Feasibility of Beam Emission Spectroscopy and Neutral Beam Fraction in VEST

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The Versatile Experiment Spherical Torus (VEST) project utilizes Neutral Beam Injection (NBI) and various diagnostics to investigate MHD instabilities and high beta operations in nuclear fusion environments. This study outlines the application of Beam Emission Spectroscopy (BES) for the precise measurement of plasma ion parameters, which are crucial for the effective control and manipulation of plasma states. A multi-channel BES system is configured using photomultiplier tubes (PMTs) to acquire high-resolution data of the Hα spectral line (656.28 nm) emissions induced by hydrogen atoms in the plasma. These emissions are analyzed to determine plasma density via the density perturbation method and to assess the beam fraction based on shifts in the spectral line due to Doppler effects. The preliminary results indicate that the spectral line shifts and particle velocities at various angles provide a quantitative measure of plasma characteristics, thereby enhancing the diagnostic capabilities. And beam fraction measurements of NBI are now possible.

Introduction

Versatile Experiment Spherical Torus (VEST) [1] is a low-aspect tokamak that allows the study of MHD instability and high beta operation corresponding to major radius R = 0.44m and minor radius r = 0.32m. For nuclear fusion, it is necessary to control instabilities and control the plasma with high ion temperature. For this purpose, it is important to accurately measure ion parameters such as ion temperature, velocity and density. And heating is also important to accomplish high-temperature plasma. The Neutral Beam Injection (NBI) [2] at VEST has beam size of 240 mm*692 mm, power of 0.6 MW and current of 40 A at 15 keV. The beam divergence is 1 degree and the pulse length is adjustable to 10ms. The ion source is arc discharge type using hydrogen gas. The beam is injected from the VEST port at 2 o'clock and the beam dump is installed at 7 o'clock.

At VEST, the system will be configured for over 10 channels with a heating neutral beam. Photons will be received by PMTs instead of CCDs to track intensity fluctuations better than microsecond scale. The first step is to configure the spectrometer to detect the H alpha signal band from the neutral beam and measure the shift of the beam particle velocity (beam acceleration voltage) and view angle of the NB. Following this, PMTs will be installed on each channel within the shift range.

Principle of Beam Emission Spectroscopy

$$(1)\ H^0_{beam} + H^+_{plasma} \rightarrow H^{0*}_{beam} + H^+_{plasma} \rightarrow H^0_{beam} + H^+_{plasma} + h\nu$$

Equation (1) shows that BES observes the light emitted from the neutral particle beam, with the most dominant light being the H_α line (656.28nm). This occurs when the plasma excites and de-excites the hydrogen atoms (n=3→n=2) when is shifted by Doppler effect from neutral beam.

$$(2)\ \frac{\delta n}{n} = K(T_e, n_e)\frac{\delta I}{I}$$

The intensity of H_α emitted by collisions between the neutral particle beam and main ions, electrons, impurity ions in the plasma is approximately proportional to the plasma density. The density can be measured by density perturbation using the equation (2).

$$(3)\ \Delta\lambda = \lambda_0 \frac{V_{beam}}{c} \cos\theta$$

The above equation (3) is Doppler shift effect. Δλ is shifted wavelength, λ_0 is wavelength of H_α (656.28nm), V_{beam} is velocity of neutral beam, c is speed of light, θ is angle between neutral beam path and view path.

