Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Feasibility of Beam Emission Spectroscopy and Neutral Beam Fraction in VEST

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1. 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 discharge 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.

2. Principle of Beam Emission Spectroscopy

Beam Emission Spectroscopy (BES) is operated in various devices (DIII-D, ASDEX, EAST, etc.) that have neutral particle beams. 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. The following is the reaction equation for a neutral beam and plasma:

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

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 below:

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

In addition, magnetic field information can be obtained through the motional Stark effect by measuring the lines of different components that are polarized. However, since the magnetic field strength of VEST is B=0.1T, the magnetic field is currently not strong enough to cause the motional Stark effect.

The below equation is Doppler shift effect. $\Delta\lambda$ 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:

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

To distinguish between H_α from H in the plasma and H_α from the neutral beam, we need to set θ small to maximize $\Delta\lambda$. The ions present in the hydrogen neutral beam are H^+, H_2^+, and H_3^+, and the degree of shift will vary accordingly.

2. Experimental setup

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.

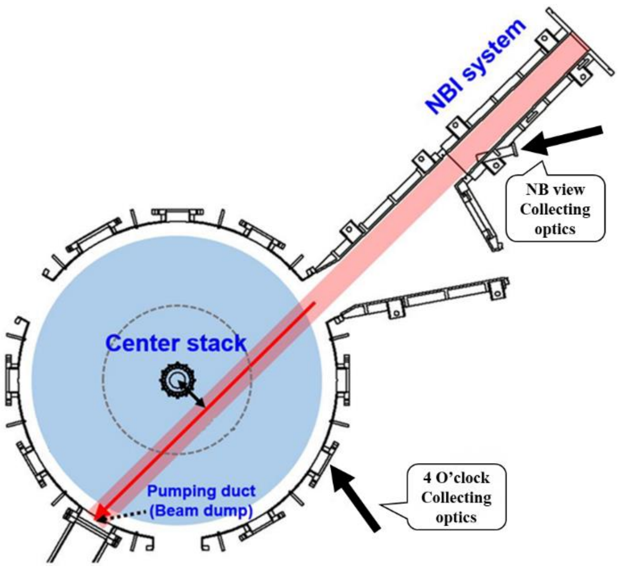

Fig.1. Schematic view of BES collecting optics channel with NBI in VEST.

2.1 Collecting optics and view angle

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.

The Figure 2 shows collecting optics collect the light at 4 O'clock view port through a 50mm, f1.2 lens as shown in the figure, and a rail is fixed to the optical breadboard to fix the view angle and path. After that, an optical fiber bundle is fixed to transmit light. After that, it is connected to the patch panel near the spectrometer.

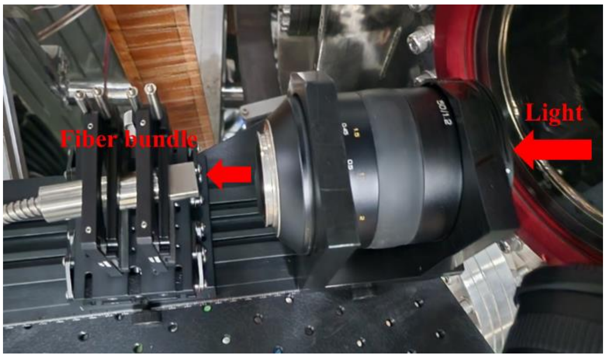

Fig.2. 4 O'clock view port collecting optics bird's eye view.

2.2 Spectrometer

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.

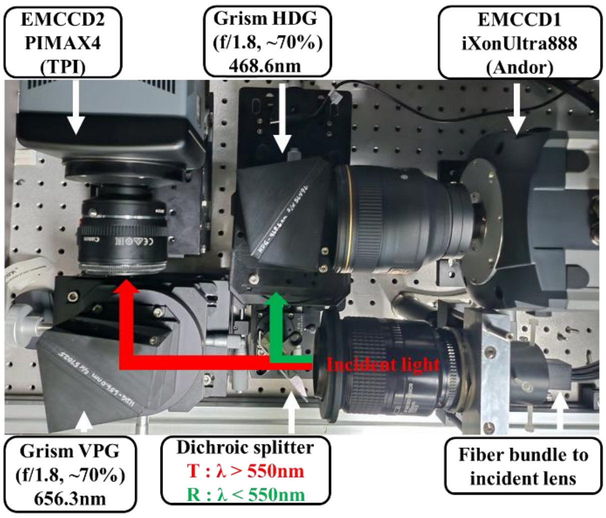

Fig.3. Image inside of spectrometer and detector.

3. Experimental data

The experimental data will be presented in the following order: calibration, 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.

3.1 Calibration

The wavelength calibration process involved Gaussian fitting of the 650.653nm, 653.288nm, 659.895nm, 667.828nm, and 671.704nm peaks from Intelical. The coefficient was calculated by polynomial fitting through the peaks to calibrate the pixel of the CCD to the wavelength. The wavelengths observed on the CCD through the grism in this spectrometer ranged from 649.24nm to 681.91nm.

