Charge exchange radiation diagnostic with gas jet target for measurement of plasma flow velocity in the linear magnetic trap

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Abstract. The study of longitudinal fluxes of energy and particles is one of the most important fundamental problems in the physics of open magnetic traps. The solution to this problem is the key to the successful implementation of fusion power in linear magnetic systems. The plasma electrostatic ambipolar potential largely determines the physics of longitudinal transport of particles and energy. In this work, we used the spectroscopic method CXRS (Charge eXchange Recombination Spectroscopy) to measure the plasma ion velocity distribution via the analysis of light emitted in this atomic process. The experiments were carried out in the gas dynamic trap (GDT), which is a linear plasma confinement system with an axially symmetric magnetic field configuration. We measured plasma potential and ion temperature of two plasma components: the main (hydrogen and deuterium) and the helium impurity. The paper presents the emission spectra of the lines H-α (656.28 nm) and He-I (667.8 nm). This method was applied for the first time to measure the spatial profile of the ambipolar potential in an open magnetic trap.

1. Introduction
Measurement of the distribution function of plasma ions in linear magnetic traps is important for studying the processes of longitudinal transfer of particles and energy. A decrease of axial losses is one of the critical conditions for the implementation of CTF (Controlled Thermonuclear Fusion) in an open magnetic trap.

The diagnostic method utilizes the Doppler effect, based on the change in the recorded wavelength due to the movement of the radiation source relative to the detector. The accelerated plasma ions collide with hydrogen atoms of the artificial target. A portion of them captures the electron in a charge exchange event thus converting to excited atoms preserving the original velocity. This excited state is finally decays via the optical transition with the emitted photon carrying the information of interest. The optical system collects the emitted radiation and transmits to the spectrometer of the Czerny-Turner scheme with a diffraction grating. Then the low-noise high-speed CCD camera registers the radiation.

The shape of the measured spectrum corresponds to the ion velocity distribution function. The Doppler shift of the spectrum provides the directional velocity of the particles, and the broadening (FWHM - Full Width at Half Maximum) gives the temperature of the ions.

Any experimental scenario of the plasma startup and heating by neutral beam injection in GDT [1, 2] is accompanied by buildup of a positive electrostatic plasma potential. This so called ambipolar potential
decreases along each field line from the maximum in the center to zero on the grounded wall [3]. The quasineutrality of the plasma at each point, as well as by the equality of the longitudinal currents of electrons and ions to the end wall define the spatial distribution of this potential. The potential creates a barrier for electrons leaving the trap and accelerates ions escaping in the plasma flow through the magnetic mirror. The existing theory predicts a linear dependence of the potential on the electron temperature with a proportionality factor of 3-8. Longitudinal (z) and radial (r) profiles of the potential, as well as its maximum value, are essential factors in the physics of longitudinal transport in the GDT.

2. Charge eXchange Recombination Spectroscopy (CXRS)

In the CXRS method we used, bulk plasma or impurity ions convert into excited atoms in the hydrogen gas target with subsequent emission of light. In order to calculate the desired physical parameters, we used the linear approximation Doppler effect [4] equation

$$\Delta \lambda = \frac{\Delta \lambda}{\lambda_0} v c \cos \theta$$  \hspace{1cm} (1)

Helium (He) was injected into the central part of the gas dynamic trap (GDT), then He ionized in the plasma to He$^{2+}$. He$^{2+}$ ions are accelerated in the potential drop $\Delta \varphi$ before they neutralize on the target. We acquire He-I line emission for diagnostic purposes. Accordingly, the two-step charge exchange conversion is involved for plasma alpha particles (He$^{2+}$):

$$He^{2+} + 2H \rightarrow He^+ + 2H^+$$  \hspace{1cm} (2)

One of the process channels is the singlet optical transition 2P-3D with emission of photons of the wavelength $\lambda = 667.8$ nm:

$$He^* \rightarrow He + h\omega$$  \hspace{1cm} (3)

