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Energy composition of high-energy neutral beams on the COMPASS tokamak

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Abstract. The COMPASS tokamak is equipped with two identical neutral beam injectors (NBI) for additional plasma heating. They provide a beam of deuterium atoms with a power of up to ~(2 × 300) kW. We show that the neutral beam is not monoenergetic but contains several energy components. An accurate knowledge of the neutral beam power in each individual energy component is essential for a detailed description of the beam--plasma interaction and better understanding of the NBI heating processes in the COMPASS tokamak. This paper describes the determination of individual energy components in the neutral beam from intensities of the Doppler-shifted Dα lines, which are measured by a high-resolution spectrometer viewing the neutral beam-line at the exit of NBI. Furthermore, the divergence of beamlets escaping single aperture of the last accelerating grid is deduced from the width of the Doppler-shifted lines. Recently, one of the NBI systems was modified by the removal of the Faraday copper shield from the ion source. The comparison of the beam composition and the beamlet divergence before and after this modification is also presented.

Key words: tokamak • neutral beam injection (NBI) • Doppler effect • beam composition • beamlet divergence

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Introduction

Neutral beam injection (NBI) is used for additional plasma heating in the COMPASS tokamak [1]. The neutral deuterium beam is produced by neutralization of the fast ions extracted from the radio frequency (RF) ion source with an acceleration voltage up to 40 kV. It has to be emphasized that the neutral beam generally consists of not only fast atoms with full energy E_b = 40 keV but also fast atoms with fractional energies $E_b/2$, $E_b/3$, and $E_b/10$. Their origin is described in the next section in more details.

The region where the neutral beam is ionized and deposits its energy in the plasma depends on the profile of the plasma density n_e and the stopping cross section σ_s, which depends mainly on the energy of the neutral particles. In general, the higher the beam energy is, the farther it can penetrate to the plasma. On the COMPASS tokamak, the beam is injected tangentially and the length of trajectory through the plasma is ~1 m. For typical plasma parameters on COMPASS (T_e = 1 keV and $n_e = 4 \times 10^{19}$ m^{-3}), the mean free path for ionization of atoms with full energy of 40 keV is 0.35 m, assuming homogeneous plasma. Therefore, these atoms heat the central part of the plasma column. The mean free path of atoms with fractional energies $E_b/2$ and $E_b/3$ is 0.24 and

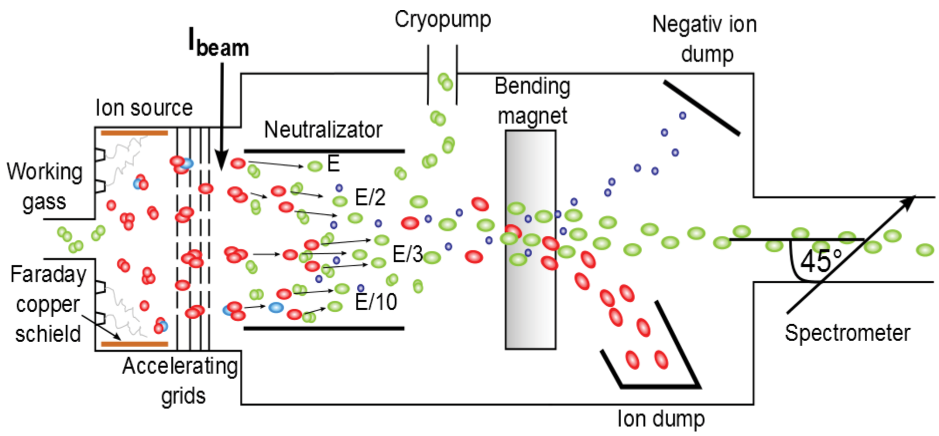

Fig. 1. Scheme of the NBI and the location of the visible spectrometer viewing the beam under the angle 45°.

0.2 m, respectively, that is, their energy is deposited closer to the plasma edge. The beam fraction with $E_b/10$ is ionized at around 0.14 m from the entrance of the neutral beam to the tokamak, that is, at the very edge of the plasma column, and therefore, it contributes to plasma heating just marginally.

