Evaluation of ambipolar potential barrier in the gas dynamic trap by Doppler spectroscopy

Andrej Lizunov1,*, Vladimir Maximov1 and Andrey Sandomirsky2

1 Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russian Federation
2 Novosibirsk State University, 630090 Novosibirsk, Russian Federation

E-mail: lizunov@inp.nsk.su

Received 23 November 2021, revised 28 December 2021
Accepted for publication 12 January 2022
Published 22 April 2022

Abstract

The recently developed Doppler spectroscopy diagnostic has been used to evaluate the height of the ambipolar potential barrier forming in the gas dynamic trap (GDT) plasma between the central cell and the region with a large magnetic expansion ratio beyond the mirror. The diagnostic technique based on the gas jet charge exchange target, allowed to measure the potential profile along the line of sight covering the radial range from the axis to the limiter. The on-axis potential drop was found to be $2.6 \div 3.1$ in units of the central plane electron temperature, which supports the existing theoretical understanding of suppression of electron thermal conductivity in the GDT expander.

Keywords: magnetic mirror, gas dynamic trap, plasma confinement, ambipolar potential, spectroscopy

(Some figures may appear in colour only in the online journal)

1. Introduction

Linear magnetic mirror traps for plasma confinement have an intrinsically simpler design comparing to toroidal systems. This simplicity is the most ample for an axially symmetric magnetic field configuration. The gas dynamic trap (GDT) [1] is a device of this kind for confinement of two-component plasmas with anisotropic fast ions generated with angled injection of eight 25 keV deuterium beams firing the total power of $\approx 5$ MW. In a classical scenario, the ‘target’ plasma remains in a strongly collisional confinement regime. That means that the axial particle outflow is proportional to the density and the mirror ratio (which is relatively large, $k_\text{m} = H_\text{m} / H_0 \geq 40$). A similar gas dynamic flow scaling would be inherent for the pressurised vessel with a pinhole leak. Numerous direct measurements in GDT demonstrate the peak transverse plasma $\beta$ reaching 0.6 [2] within a pulsed discharge with the heating stage duration of only $\approx 10$ ms. The later upgrade with the ECRH hardware has allowed us to extend the range of available electron temperatures in confined plasmas beyond one keV [3]. These results among other recent achievements in the GDT [4] could not be real without a strongly pronounced suppression of axial heat flux through the mirror with respect to a straight-forward exchange of hot and cold electrons on the end wall [5]. It is common knowledge that any competitive concept of a linear magnetic trap for fusion (see, for example [6–9]) would ultimately require a radical depression of axial heat losses. The basic physics of axial plasma confinement in the GDT with the magnetic expander section has been reviewed in [10]. The theory shows the longitudinal profile of the plasma electrostatic potential with the maximum at the centre of the confinement section and the major slope located beyond the mirror waist as schematically drawn in figure 1. The potential shape in the central zone follows either curve 2 or 3 depending on the fast ion density in the turning point relatively to that of the target plasma. In either case, we mark $\varphi_0$ the maximum of potential in the central zone. For given experiments with the typical target plasma density of $n_\text{p} \leq 2 \cdot 10^{19}$ m$^{-3}$ and the ion temperature of $\approx 100$ eV, the target plasma ion scattering mean free path is $\lambda_i \geq 5$ m which notably exceeds the half mirror-to-mirror distance of 3.5 m. A rather moderate temperature of $100 \div 250$ eV characterises the electron component as no auxiliary ECR heating.
A. Lizunov et al.

Table 1. The main GDT parameters.

| Parameter                  | Value       |
|----------------------------|-------------|
| Mirror-to-mirror length    | 7 m         |
| Magnetic field $H_0$       | 0.35 T      |
| Deuterium beam energy      | 25 keV      |
| Total NB power             | 5 MW        |
| NB pulse duration          | 5 ms        |
| Electron temperature       | $100 \div 250$ eV |
| Fast ion mean energy       | 10 keV      |
| Plasma density             | $1.5 \cdot 10^{19}$ m$^{-3}$ |
| Typical plasma radius      | 12 cm       |
| Maximum $\beta_\perp$      | 0.5         |

2. Measurement of potential by Doppler spectroscopy

The GDT layout is shown in figure 2, several main parameters of the machine and the experimental scenario are listed in table 1.