For the temperature of the “target” plasma in the GDT of the order of 100 eV and more, the relative concentration of this charged fraction of helium reaches 95% after $\approx 200$ us. According to the measured Doppler shift $\Delta \lambda$, corresponding to the ion velocity distribution function, we calculated the potential drop $\Delta \varphi$ (between the point in the central section of the GDT and the gas target in the expander):

$$\Delta \varphi = \frac{m_e c^2}{2q} \left( \frac{\Delta \lambda}{\lambda_0} \right)^2 \frac{1}{(\cos \theta)^2}$$  \hspace{1cm} (4)

The ion temperature was calculated from the width of the Gaussian spectrum at half maximum $\delta \lambda_{1/2}$, corresponding to the temperature distribution:

$$T = \frac{m_e c^2}{2 \ln 2} \left( \frac{\delta \lambda_{1/2}}{2 \lambda_0} \right)^2$$  \hspace{1cm} (5)

Before measurements in the GDT plasma, the spectral dispersion and the instrument response function (IRF) of the spectrometer were calibrated using laboratory H and Ne gas-discharge lamps.

3. Gas Dynamic Trap (GDT)

In a typical GDT shot scenario, eight deuterium beams of 625 kW each fire into the central section “target” plasma (figure 1). Trapped beam particles produce the fast ion plasma population which gradually passes energy to the Maxwellian “target” plasma. In the collisional confinement regime, bulk plasma ions flow through the magnetic mirrors into the expanders to the plasma receivers.
The diagnostics was installed in the left expander of the GDT (figure 2). The quartz capillary 2 mm in diameter connected to the H₂ reservoir, was introduced into the expander tank via the motion vacuum feedthrough. This assembly allowed to create the gas jet serving as the charge exchange target at some point along the line of sight (LOS).

Figure 1. Gas Dynamic Trap (GDT).

Figure 2. Spectral diagnostics in the left expander of the GDT. 1 – conical part of the central cell of the GDT, 2 – magnetic coil, 3 – mirror magnetic coil, 4 – gas ionization region, 5 – magnetic surfaces, 6 – vacuum chamber of the expander, 7 – plasma absorber, 8 – vacuum input of the gas tube with the diagnostic target, 9 – quartz tube for creating the target, 10 – diagnostic gas target, 11 – reservoir with H₂, 12 – optical system, 13 – line of sight, 14 – fiber optic assembly, 15 – spectrometer.

4. Upgraded spectrometer MDR-23
To register the radiation from the target, we used the upgraded MDR-23 spectrometer manufactured by the LOMO company (St. Petersburg, Russia). The major improvement is the astigmatism reduction optimizing spherical mirror positions and introduction of the additional non-spherical lens. The optical configuration of this spectrometer is based on the Czerny-Turner scheme. The grating diffracts the collimated light, then another mirror collects the scattered light and refocuses it at the exit slit. Table 1 shows the characteristics of the upgraded MDR-23 spectrometer.
Table 1. Parameters of spectrometer MDR-23.

| Element                              | Value                                           |
|--------------------------------------|-------------------------------------------------|
| Optical design                       | Czerny-Turner with astigmatism correction       |
| Focal length                         | 600 mm                                          |
| F/#                                  | f/6                                             |
| Density of line rulings on the diff. grating | 1800 lines/mm                                  |
| Gloss angle                          | 550 nm                                          |
| Inverse linear variance              | 0.69 nm/mm                                      |
| Astigmatism                          | < 10 um                                         |
| Working range of the entrance slit width | 20-50 um                                        |
| Spectral resolution                  | 0.041 nm (for the slit 25 um)                   |

5. CCD camera  
To record the radiation, we used a PyLoN camera from Princeton Instruments with a CCD matrix [5], which was cooled to -120 °C with liquid nitrogen to avoid thermal noise. The operation of the CCD is based on the principle of the internal photoelectric effect. The camera specifications are shown in Table 2.