An accurate knowledge of the ratio of atoms with different energies is, therefore, crucial for the correct understanding of the interaction of the injected neutral beam with the tokamak plasma. This paper describes the technique to determine the beam composition from measurements of the Doppler shifted Dα lines emitted by the fast neutral beam atoms. Recently, the ion source of one NBI system of COMPASS was modified by the removal of the Faraday copper shield, resulting in a different composition of the neutral beam. A comparison of the beam composition before and after modification is presented in this paper as well.

Neutral beam injector (NBI)

Two NBI systems were designed and manufactured at the Budker Institute of Nuclear Physics, Novosibirsk, for the COMPASS tokamak [2]. Each of them can produce the beam with energy of up to 40 keV and the power of up to 300 kW.

The main components of NBI, the RF ion source, the accelerating and focusing grid system, and the neutralizer are shown schematically in Fig. 1. During operation, the ion source is filled with a working gas (D_2) and an RF discharge is ignited inside the ion source. The resulting ions are extracted from RF plasma, accelerated, and focused by a system of four electrostatic grids to the required energy. Injector installed at the COMPASS tokamak can operate with accelerating voltage of up to 40 kV. The grids are perforated four circular plates with 887 circular apertures with precisely defined shape and mutual position. The beam escaping a single hole of the last grid is called a beamlet, and its divergence is responsible for the quality of the beam focusing. At a fixed accelerating voltage, the extracted ion beam current I_{beam} can be changed by variation of applied RF power into the ion source. Fast ions are passing through the neutralizer filled with a neutral D_2 gas of a sufficient pressure, and then they are neutralized in charge-exchange collisions. At the output of the neutralizer, the beam is composed of fast neutral atoms and (non-neutralized) fast ions. Residual ions are deflected by the bending magnet to the ion dump. Two cryopanels, cooled down to 4 K and located close to the beam trajectory, are used to pump an excess gas from the neutralizer in order to avoid it from entering the tokamak. The pumping speed is about 10^5 l/s. In this way, only fast neutral atoms enter the tokamak vessel.

The RF discharge creates in the ion source not only D^+ ions but also molecular ions D_2^+, D_3^+, and D_2O^+. They are also accelerated by the grids to the same energy as the D^+ ions. These heavier ions can dissociate into neutral atoms or ions. However, when neutralized, the resulting atoms have only fractional energies depending on their original ion mass, that is, $E_b/2$, $E_b/3$, and $E_b/10$.

The cylindrical part of the ion source made of copper (shown in Fig. 2) is Faraday shielding of the ceramic cylinder inside the ion source. Recently, the Faraday shield was removed from the ion source in one of the NBI system of COMPASS in order to improve the coupling of RF power to the plasma in the ion source. Thus, in the modified system the RF discharge is in direct contact with the ceramic

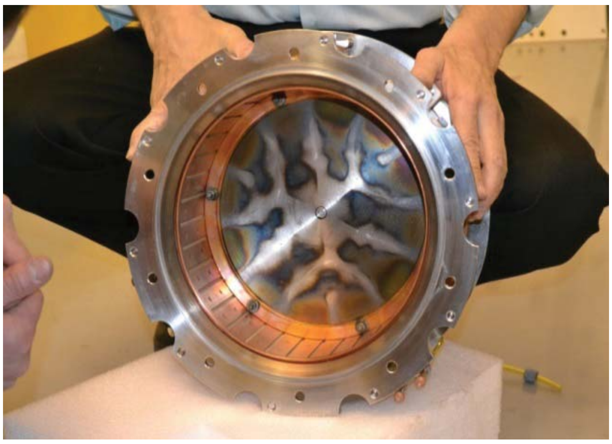

Fig. 2. Photo of the inner part of the ion source. Patterns seen on the surface of the back plate part are caused by the contact of the RF discharge with the surface. Structure of the patterns is influenced by permanent magnets hidden behind the back plate.

wall of the ion source, which was originally partially covered by a Faraday shield.