Though the energy balance patterns in the GDT are well established at least for certainly collisional target plasmas, the properties of the ambipolar potential have not been studied exhaustively so far. Earlier experiments (see [1], p 27) with the wall-mounted grid ion energy analyser have provided only on-axis data taken within a limited expansion ratio numbers. Multiple accompanying probe measurements typically show large discrepancies and generally are not trustworthy. The best undisturbing and direct method combining a sub-centimetre spatial localisation with a time resolution of $\sim 100$ $\mu$s, is a heavy ion beam probe (HIBP [11]). Such diagnostics provide data for equilibrium spatial distributions of the plasma potential [12–14] as well as for fluctuations. The central GDT plane will be equipped with the HIBP on a Xe$^+$ when the currently ongoing manufacturing of the ion optical system and beamline components is finished. Meantime, optical diagnostics could offer comparable measurement capabilities at a lesser cost of R&D. In this particular case, the open-ended geometry of our magnetic system can be exploited. Recently the approach of optical Doppler spectroscopy was successfully adopted to measure the potential drop and the ion temperature in the plasma flow in the GDT expander [15]. The method relies on charge exchange (CX) conversion of streaming ions into atoms with the subsequent light emission, which implies the classical charge exchange radiation spectroscopy (CXRS) scheme:

$$A^{Z+} + H^0 \rightarrow A^{(Z-1)+} + H^+ \rightarrow A^{(Z-1)+} + H^+ + h\nu.$$  

The local CX target is the thermal H$_2$ jet produced by a pulsed gas valve and a movable thin quartz nozzle, see [15] for more detail. The shape of spectrum emitted by CX atoms follows the velocity distribution of source ions. The ion temperature...
can be derived from the Doppler width of the spectrum and the average velocity is linked to the Doppler shift. Assuming conditions (1), we have a simple equation for the potential drop accelerating ions:

\[
\Delta \phi = \frac{m_i c^2}{2q} \left( \frac{\Delta \lambda D}{\lambda_0} \right)^2 \frac{1}{\cos^2 \Theta},
\]

where \(\Delta \lambda D\) is the Doppler wavelength shift, \(\Theta\) is the angle between the ion velocity and the LOS direction.

The CXRS diagnostic currently has the single LOS hitting the machine axis at the plasma absorber plate as shown in figure 2. The pulsed gas stream of H\(_2\) puffed from the thin quartz capillary (16 in figure 2) provides the target to produce CX atoms emitting an optical signal of the good intensity for the spectral analysis. We observed a high contrast ratio \(R_c = \text{Active CX signal/Background signal} \simeq 20\) in the working spectral regions comparing the spectra acquired with the CX gas target and without it. Within this accuracy, we can consider measurements local neglecting the line-integrated background light pickup. The localisation is defined by the CX target size \(\Delta r_0 = \Delta r(z) \sqrt{H(z)/H_0} \lesssim 0.5\) cm. Here \(\Delta r(z)\) and \(\Delta r_0\) are transverse sizes in the measurement point and in the projection to the central plane along the magnetic surface, respectively. Gas tube 16 is installed via the vacuum feedthrough allowing to translate it along the LOS, see figure 2. Profiles of potential along the LOS are acquired repositioning the gas target from the plasma edge to the axis. Presuming a flat profile over Z in the area III in figure 1, the transverse profile is similar to the profile over LOS.

Ongoing research programmes in GDT lean on the scenarios where the target plasma and heating beams are both deuterium. The plasma startup is initiated by the electron cyclotron discharge with a microwave burst of a moderate power [16]. Later on, the target plasma density is maintained with the peripheral puff of \(D_2\) from the gas box integrated within the right mirror coil assembly, see figure 2. For the given viewing geometry, Doppler spectroscopy measurements on deuterium are severely complicated by cold hydrogen emission which inevitably presents in GDT expander spectra. The noted inconvenience can be easily bypassed using hydrogen as a diagnostic impurity in the central cell. For that, the similar left-side gas box injects this impurity of H\(_2\) into the plasma. This arrangement bounds the birthplace of tracer H\(^+\) ions to the vicinity of the left mirror, which is on the side of the spectroscopic diagnostic. Considering gas spreading over the plasma periphery, the upper estimate for the ionisation zone length might be 1 m or so. This location is shown as the zone II in figure 1. The spectroscopic method yields an additional benefit like observation of multiple emission lines at once coming from different impurities. For that, the second tracer impurity of He is injected in the central zone I, see figure 1. As it is described in [15], the monochromator is tuned in the spectral region for the simultaneous acquisition of two lines, H\(_\alpha\) and He–I with the wavelengths of 656.3 nm and 667.8 nm respectively. The accelerating potential drop extracted from the H\(_\alpha\) Doppler shift is averaged over the birthplace of H\(^+\) ions—the mirror zone II. In the same way, the He–I Doppler shift is linked with the averaged potential over the central zone I.