Table 2. Parameters of PyLoN CCD camera.

| Element                | Value                                           |
|------------------------|-------------------------------------------------|
| Model                  | Princeton Instruments PyLoN                     |
| Cooling                | -120 °C (LN)                                    |
| Sensor                 | 2048x512 pixels, 13.5x13.5 um                   |
| Sensor mode            | Kinetics, 1 subframe = 50 rows binned           |
| Number of subframes    | 10                                              |
| Maximum subframe rate  | 2531.6 Hz (in this configuration of CCD)        |
| Maximum time resolution| 1 us                                            |
| Dark current           | 0.1 e-/pixel/hour                               |
| System noise           | ≈3.5 e-                                         |

6. Results  
The measurements using H-α line, were performed with the hydrogen main plasma. Helium impurity line observations were done in both regimes with hydrogen and deuterium main plasmas. Considering the balance between the accumulated optical signal intensity and the effective time resolution, we set the CCD exposure duration to 500 us. The resulting frame rate was approximately 1.5 kHz, as one can see in following time traces. Two series of measurements were implemented, with and without a target representing the sum active + passive signal and the passive signal only, respectively. We observed that only the active spectrum (with diagnostic gas target) features a detectable Doppler-shifted
component. This component delivers the ion velocity distribution function and accordingly, both the potential drop $\Delta \phi$ and the ion temperature.

Spectra were measured for two lines: H-$\alpha$ of the main plasma with a wavelength $\lambda = 656.3$ nm and the He-I impurity line with a wavelength $\lambda = 667.8$ nm (figure 3). The experimental data were processed using the OriginPro scientific analysis system [6].

![Figure 3](image.png)

**Figure 3.** An example of a radiation spectrum with a diagnostic gas target (near the axis). 1 – H-$\alpha$ spectrum (656.3 nm) with Doppler component, 2 – C-II lines, 3 – He-I (667.8 nm) spectrum with Doppler component.

As seen in figure 3, the intensity of the Doppler component with a diagnostic gas target is more than 20 times higher than the corresponding intensity of the optical signal without a target. High contrast ratio (with/without target) allows the measurements to be considered local. In this case, the size of the gas jet determines the spatial resolution, which is $\Delta r_0 \approx 5-10$ mm in the radial coordinates of the central plane of the GDT. Radii were mapped from the measurement area in the expander to the center of the GDT by projection along the magnetic surface.

In the measurements of H-$\alpha$ emission spectrum, the gas target was located on the axis (see figure 4). The examples shows that the typical signal to noise ratio $\text{SNR} \geq 10$. The spectrum sample used for the fit contained about 50 points. This made it possible to achieve an acceptable accuracy of measuring the potential $\approx 20$ V, which was defined as the root-mean-square error when fitting the model function using the standard maximum likelihood method. However, the amplitude of the "cold" (without the target) H-$\alpha$ line from the plasma edge is two orders of magnitude higher than the active CXRS signal, which causes some difficulties with the implementation of the approximation algorithm. Such difficulties do not arise when processing He-I emission spectra.
Figure 5 shows the emission spectrum of the He-I line at the wavelength of 667.8 nm on the axis. The Doppler component is not observed in the spectrum without the target. The fit procedure by the sum of Gaussian profiles gives an accuracy of calculating the potential of 5-10% (in absolute units: about 20 V).

Figure 4. H-α emission spectrum and Gaussian approximation. 1 – spectrum of hydrogen with $\lambda = 656.1$ nm, 2 – spectrum of hydrogen with $\lambda = 656.3$ nm, 3 – spectrum of hydrogen with a Doppler shift.
Figure 6 demonstrates the dynamics of the plasma potential $\Delta \varphi(t)$ in GDT shots (plasma discharges) №48999 and №49026. These measurements were made in the regime with a hydrogen “target” plasma with a small admixture of helium. Hydrogen puff in the plasma was implemented via the gas box of the magnetic mirror unit on the left side of the GDT (see figure 1 and figure 2), so the results of H line measurements were interpreted as “potential in the mirror”. Accordingly, the injection of an admixture of helium into the central part of the GDT allowed to interpret the results as a “potential in the center”. It was shown that the potential in the magnetic mirror was about 85 % of the potential in the center. Figure 6 also contains the potential dependence on time measured from the Doppler shift of the second He-I line (587.562 nm).