Doppler-shifted spectral lines

As described earlier, the neutral beam injected into the tokamak plasma consists of atoms with several discrete energies. A fraction of these fast atoms is in an excited state. The visible emission from these atoms is observed with the Ocean Optics HR2000+ spectrometer with a high spectral resolution at the exit of the NBI, as shown in Fig. 1. Spectral lines are shifted because of the Doppler effect according the expression

$$\Delta\lambda_D = \lambda_0 \frac{v}{c} \cos\Theta_0 \tag{1}$$

where $\Delta\lambda_D$ is the shift in wavelength, $\lambda_0 = 652.10$ nm is the unshifted Dα line, v is the velocity of the particle emitting the light, c is the velocity of light, and Θ_0 is the observing angle, which is in our case about 45°.

An example of the measured spectrum is shown in Fig. 3. This spectrum is automatically fitted by a sum of seven independent Gaussian functions and a constant background. A starting point of the fitting process is an estimate of the lines central wavelengths according to Eq. (1) and a guess of the peak width and amplitude. It leads to faster convergence of the fit.

The intensity of the shifted line is proportional to the density of the extracted ions. However, it is difficult to calculate the density of the extracted ions directly from the intensities of the corresponding lines. The easiest way is to calculate ratios of ion concentrations from the corresponding line intensities.

$$\frac{n_{D_2^+}}{n_{D^+}} = c_2 \frac{I_{E/2}}{I_E} \tag{2}$$

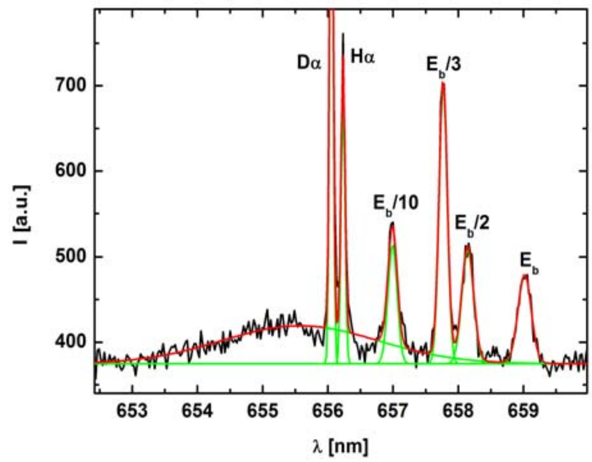

Fig. 3. Example of measured spectrum of the beam – black line. Together with Dα and Hα lines, we also observe several Doppler shifted. Dα lines, which corresponds to emission of fast atoms with energy $E_b/10$, $E_b/3$, $E_b/2$ and E_b. The broad peak with the maximum around 655.5 nm corresponds to background radiation. The green lines show six independent Gaussian fits of individual spectral lines. The red line represents the sum of all these fits.

$$\frac{n_{D_3^+}}{n_{D^+}} = c_3 \frac{I_{E/3}}{I_E} \tag{3}$$

where I_E is the intensity of the shifted line emitted by fast atoms with full energy E_b; $I_{E/2}$ and $I_{E/3}$ are the intensities of the lines that correspond to half and third energy of fast atoms, respectively; n_i is the density of extracted i-type ions; c_2 and c_3 are constants that depend on a neutralization efficiency of the accelerated ions, and probability of that atoms are excited to a radiative state. The contribution of emission from the molecules is not taken into account because sufficient number of collisions occurs in the neutralizer to dissociate all molecules and reach a stable ratio of the formed neutral atoms and the atomic ions. Also, it is not necessary to include into the calculation the emission from charged particles, because they are deflected by the bending magnet and are not present in the observed region. The procedure to calculate the beam composition from the intensities of the Doppler shifted lines is described in more detail in Refs. [3–6].