3. Spatial profiles of potential and scaling over electron temperature

Independent scans over radial and axial coordinates would be necessary to recover the spatial distribution of the electrostatic potential drop. As figure 2 illustrates, both \(r\) and \(z\) coordinates change along the diagnostic LOS so the scan across the LOS gives some slice of the spatial distribution \(\varphi(r, z)\). This dependence is presented in figure 3 as a function of the radii along the LOS. Each point acquired over five to ten shots, where the error bars reflect the standard deviation. Each shot in a series delivered two data samples, one for the central potential and another one for the mirror.

As previously shown, the radial coordinate is projected to the GDT central plane along the magnetic surface. In measurements of the mirror potential, no valid samples were taken beyond \(r_0 \simeq 10\) cm due to the abrupt signal decrease. The profiles feature a small descent towards the axis, which is a more significant on the central potential. One may also notice the dip on the mirror potential profile around \(r_0 \simeq 7\) cm. The plasma absorber 8 (see figure 2) has three rings with outer radii of...
7, 14, 25 cm. The outermost ring is overlapping with the limiter which has the inner radius of 14 cm so they are always supplied with the same bias voltage, $U_{bias} = +200$ V in the described experiment. Sectioned end walls and limiters with independent power supplies provide a versatile control over the radial electric field in the plasma. In the actual regime, two central rings are grounded. There is however the resistance of $\approx 0.2$ Ohm between the two rings coming from grounding cables that may affect plasma potential and current distributions. We assume that the internal layer with the sheared rotation may develop near the boundary, which is reflected as the above mentioned feature in figure 3. At the same time, the error bars in figure 3 are close to the potential dip value and more data would be necessary to assess this point in more detail.

The paper in [15] presents the target plasma ion temperature dynamics measured by the CXRS diagnostic in the same regime being discussed here. The peak ion temperature is appeared to be $\approx 15\%$ lower than the electron temperature on the axis. A separate experiment was dedicated to evaluate the on-axis ambipolar potential drop in units of the electron temperature and to calculate the relation coefficient. All numbers are measured on the axis at $t = 8.5$ ms corresponding to the peak of the fast ion energy content and $\beta_L$. The electron temperature was provided by the Thomson scattering in the central plane. For an on-axis observation of the potential drop, the measurement point is the plasma absorber centre where the magnetic expansion ratio $k_B = \sqrt{H_m/H_0} \approx 100$.

Figure 4 shows scatter plots $\Delta \varphi(T_e)$ and two least square linear approximations. Open blue circles represent measurements of the mirror potential via the Doppler $H_m$ and the blue dashed line is the corresponding linear fit. Filled red rectangles, dotted red circles and open magenta rectangles all correspond to the central potential via the He–I@667.8 nm line acquired in different series of shots. They belong to the same experimental scenario, but we distinguish them by the type and colour in the plot, because there were several-day machine vents in between those series. The dashed red line shows the linear fit for central data points. A varied number from four to eight of heating deuterium beams was fired to get the range over electron temperature. We mark the shot valid for statistics if there is no evidence of plasma instabilities or confinement disruptions caused e.g. by the limiter breakdown. The statistics accumulated in this GDT regime with a moderate electron temperature, allowed us to get the following coefficients:

$$\left\langle \frac{\Delta \varphi}{T_e} \right\rangle_{\text{mirror}} = 2.6 \pm 0.6, \quad \left\langle \frac{\Delta \varphi}{T_e} \right\rangle_{\text{centre}} = 3.1 \pm 0.5.$$

Several shots were made with the helium target plasma and deuterium heating beams, these points are shown as filled dark green triangles in figure 4. Measurements were done using the same spectral line of He–I@667.8 nm. However, in this regime we cannot bind the result to the mirror region or the central region either. For the helium target plasma, the first scarce data yielded the coefficient estimate as $\left\langle \frac{\Delta \varphi}{T_e} \right\rangle_{\text{He}} = 3.5 \pm 0.4$.

