise. The residual intensity observed immediately after the NBI cut-off represents the level of background light observed in the signal which is typically 5-10% of the total signal level.

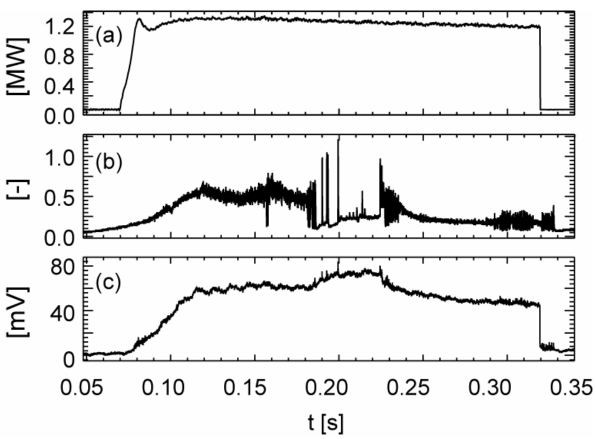

Fig. 1 Evolution of (a) SW NBI power, (b) D_α intensity and (c) beam emission intensity from ch. #3 during discharge #17068 exhibiting L- and H-mode phases.

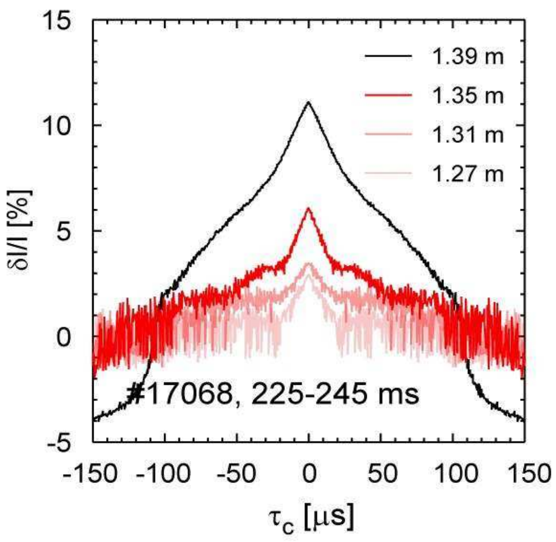

Fig. 2 Square root of the auto-covariance of BES signals normalized with the signal level from chs. #2-5 during an L-mode phase of the discharge shown in Fig. 1.

As the bandwidth of the noise is much broader than the frequency band of the density fluctuations, correlation analysis techniques [6] can be used to remove the noise and determine the level of any underlying correlated fluctuations in the signal. By calculating the temporal auto- or cross-correlations of the signals over a period T ~ 10-100 ms, i.e. much longer than the integration period, the effective SNR can be increased at the expense of losing temporal information. From such analysis the characteristic de-correlation time τ_C, relative fluctuation amplitude levels and the radial propagation delay of turbulent structures can be extracted. The covariance of signals $\tilde{S}_i(t)$ from two channels is defined as $C_{ij}^S(\tau) = \int_0^T \tilde{S}_i(t)\tilde{S}_j(t+\tau)dt/T$, where the intensity distribution can be written as a sum of an average and a fluctuating part, $S(t) = S^0 + \tilde{S}(t)$. The auto-correlation of selected radial channels is shown in Fig. 2 for the later L-mode phase of the discharge shown in Fig 1. In the outermost channel, observing just inside the separatrix, relatively high amplitude structures ($\delta I/I$ ~ 10 %) are observable with long de-correlation time (τ_c > 100 μs).

The character of the edge turbulence changes strongly in the H-mode phase. Density perturbations of ~ 10% amplitude produced by coherent MHD activity at ~ 5 kHz are frequently observed in the edge channels. Superimposed on this, turbulent fluctuations with ~ 2% amplitude and τ_c ~ 20 μs can be observed. In the core plasma, low amplitude ($\delta I/I$ ~ 1-2 %) structures with the correlation time of τ_c ~ 5-20 μs are observed, with amplitude close to the detection limit. Intensity fluctuations of a similar character are also observed in all channels when the beam is fired into a gas target, which are produced by fluctuations in the ion current from the beam source. Attempts to remove this common-mode component from the signals have so far been unsuccessful due to the relatively high level of noise.