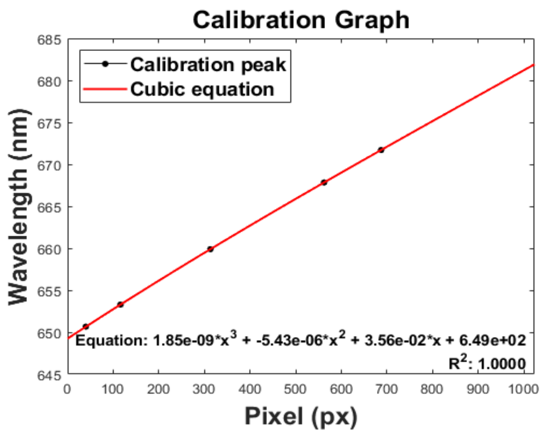

Fig.4 Pixel to wavelength calibration equation graph.

3.2 Data

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.

Upon examining the data obtained from the NB extraction, we can observe the unshifted peak, E/3, E/2, and E from the left. Following calibration, we calculated the Doppler shift at 656.28 nm to be Δλ = 1.49 nm, 1.85 nm, and 2.58 nm, respectively. Additionally, we found that the particle velocities at mass ratio $m_{H}^{+} : m_{H2}^{+} : m_{H3}^{+} = 1 : 2 : 3$ for the same acceleration voltage, $V_{H}^{+} : V_{H2}^{+} : V_{H3}^{+} \sim 7 : 5 : 4$, were consistent when compared to Δλ.

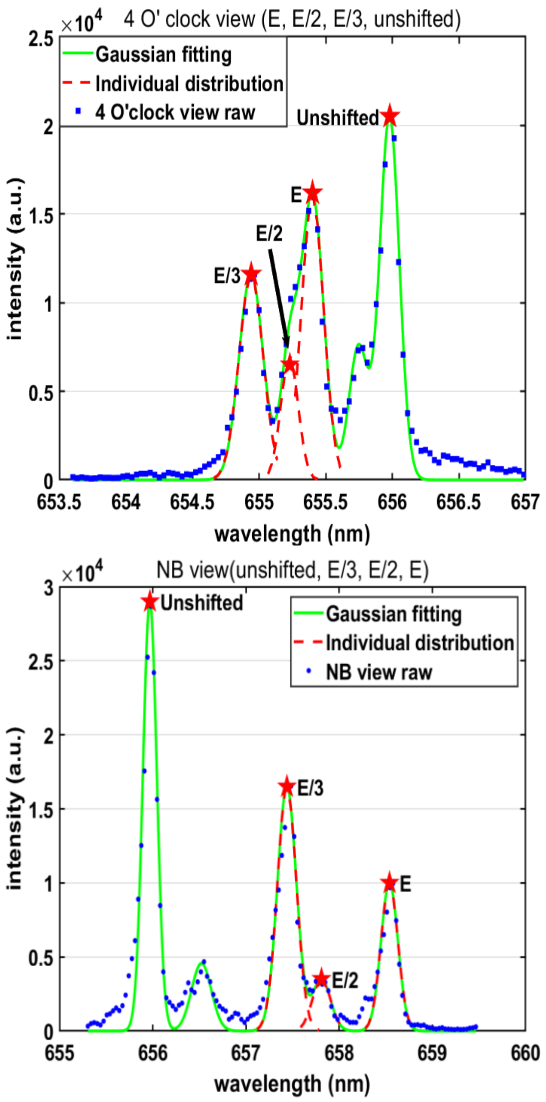

Fig.5. Beam shift data graph at (a) 4 O'clock view and (b) NB view

Similarly, for the data measured at the 4 o'clock window, we can observe E/3, E/2, E and the unshifted peak from left to right. Following the same process as above, the values of Δλ are 1.04 nm, 0.76 nm, and 0.59 nm, respectively, which are consistent with a ratio of 7 : 5 : 4 again.

3.3 Beam fraction

To calculate the neutral beam fraction[5], use the following formula.

$$(4) \quad s_i = \frac{c_i I_{E0/i}}{\sum_{k=1}^{3} c_k I_{E0/k}} \quad , i = 1..3.$$

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. The beam fractions in order E/3, E/2, E are 27.1%, 9.6%, and 63.3% at the 4 O' clock view and 34.2%, 8.2%, and 57.5% at the NB view.

Table I : Shift and Fraction at 4 O' clock

4 O' clock view	**E/3**	**E/2**	**E**
V_H(ratio)	7	5	4
Δλ(nm)	0.59	0.76	1.04
Beam fraction(%)	27.1	9.6	63.3

Table II : Shift and Fraction at NB view

NB view	**E/3**	**E/2**	**E**
V_H(ratio)	7	5	4
Δλ(nm)	1.49	1.85	2.58
Beam fraction(%)	34.2	8.2	57.5

The varying beam fractions within the same NB specification are due to errors in repeated NB extraction. The primary cause of this error is the large view angle in the 4 o'clock window, which results in the shift of the peak of E/2 being buried in E and not accurately measured.

And the tendency is that the beam fraction will be measured differently from the 4 o'clock window because of the NB window while passing through the neutralizer. This is because at the 4 o'clock window, the full energy will be measured more because the neutralization is already complete.

4. Conclusion and Future plan

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.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2021M3F7A1084418).

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