An additional information that can be derived from the measured Doppler shifted lines is the beamlet divergence, which contributes to the quality of beam focusing. With the assumptions, adopted from [7], the dependence of the beamlet divergence ε on the width of the shifted line is as follows.

$$\varepsilon = \sqrt{\frac{\delta^2}{\Delta\lambda_D{}^2 \mathrm{tg}^2\Theta_0} - \frac{R^2}{f^2} - \frac{T_{\parallel}}{E\,\mathrm{tg}^2\Theta_0}} \tag{4}$$

where δ is the width of the shifted spectral line determined at the $1/e$ value of its maximum, R is the radius of the last grid, f is the focal length of the accelerating system, $T_{\parallel}$ is the particles temperature in the direction parallel with the beam axis, E is the energy of observed particles, and $\Theta_0 = 45°$ is the observation angle.

Experimental results

Doppler-shifted spectra are recorded and processed on the COMPASS tokamak during each discharge with neutral beam injection. All presented data were measured with an acceleration voltage of 40 kV. The beam current (proportional to the RF power applied into the ion source) was adjusted depending on the requirement of the experiment.

Experimental results on the beam composition before and after removing the Faraday shield are summarized in Figs. 4 and 5. As it is seen in Fig. 4, the ion beam was originally composed of 30% of D_3^+, 25% of D_2^+, and 45% of the D^+ ions. The fraction of D^+ ions slightly increases with increasing beam current, while the fraction of the D_3^+ ions is reduced. The fraction of D_2^+ ions remains roughly constant for all values of the beam current.

After removal of the Faraday shield, the species mix has changed noticeably, as it is apparent in Fig. 5. The proportion of the D_3^+ ions has decreased noticeably, while an increase in D_2^+ ions is observed. However, the proportion of the D^+ ions, which is the most important, remains unchanged. The tendency of the species mix with increasing beam current is

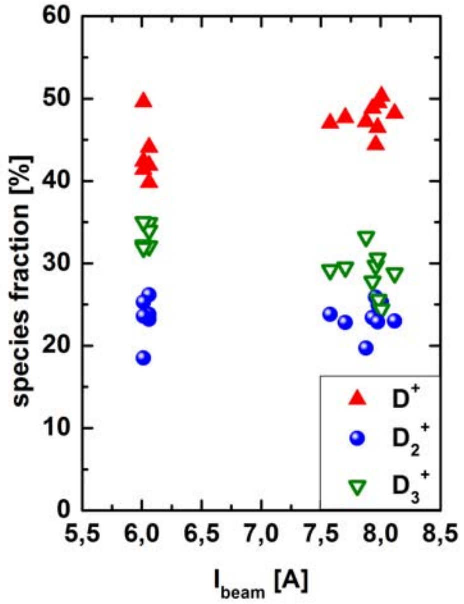

Fig. 4. Species mix of the accelerated ions as a function of the beam current before modification of the ion source.

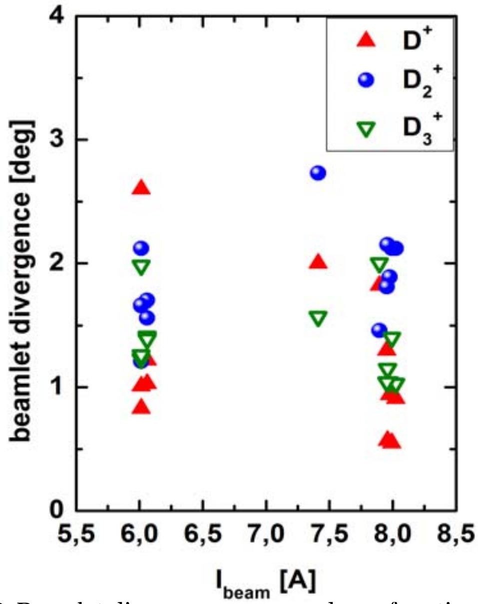

Fig. 6. Beamlet divergence measured as a function of the beam current before removing of the Faraday shield.