Collecting optics

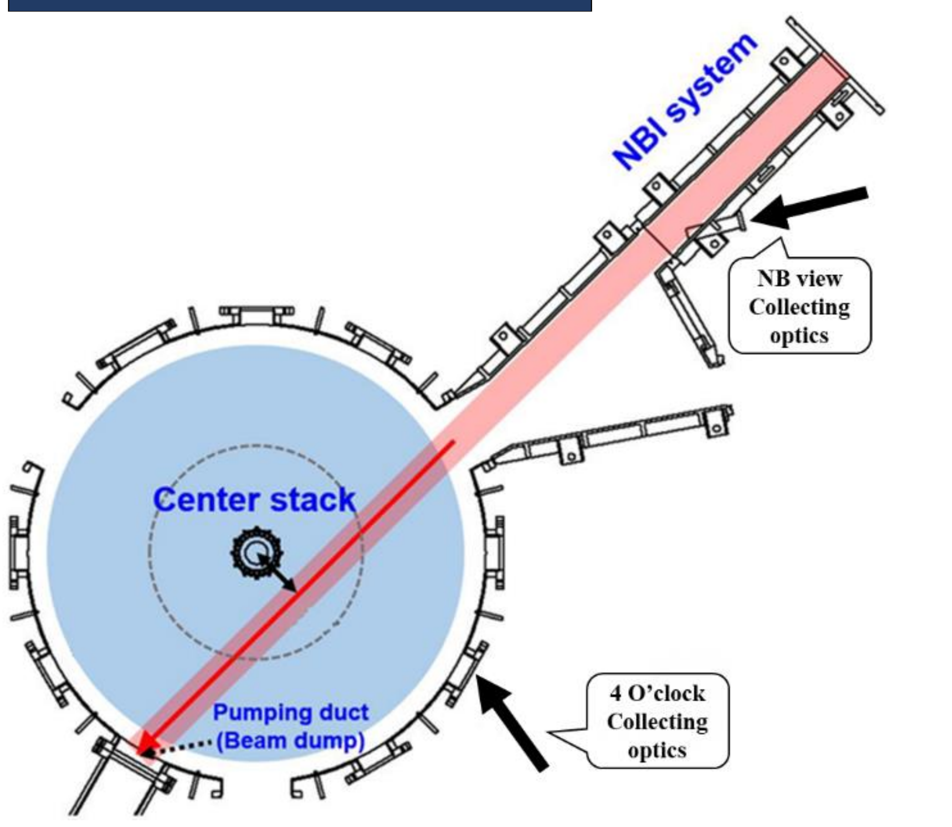

Fig.1. Schematic view of BES collecting optics channel with NBI in VEST.

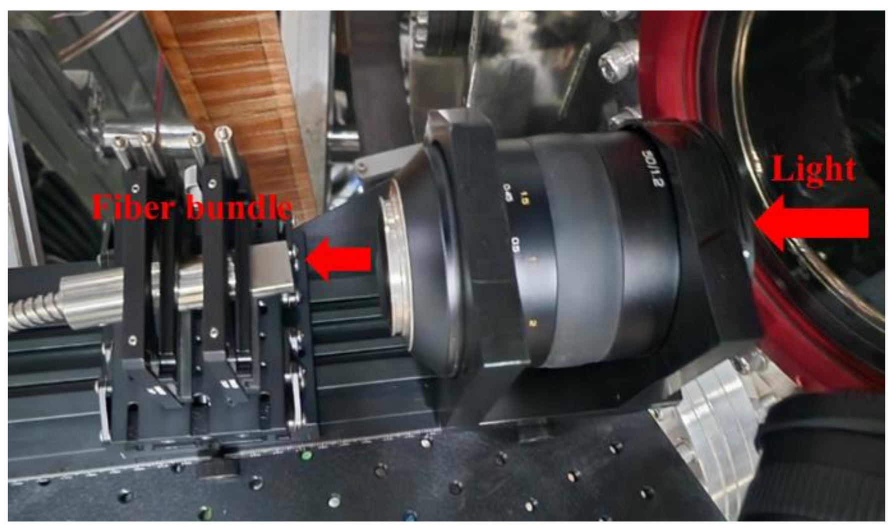

Fig.2. 4 O'clock view port collecting optics bird's eye view.

The Figure 1 shows view angle and path were placed at the 4 o'clock viewing window, and the channel with the lowest angle to the NB was used to collect the signal first. When the accelerating voltage of the NBI of the VEST is 10 keV, it is calculated that the wavelength is shifted by 3.032 nm when the angle is 0 degree and 1.516 nm when the angle is 60 degree.

