A Beam Emission Spectroscopy Diagnostic for the TJ-II Stellarator

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Introduction

Beam emission spectroscopy (BES) is being evaluated as a diagnostic for the TJ-II, a 4-period heliac-type stellarator with major radius of 1.5 m, a bean shaped plasma cross-section with an average minor radius of ≤0.22 m, and magnetic field B(0) ≤1 T [1]. BES is widely applied in magnetically confined plasma devices to characterize long wavelength plasma turbulence [2,3], typically for $k_\perp \rho_i \ll 1$, and its application in TJ-II is attractive given the inherent flexibility of this device which is designed to explore a wide rotational transform range ($0.9 \leq \iota(0)/2\pi \leq 2.2$) in low, negative shear configurations ($\Delta\iota/\iota$ <6%). For TJ-II, a diagnostic neutral beam injector (DNBI) used for charge-exchange recombination spectroscopy (CXRS), plus the existing toroidal viewing CXRS optical system, will form the basis for this system [4].

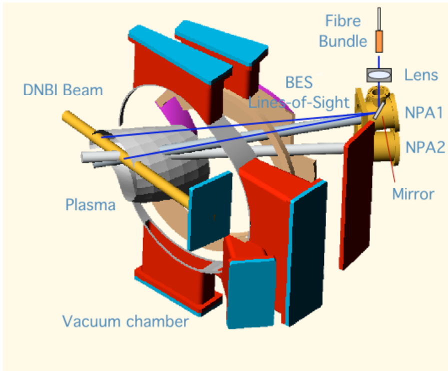

Fig. 1: Artistic sketch showing the DNBI beam & the tangential viewing porthole (shared with NPAs) for BES in TJ-II.

In this paper, after summarizing the TJ-II and reviewing the principal aspects of the DNBI, optical components and light detection systems, estimates of signal levels at the detector inputs are made and compared with measured signal levels before discussing the potential and limitations of BES for fluctuation studies in TJ-II.

Experimental set-up

In TJ-II, two gyrotrons operated at 53.2 GHz, the 2nd harmonic of the electron cyclotron resonance frequency (P_{ECRH} ≤600 kW, t ≤300 ms) are used to heat plasmas, created with hydrogen, to central electron densities, $n_e(0)$, and temperatures, $T_e(0)$, up to 1.7×10^{19} m^{-3} and 2 keV, respectively. Additional heating by the injection of ≤1 MW of neutral hydrogen particles accelerated to 30 keV raises the line-averaged electron density, $\tilde{n}_e$, to ≤$5x10^{19}$ m^{-3}. The TJ-II is also equipped with a broad range of diagnostics, several of which are used to study short wavelength plasma fluctuations ($\Delta k_\perp$ >2 cm^{-1}), *e.g.* a Doppler microwave reflectometer and probes. However, to-date diagnostics that can access the unexplored region of long-wavelength fluctuations have not been employed.

In many devices heating neutral beams (NBI) are used for BES. However, the relatively large diameter of the TJ-II NBI's, *i.e.* ~20 cm, plus poor optical access make them unsuitable for this application. Nonetheless, a compact DNBI, with suitable optical access, is available. Its DINA-5F type arc source provides up to two 5.5 ms long pulses per discharge of neutral hydrogen particles accelerated to 30 keV with an equivalent extracted neutral current of ≥3 A [4]. Although its beam pulse length is relatively short compared to that of the NBI's, *i.e.* ≤110 ms, it produces a focused beam with an e^{-1} radius of ~2.1 cm at the plasma centre thereby facilitating localized measurements without the need to perform inversion. Moreover, access from a nearby tangential viewing porthole provides direct optical access (albeit with an in-vacuum mirror) to almost the complete plasma-beam interaction column, *i.e.* $-1 \le \rho \le 0.7$ (where $\rho = r/a$ and a is plasma radius in the beam direction). This set-up is currently used to measure toroidal velocities of C^{+6} ions by CXRS, hence the same optical components, with some modifications, will be used for BES since the lines-of-sight are almost tangential to the local magnetic flux surfaces across the whole accessible region. The resultant variable spatial pitch of 2.9 to 4.2 cm between lines-of-sight provides access to medium to long wavelength density fluctuations, i.e. $0.01 \le k_\perp \rho_i \le 0.16$.