In a realistic consideration, the fraction of trapped electrons in the expander influences the ambipolar potential drop as well as ionisation of the background gas and secondary emission do. This rather complex self-consistent bundle of processes can hardly be reduced to a single linear coefficient discussed above in a wide range of plasma parameters. One can expect a deviation from a linear scaling law at higher temperatures. In fact, a significant scatter of points in figure 4 indicates that there are more factors in play. In this respect, a linear fit allows to relate observations to the approximate analytic theory and to check its applicability.

4. Conclusion

The pilot data acquired with the CXRS diagnostic in the GDT expander, proves that it is a robust instrument to study the
physics of the plasma axial confinement even in a current status of an one-channel prototype. Making use of a gas stream CX target permitted to record optical signals with a respectable $S/N \sim 10$ on a relatively low particle density inherent to the expanding plasma flow beyond the magnetic mirror. Owing to a high magnetic expansion ratio, the gas jet does not disturb the central cell plasma parameters and provides a good spatial resolution of less than a centimetre. This experience validates important techniques of expander plasma optical diagnostics for the projects of the gas dynamic multi-mirror trap [8] and diamagnetic trap [7] now entering the design stage.

The measured quantitative relation (5) shows the height of the ambipolar potential barrier suppressing the electron heat conductivity of the central cell plasma on the end wall. Presented numbers relate to the regime without ECRH ($T_e \leq 250$ eV) and they are not far from results yielded by earlier experiments ([11], p 27). Together with measurements of the axial energy loss per electron–ion pair [17, 18], the new data satisfactorily agrees with the approximate model developed by Ryutov [10]. In the case of collisionless plasma flow through the mirror, the accurate IDF in some expander region point is the integral of the central cell IDF (which is assumed Maxwellian) over the loss cone and thus it is different from (2). The effect of phase-space filtering of ion velocities was not considered here.

The upcoming GDT experimental campaign will be supported with the upgraded CXRS diagnostic having several lines of sight to study both axial and radial profiles of the electrostatic potential. The ECRH system will be engaged as well, allowing us to extend the available range of electron temperatures for the study of axial plasma confinement in GDT.

References

[1] Ivanov A.A. and Prikhodko V.V. 2013 Plasma Phys. Control. Fusion 55 063001
[2] Bagryansky P.A. et al 2011 Fusion Sci. Technol. 59 31
[3] Bagryansky P.A., Shalashov A.G., Gospodchikov E.D., Lizunov A.A., Maximov V.V., Prikhodko V.V., Soldatkina E.I., Solomakhin A.L. and Yakovlev D.V. 2015 Phys. Rev. Lett. 114 205001
[4] Bagryansky P.A., Beklemishev A.D. and Postupaev V.V. 2019 J. Fusion Eng. 38 162–81
[5] Pastukhov V.P. 1974 Nucl. Fusion 14 3
[6] Ivanov A.A. et al 1994 Phys. Plasmas 1 1529
[7] Beklemishev A.D. 2016 Phys. Plasmas 23 082506
[8] Beklemishev A. et al 2013 Fusion Sci. Technol. 63 46–51
[9] Gota H. et al 2017 Nucl. Fusion 57 116021
[10] Ryutov D.D. 2005 Fusion Sci. Technol. 47 148–54
[11] Jobes F.C. and Hickok R.L. 1970 Nucl. Fusion 10 195–7
[12] Nedzelskiy I.S., Malaquias A., Cabral J.A.C. and Varandas C.A.F. 2001 Rev. Sci. Instrum. 72 572–4
[13] Melnikov A. et al 2004 Fusion Sci. Technol. 46 299
[14] Ido T. et al 2006 Rev. Sci. Instrum. 77 10F523
[15] Lizunov A. 2021 J. Inst. 16 P05018
[16] Yakovlev D., Bagryansky P., Gospodchikov E., Shalashov A. and Solomakhin A. 2016 Electron cyclotron resonance discharge for plasma startup in the gas dynamic trap AIP Conf. Proc. 1771 030007
[17] Yakovlev D.V., Shalashov A.G., Gospodchikov E.D., Maximov V.V., Prikhodko V.V., Savkin V.Y., Soldatkina E.I., Solomakhin A.L. and Bagryansky P.A. 2018 Nucl. Fusion 58 094001
[18] Soldatkina E.I., Maximov V.V., Prikhodko V.V., Savkin V.Y., Skovorodin D.I., Yakovlev D.V. and Bagryansky P.A. 2020 Nucl. Fusion 60 086009