Spectrometer

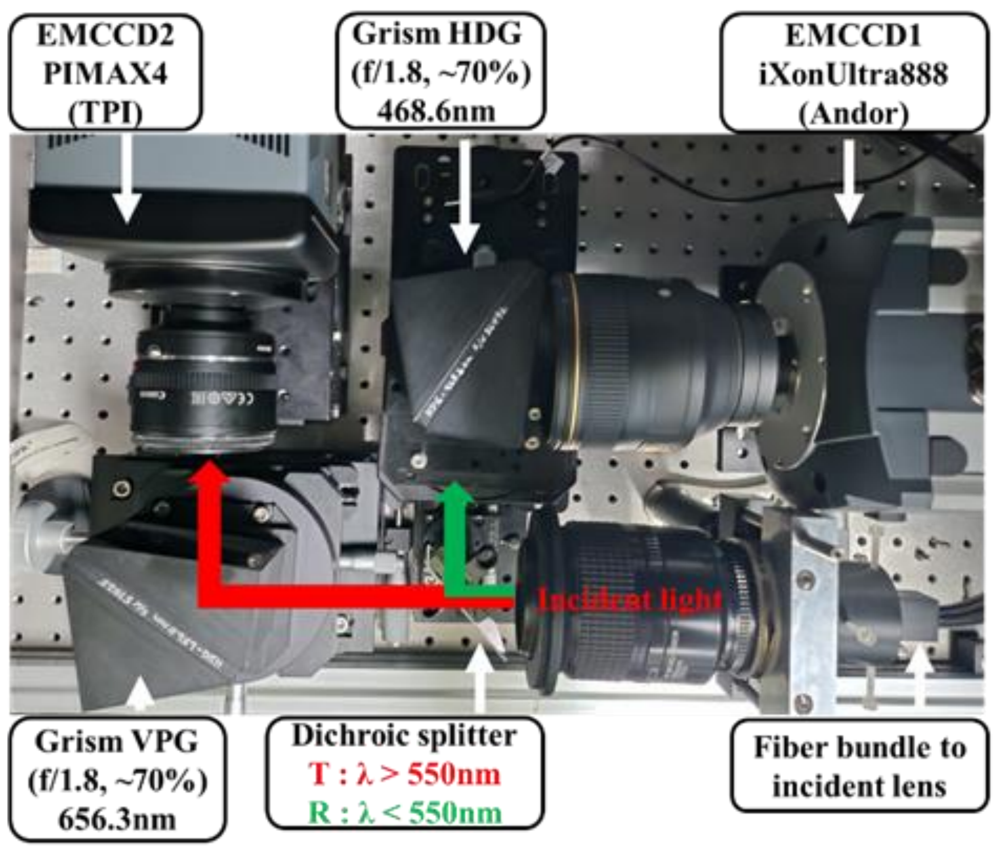

Fig.3. Image inside of spectrometer and detector.

The VEST optical spectrometer [3] consists of a CCD1 (Andor, iXon 888) for Ion Doppler spectroscopy, collecting passive C III light, or Charge Exchange Spectroscopy, collecting active He II light using NB, and a CCD2 (Teledyne Princeton Instruments, PIMAX4) for BES spectroscopy.

The light that is collimated through the lens passes through a dichroic mirror (Thorlabs, DMLP550L). This mirror reflects light with wavelength shorter than 550 nm (purpose of He II, efficiency 97.5%) through the HPG (Kaiser optical system, center wavelength 468.6 nm) and onto the CCD1. Light with wavelengths longer than 550 nm (purpose of H alpha, 98%) is transmitted through the VPG (Kaiser optical system, center wavelength 656.3 nm) [4], allowing the H_α wavelength to reach the CCD2.