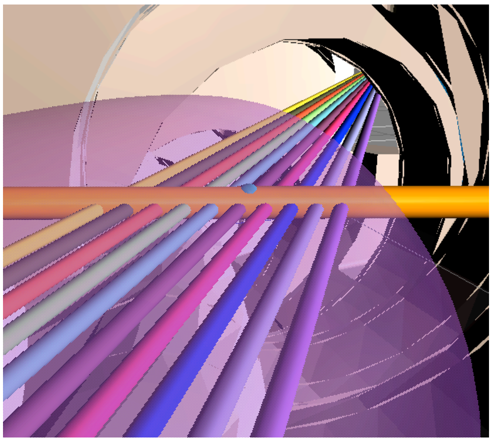

Fig. 2: Artistic view of DNBI beam (orange), plasma (violet), vacuum chamber, plus 10 lines-of-sight (ρ=-0.7 (yellow) to ρ =0.6 (purple).

Estimated Doppler shifted H_α intensity

The detectable fluctuation levels, which ultimately determine the bandwidth and frequency range accessible, are determined by photon statistics, as well as detector noise, and hence by the beam, the optical access, light transmission, detector efficiency, and plasma conditions. In order to make an evaluation, the light signal at the detector input is estimated firstly. So, the Doppler shifted H_α intensity reaching the tangential window for electron resonance heated (ECRH) conditions, *i.e.* low density plasmas, is estimated using

$$I(W) = A_{32}/(A_{32}+A_{31})\, N_i\, N_b\, V_b\, [\sigma_i + (\sigma_e |V_b - V_e|)/V_b]\, h\upsilon\, \Delta V\, \Delta\Omega/4 \quad (1)$$

where A_{32} $(H_\alpha) = 4.416\text{x}10^{7}$ s^{-1}, $A_{31} = 5.569\text{x}10^{7}$ s^{-1}, $h\upsilon = 3.03\text{x}10^{-19}$ J, $N_i = N_p \approx N_e \approx 5\text{x}10^{12}$ cm^{-3} is plasma particle density, $N_b = I_b/(q\, \pi\, r_2\, V_b) = 0.166/(1.6\text{x}10^{-19}\ 2.43\text{x}10^{8}) = 4.3\text{x}10^{9}$ H^0 cm^{-3} is beam H^0 density, $\sigma_i = 2\text{x}10^{-17}$ cm^2 (H^+ impact excitation cross-section), and $\sigma_e|V_b - V_e|/V_b = 2\text{x}10^{-17}$ cm^2 (e- impact excitation) for $T_e \le 1$ keV where $V_b = 2.43$ x 10^8 cm s^{-1} (for 30 keV). Next, for the present optical set-up, *i.e.* a 50 mm f/1.4 lens plus 600 μm core fibres covering ρ = 0.6 to -0.7, the beam/plasma interaction volumes are $\Delta V = 2r_{1/e}(\mathrm{Sin}\ \theta)^{-1}\pi R^2$ cm^3 = 12 to 13.3 cm^3 whilst the interaction volume solid angle is $\Delta\Omega/4\pi = \pi(D/2)^2/4\pi L^2 = 3.54 \times 10^{-5}$ sr, where $r_{1/e}$ is 2.1 cm, θ = 54° to 63° is the range of angles between the lines-of-sight and beam, R = 0.9 cm is line-of-sight radius at the beam, D = 3.57 cm is effective lens diameter, and L = 150 cm is beam to lens separation. For the central line-of-sight the estimated H_α intensity reaching the viewport is

$$I = 1.2\times10^{-8} \text{ (W/channel)}, \qquad (2)$$

this being equivalent to ~4×10^{10} photons/s/channel. This is compatible with other systems for similar conditions, *e.g.* 2.6×10^{-8} (W/channel) in CHS [5], 10^9 to ~10^{11} photons/s on MAST [3].

For the proposed optical set-up the Doppler shifted H_α is well separated from plasma H_α, *i.e.*, by $\Delta\lambda$ from 2.4 to 3.12 nm for ρ=-0.7 to 0.6, as well as from nearby C II emission lines at 657.78 and 658.29 nm. Hence, a single Type-3 bandpass filter with a 1 nm full-width at half-maximum (*fwhm*) transmission bandwidth centred at 659 nm has been selected. As well as background, it blocks the E/2, E/3 and E/18 H_α components of the beam, this being acceptable given that such components represent ~8% of the beam intensity. See Fig. 3. With a filter transmission of between 64% (ρ=0.6) and 32% (ρ=-0.7) plus light losses at the mirror (13.6%), viewport (11.5%), lens (31%), and optical fibre couplings (7.7%) gives an optical transmission of 16 to 31%. Finally, beam attenuation is at maximum ≤5% for $n_e(0) = 5\times10^{18}$ m^{-3}. Hence, incident photon flux on a detector is estimated to be ~10^{10} (ρ=0.6) to ~6×10^9 (ρ=-0.7) photons/s.