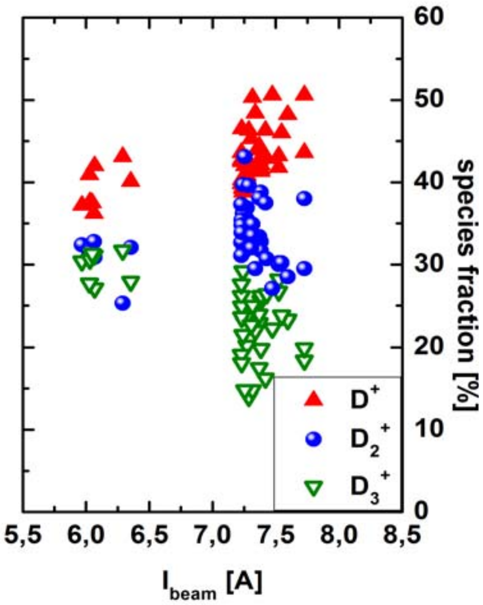

Fig. 5. Species mix of the accelerated ions as a function of the beam current after modification of the ion source.

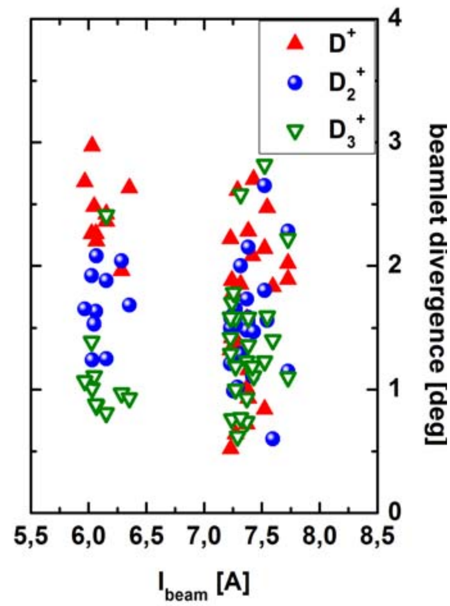

Fig. 7. Beamlet divergence measured as a function of the beam current after removing of the Faraday shield.

similar with the Faraday shield, that is, the number of D^+ ions is increasing and the number of D_3^+ is decreasing. The number of D_2^+ ions only slightly increases with beam current.

The width of the Doppler-shifted line is determined from the Gaussian fit with precision of about 3%. However, the error in calculation of the beamlet divergence according to Eq. (4) is significantly higher, that is, in the range 50–100%, because of the non-linear error propagation there. Therefore, any noticeable change in the beamlet divergence before and after the removal of the copper screen is not observed (shown in Figs. 6 and 7). In both the cases, the beamlet divergence varies in a broad range of angles 1°–3° and seems to be independent on the beam current.

Conclusion

It was shown that the heating deuterium beam on COMPASS is composed of the atoms with several different energies: the required energy of the beam E_b = 40 keV and fractional energies $E_b/2$, $E_b/3$, and $E_b/10$. The atoms with fractional energies originated from molecular ions extracted from the RF ion source. This paper is focused to determine the ratio of the numbers of the atoms with full half and third energy, because they are quite important for the core plasma heating. The atoms with energy $E_b/10$ cannot effectively heat plasma because of their rather short mean free path of ionization. They are lost at the plasma edge. It is shown in [2] that the population of this fraction is quite low (<5%); therefore, we do not include $E_b/10$ fraction in the calculations of the beam composition.

The beam composition is determined from the intensity of the Doppler-shifted spectral lines, which directly depends on the number of the extracted ions. The composition of the extracted ion beam was measured with two arrangements of the ion source: with and without the Faraday copper shield in the ion source.

It was found by systematic measurements that the dominant component of the ion beam are D^+ ions with energy 40 keV (~45%). However, the fraction of D_2^+ ions, which corresponds to atoms with energy 20 keV has increased from ~25% to ~35% after the removal of the Faraday shield. At the same time, the fraction of D_3^+ ions, which results as atoms with energy 13.3 keV, has dropped from ~30% to ~20%. Thus, an average energy of the neutral beam has increased after the removal of the Faraday shield, and consequently a better energy deposition of the neutral beam to the central part of the plasma column is expected.

Additionally, the beamlet divergences are derived from the width of a Doppler-shifted spectral lines. We found that the beamlet divergence varies between 1° and 3° for all types of the ions, independently on the status of the ion source.

The results presented in this paper are obtained just on one NBI system at COMPASS. Measurements of the composition of the ion beam extracted from the second injector are envisaged in near future.

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