When deploying the spectrometer for multichannel use, it is important to consider the wavelength resolution of the H alpha line, which is 2.26 nm/mm

Calibration and Mesurement

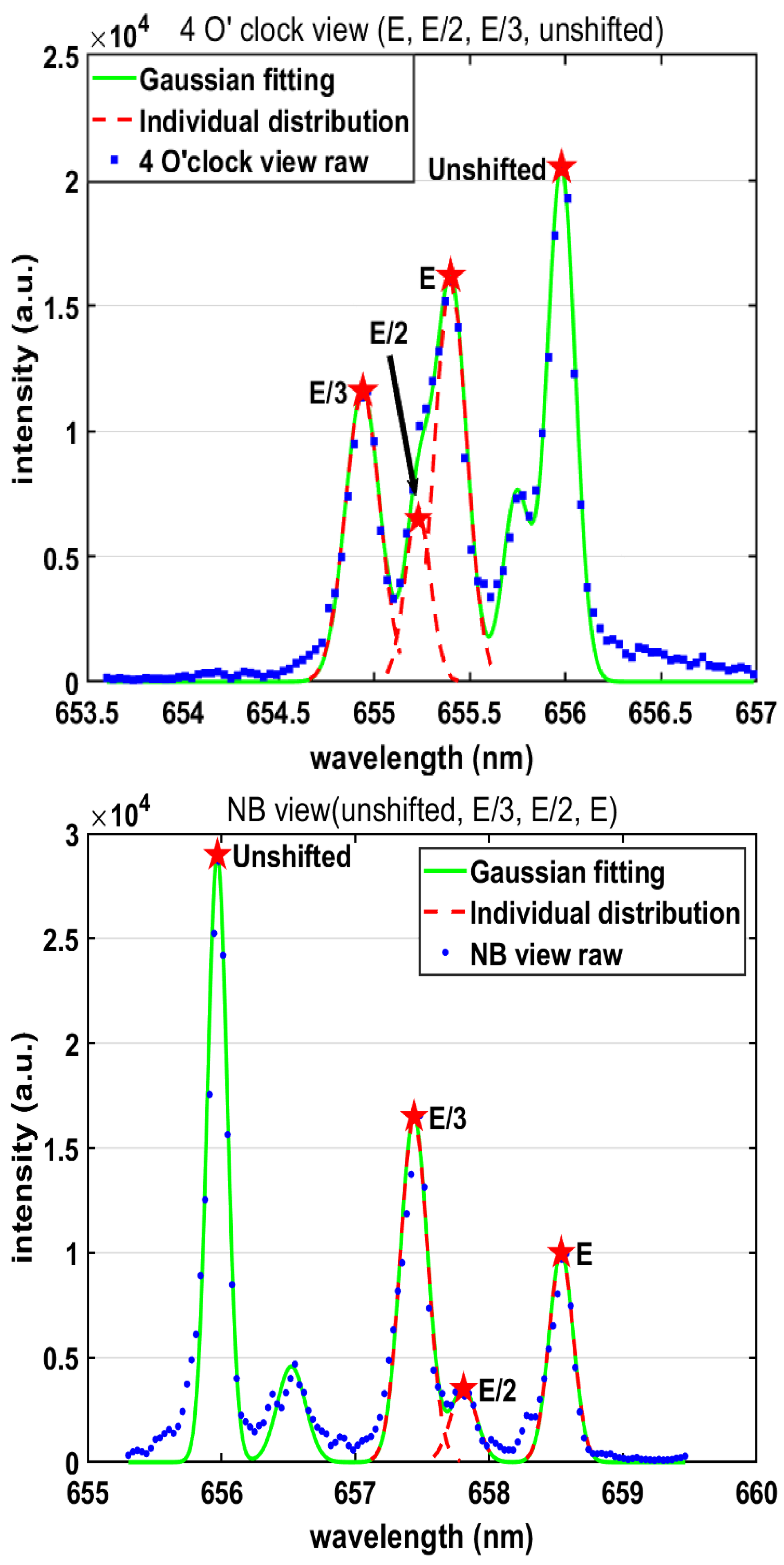

Fig.5. Beam shift data graph at (a) 4 O'clock view and (b) NB view

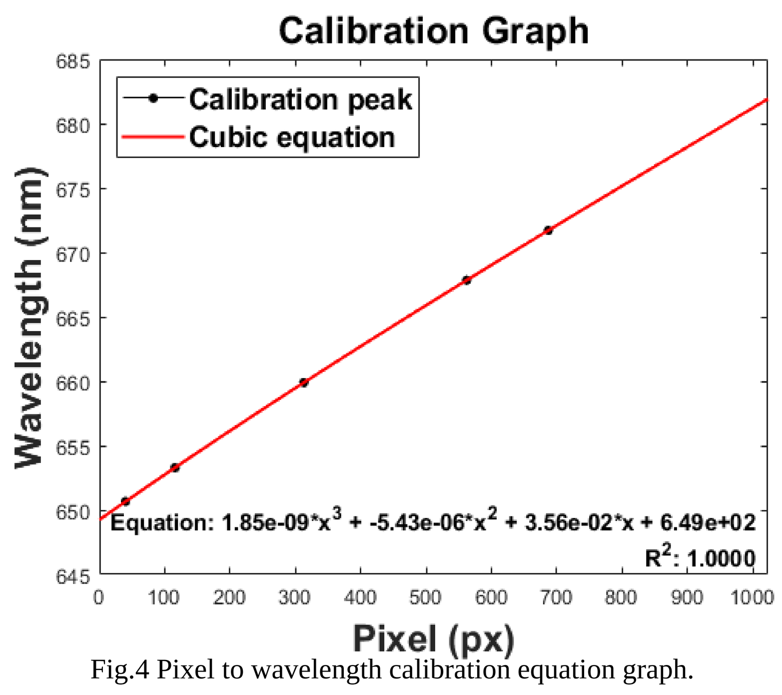

Fig.4 Pixel to wavelength calibration equation graph.

4 O' clock view	E/3	E/2	E	NB view	E/3	E/2	E
V_H(ratio)	7	5	4	V_H(ratio)	7	5	4
Δλ(nm)	0.59	0.76	1.04	Δλ(nm)	1.49	1.85	2.58
Beam fraction(%)	27.1	9.6	63.3	Beam fraction(%)	34.2	8.2	57.5

Table I , II : Shift and Fraction at 4 O' clock, NB clock

The experimental data are presented including calibration, experimental data, and beam fraction. The experiments were conducted with NBI acceleration voltage of 10 keV, power of 150 kW, and pulse length of 10 ms. The calibration is carried out using an Intelical (Teledyne Princeton Instruments) neon light source with five peaks to perform a wavelength calibration through polynomial fitting. A signal is measured at different angles from two viewing windows to detect the shift peak according to the type of ion and to compare the theoretical shifted degree.

The measurements were taken from two viewing windows: one at the NB extraction point at a 30-degree angle, and the other at the 4 o'clock viewing window at an angle of approximately 75 degrees. At the NB extraction point, the NB is extracted away from the observer's position, resulting in a red shift. Conversely, at the 4 o'clock viewing window, the NB is extracted towards the observer's position, resulting in a blue shift.

As the NB was injected in the gas state rather than in a plasma discharge, the beam fraction is calculated from the measured intensity using the equilibrium fraction [6] for hydrogen gas and the measured intensity.

Summary & Future Work

This study investigated the design and measurability of BES with NBI and measured the shift and beam fraction resulting from the observation angle. The results demonstrate that BES measurements in the VEST can detect plasma density fluctuations and identify the characteristics of NBI.

Additionally, replacing the collecting lens to form a multi-channel optic with a wider angle enhances the visibility of the shift peak and reduces errors. Installing PMTs in each channel after configuring the multi-channel collecting optics is expected to provide a deeper understanding of nuclear fusion research using VEST in the future by measuring the density fluctuation.

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