Figure 5. He-I emission spectrum (667.8151 nm) on the axis without and with a target and approximation using the sum of Gaussian functions. 1 – the "cold" He-I line, 2 – the He-I line with a Doppler shift, 3 – the He-I line with a Doppler shift to the left (due to secondary particle recharge), SNR $\geq$ 10.
Discussion

Figure 7 shows the dynamics of the ion temperature $T_i(t)$. Both the bulk hydrogen plasma ion temperature and the helium impurity temperature were measured by the CXRS diagnostic, the electron temperature was measured by the Thomson scattering. As anticipated, the electron temperature is bigger than the ion temperature due to the direct electron heating by fast ions creating by neutral beam injection. In turn, electrons transfer energy to ions via two-body collisions. This collisional relaxation is also accounted for the smaller helium ion temperature comparing to the hydrogen ion temperature. The impurity thermalization time is proportional to the square root of its mass. The effect of different specie temperature is well pronounced in the GDT plasma confinement regime which does not reach steady state.
Figure 8 shows the profile of the ambipolar electrostatic potential of the plasma along the line of sight. Worth to note, that both the radius and the axial coordinate Z change when translating the measurement volume (the gas target) along the LOS. In this paper, we have plotted the potential profile along the LOS as a function of radius (see figure 8). The existing theory predicts a stronger radial dependence which is governed by the electron temperature gradient. The theoretical axial potential profile is flat across the expander volume where CXRS observations were made. This statement requires validation and the study of Z-profiles is a matter of future experiments.

At each point, a set of statistics was accumulated, according to which the measurement error was calculated. The potential at the radial limiter ($r_0 = 140$ mm) was set to $+270$ V by the power supply. Two gas puff capillary tubes were used; a longer one covering the central plasma zone up to the axis and a shorter one covering the plasma periphery. A brief intermediate machine vent was necessary for a tube change. Results taken in these two sub-series of experiments are shown in different colors in figure 8.

The nature of the prominent potential dip in the paraxial region is not entirely clear and requires further research. The potential varies slightly from the axial region ($r_0 \approx 30$ mm) to the limiter; such a profile corresponds to the minimization of the radial electric field in the plasma and the corresponding velocity of azimuthal drift.
8. Conclusion
In this work, the experimental emission spectra of the H-α (656.28 nm) and He-I (667.8 nm) lines were presented. High amplitude contrast (more than 20 times) provided a spatial resolution of 5-10 mm in potential measurements. The CXRS method with a diagnostic target in the form of an H₂ jet was implemented on the GDT facility. It is the first application of this method to measure the electrostatic potential of a plasma in a linear magnetic trap. The Δφ error was 5-10 % in one measurement. The time dependences of the potential and ion temperature were obtained. The radial profile of the potential was measured. In the future, it is planned to obtain a complete spatial profile of the potential by measuring the dependence on z-coordinate of potential Δφ(z), which will allow to conclude about the efficiency of plasma confinement in a trap with such parameters.

9. References
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[3] Mirnov V V and Tkachenko O A 1985 ‘Electrostatic potential distribution in the gas-dynamic trap Report 85-32 Institute of Nuclear Physics
[4] Lizunov A 2021 Charge exchange radiation diagnostic with gas jet target for measurement of plasma flow velocity in the linear magnetic trap arXiv preprint arXiv:2101.12484
[5] PyLoN System Manual 2016 p 10
[6] Origin User Guide 2017 p 285

Figure 8. Radial profile of the potential Δφ(r). Two series of measurements are shown: in the central area (blue dots) and at the periphery (pink dots).