Multi-channel, cross correlations of the signals relative to a specified reference channel are shown in Figs. 3 and 4. Data from the L-mode phase is shown in Fig. 3 in which the time lag of the fluctuations in the

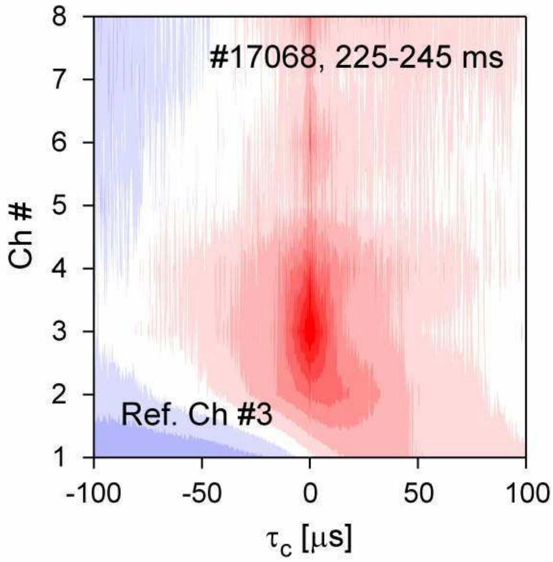

Fig. 3 Multi-channel, cross-correlation of BES signals from an L-mode phase of the discharge shown in Fig. 1.

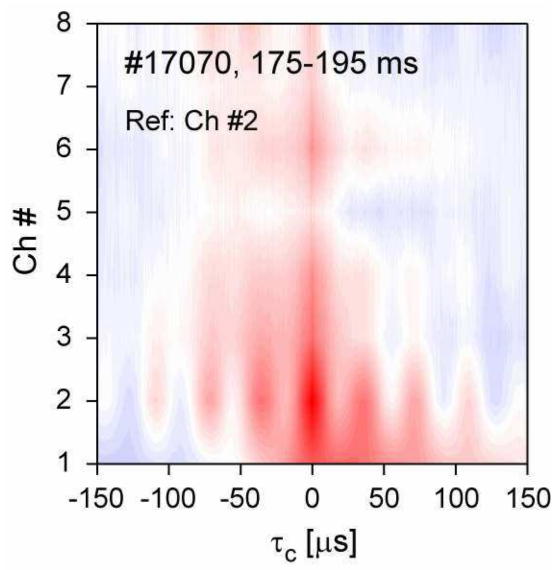

Fig. 4 Multi-channel, cross-correlation of BES signals with ch. 2 as reference from an ELMy H-phase of a discharge with 1.3 MW NBI power.

outermost channel, which is 4 cm outside the separatrix, relative to the next channel, which is at the separatrix, is evidence of the apparent radial propagation of the SOL turbulence at an estimated velocity of ~ 2 km/s.

Data from an ELMy H-mode phase is shown in Fig. 4, where a quasi-coherent mode at ~ 27 kHz is present just inside the separatrix (r/a ~0.98), which is strongly correlated with magnetic data. The magnitude of the cross-correlation with neighbouring channels decreases, indicating that the correlation length of this edge turbulence is ~ 4 cm.

Summary

With the trial BES system currently installed on MAST it is possible to characterise relatively high-amplitude density turbulence at the periphery of L-mode plasmas and also to localise coherent MHD at the edge of H-mode plasmas. It is not possible, however, to characterise the core turbulence with confidence due to the limited signal level. Using these results, simulations of the BES system have also been benchmarked against experiment. This gives confidence in the predicted performance of a BES 2D imaging system, which is planned to be built for MAST in 2008. This system is to utilise in-vessel optics with much increased étendu (×40) and should be able to detect fluctuations at the 0.3% level at 1 MHz bandwidth. It is planned to use a custom camera based on an 8×4 channel APD array sensor (Hamamatsu S8550) imaged with direct coupled optics to a 16×8 cm^2 region in the plasma. With such a 2D imaging system it should be possible to observe turbulence flow patterns and features such as GAMs and zonal flows, as have been observed using the system installed on the DIII-D tokamak [2].

References:

[1] A. Thyagaraja, P. J. Knight, M. R. de Baar, et al., Phys. Plasmas, **12** (2005) 090907-1.
[2] G. R. McKee, R. J. Fonck, D. K. Gubta, Rev. Sci. Inst. **77** 10 (2006) F104.
[3] N. J. Conway, P. G. Carolan, J. McCone et al., Rev. Sci. Inst. **77** 10 (2006) F131.
[4] H. P. Summers, 'Atomic Data and Analysis Structure', JET Report, JET-IR (94) 06.
[5] R. J. Fonck, P. A. Duperrex, S. F. Paul, Rev. Sci. Inst., **61** 11 (1990) 3487.
[6] S. Zoletnik, S. Fiedler, G. Kocsis, et al., Plasma Phys. Cont. Fusion, **40** (1998) 1399.

This work was funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.