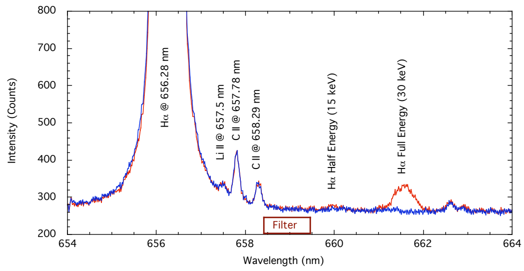

Fig. 3: Spectra taken from behind the beam (θ = 13°) showing background spectral lines and Doppler shifted Hα (red). The bandpass filter wavelength range is free of background spectral lines. Full (92%) and half (8%) energy contributions are seen.

Results from trial system

A trial system incorporating the optical components outlined plus two APSD modules has been tested on TJ-II under NBI heated plasma conditions. The detectors chosen are Avalanche Photodiode modules (model LCSA3000-01) by Laser Components GmbH [6]. These are 3 mm diameter silicon detectors with 45 A/W responsivity (gain M=100). The modules have ×100 amplification and load resistance $R_L = 10^5$ ohm resulting in 360 MV/W at 650 nm (QE = 85%). Finally, the modules have 10mV/√Hz output noise density at 100 kHz, a bandwidth from DC to 1 MHz, and can be operated at room temperature with a compensated from 0.5 to 2 V/ºC.

Two lines of sight were chosen (at ρ=-0.48 and -0.58). Fig. 4 shows BES signals for a beam current of 2.28 equ A, beam attenuations of 13.6% (ρ=-0.48) and 16% (ρ=-0.58), filter transmissions of 54.5% (ρ=-0.48) and 42% (ρ=-0.58), APD's operated with ~$1.8x10^8$ V/W (M~50), and output signals RC filtered to ≤0.1 MHz. The signal level for ρ=-0.48 (~0.25 V) is equivalent to ~$1.4x10^{-9}$ W at the detector input, this being in reasonable agreement with the predicted value for the test conditions (~$2.5x10^{-9}$ W).

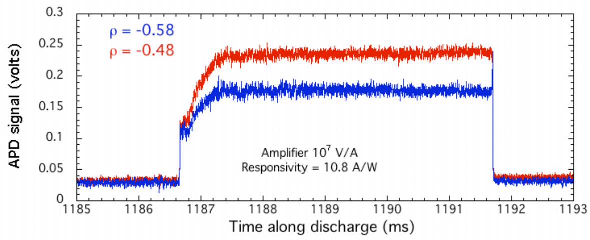

Fig. 4: TJ-II shot #27134. BES signals collected at two radii with test set-up. Note: signals RC filtered (≤100 kHz) and collected with 9 bit vertical resolution.

System Noise

An important consideration for studying fluctuations is the detector noise-to-signal ratio (N/S). Generally, fluctuation levels are a few percent or less and H_α intensity is not a linear function of plasma density, *i.e.* δI/I = Kδn/n, where K~0.5 [2] for the test density here. Overall system noise is determined by shot noise, N_{shot} = 3.58 mV for ρ=-0.48 in Fig. 4, and Johnson noise of the load resistor, N_J = 1.28 mV, giving N_{total} = 3.8 mV which is equivalent to a N/S of 0.015 for the 100 kHz bandwidth used.

Conclusions

Tests with a trial diagnostic system indicate optimism for performing BES on TJ-II. The high DNBI beam particle density and the short beam to optics separation result in signal light levels are compatible with other BES systems. Moreover, optical access to almost the whole beam/plasma interaction column plus lines-of-sight that are almost parallel to $k_\perp$ make BES attractive for TJ-II.

Acknowledgements

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References

[1] J. Sánchez *et al.*, Nucl. Fusion 49 (2009) 104018

[2] R. J. Fonck *et al.*, Rev. Sci. Instrum. 61 (1990) 3487.

[3] A. R. Field *et al.*, Rev. Sci. Instrum. 80 (2009) 073503.

[4] J. M. Carmona *et al*. Rev. Sci. Instrum. 77, 10F107 (2006).

[5] T. Oishi *et al.*, Rev. Sci. Instrum. 75 (2004) 4118.

[6] www.lasercomponents.com