A novel approach for the improvement of the sensitivity of the flow visualization system on supersonic molecular beam of tokamak fuelling

G.L. Xiao, J. Yin, C.Y. Chen, B.B. Feng, Y.R. Zhu, W.L. Zhong, Y.P. Zhang, T.B. Wang, M. Xu and X.R. Duan

Southwestern institute of Physics, Chengdu, China

E-mail: zhongwl@swip.ac.cn

ABSTRACT: Supersonic molecular beam injection is a robust alternative to control the particles in fusion plasma devices. It is widely used in many experimental studies on the plasma physics. Direct visualization of beam makes it possible for precise optimization of the beam characteristics. However, a normal visualization system does not fully meet the requirements of the measurement of the beam distribution in the low gas density vacuum environment. This paper reports a newly designed multi-pass visualization system without changing the schlieren mirrors. This multi-pass system is designed to make the light passing the testing area several times, where the deflection angle of the light would simultaneously increase. Thus, the sensitivity of the schlieren image is enhanced. The testing result proves the improvement of the sensitivity, which makes it possible to optimized the beam structure in low gas density working conditions.

KEYWORDS: Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - high speed photography

*Corresponding author.
1 Introduction

Supersonic molecular beam injection is widely used on magnetic fusion devices for plasma fueling and particle control [1]. This supersonic beam is formed by the adiabatic expansion process when the gas passing through a Laval-like nozzle. During this process, the inner energy of the gas source transforms into translational energy, presenting an oriented gas beam with high-speed, generally higher than the ultrasonic speed with Mach number larger than 1. As a consequence, the supersonic molecular beam could fuel the plasma with low wall retention, which performs distinct advantages in plasma fueling and related physical studies than the normal gas puffing method [2–4]. To further optimized the beam with a smaller divergence angle, the beam should be directly measured.

Recently, a schlieren system is established and successfully visualized the beam with a clear beam structure on the SMBI testing platform [5, 6]. This system is designed to be in Z-type to fit the long focal length of the schlieren mirrors, ensuring the high sensitivity. However, the previous work suggests that the sensitivity of the current schlieren system does not meet the requirements for the beam visualization in the low gas density working condition like the environment in the vacuum tube of SMBI system on tokamaks. Thus, the sensitivity of the schlieren system should be further improved for beam visualization.

The single-pass (SP) system, including the Z-type one, in which the parallel light passes through the testing area with two mirrors, is a commonly used schlieren configuration [7]. This two-mirror based system with single pass configuration could provide quantitative information of the refractive index in the homogeneous medium. In addition, the single-mirror coincident system is a single mirror-based systems without the advantages of parallel light, but the double-pass (DP) [8] of the light crosses the test section would theoretically increase the optical sensitivity [9]. Although this system has double-pass configuration, the divergence or the convergence light beam is not appropriate for quantitative measurement, since the identical inhomogeneities at different location would lead to different deflection angle. Inspired by this single-mirror coincident system with double-pass configuration, the idea of the multi-pass system with the advantage of the parallel light is proposed and its sensitivity is theoretically calculated [10]. In this work, we presented the newly developed
multi-pass schlieren system, which improves the sensitivity according to the preliminary testing result. The paper is organized as follows. Section 2 describes the system design. Section 3 shows the preliminary experimental result of the multi-pass schlieren system. Section 4 is the summary.

2 System setup and design

2.1 Experimental platform

A testing platform has been established to test the characteristics of the SMBI system. This testing platform is composed of several facilities including the gas injection system, the vacuum chamber, the vacuum support system, and the diagnostics. The gas injection system is the input of the gas for this platform, which usually connects with the SMBI system including the high-pressure gas source, the SMB pulse time controller. It injects the SMB into the vacuum chamber with pre-set pressure and pulse duration with signal pulse mode and cycle pulse mode. The vacuum chamber includes two parts, the large cylinder chamber in the vertical direction and the long cylinder tube in the horizontal direction. The large cylinder chamber provides sufficient area for the expansion of the gas and enables the detection at the outlet of the nozzle. The long vacuum tube simulates the working environment for the fueling at the tokamak, where the status of the fueling beam could be diagnosed. The vacuum chamber and the vacuum tube are sustained by the three mechanical pumps and three turbo molecular pumps, by which the vacuum degree could be reduced to $10^{-5}$ Pa after baking by the heaters at the inner wall of the vacuum components. In addition, film gauges are installed on the platform to supervise the vacuum degree. The diagnostics are changeable for different requirements, such as the schlieren diagnostic system, the Rayleigh scattering diagnostic system, and the high-voltage discharge system. The Zigzag schlieren diagnostic system has been already installed on the testing platform, which provides a larger field-of-view than our other attempt with the single-mirror coincident system, and the structure of the beam is clearly observed [5, 6].

2.2 System design of the multi-pass visualization system

Sensitivity is a basic characteristic for the schlieren system, which is usually typified by the amplitude or grayscale contrast variations. The sensitivity of the constructed Z-type schlieren system is convenient to be illustrated by its geometrical optics. It can be derived that the schlieren image illuminance with the knife-edge cutoff can be described as [9]:

$$E = \frac{B \cdot b \cdot a}{m^2 f_1 f_2}, \quad (2.1)$$

where $B$ is the luminance emitted by the light sources, $m$ is the magnification factor of the image size, $b$ is the breadth of the slit, $a$ is the height of the knife edge at the focal point for the second schlieren mirror, $f_1$ and $f_2$ are the focal length of the first and the second schlieren mirror, separately. Considering the light deflected by the schlieren object with the deflection angle $\varepsilon_y$, the deflected distance at the second focal point is described by:

$$\Delta a = \varepsilon_y f_2 \quad (2.2)$$

Substituting $\Delta a$ for $a$ in eq. (2.1), it can be obtained that:

$$\Delta E = \frac{B \cdot b \cdot \varepsilon_y}{m^2 f_1} \quad (2.3)$$
The contrast of the schlieren image is then given by the following equation:

\[ C \equiv \frac{\Delta E}{E} = \frac{f_2}{a} \varepsilon_y \]  

(2.4)

Thus, the sensitivity for the Z type normal system is limited by the width of the slit and the focal length of the second schlieren mirror, which is hardly optimized when the system is settled. The sensitivity factor for the Z type schlieren system is given by the following equation:

\[ s = \frac{f_2}{a} \]  

(2.5)

The ideal of the multi-pass system is inspired by the double passed system, and was theoretically proved in 1966 [10]. Since the width of the slit and the focal length is constrained by the hardware of a fixed system, another approach to increase the contrast of the schlieren image is the increase the deflection angle as shown in figure 1. The red dashed line means the interface between the regions with tiny difference on density and its normal line. The incident light passes through the test area with a deflection angle \( \varepsilon \). The deflected light is reflected by a mirror and passes the test area again with the deflection angle \( \alpha \). According to the law of the refraction, the twice pass light follows the equation below:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  

(2.6)

\[ n_2 \sin(\theta_1 + \varepsilon) = n_1 \sin \alpha \]  

(2.7)

It should be noted the deflection and the reflection happens in a small region, and deflection angle of the light ray \( \varepsilon \) is also small enough, which allows the light rays keeps in the similar direction to the incident light ray. Thus, under the assumption of the small angle reflection, the deflection angle \( \alpha \) for light ray passing the testing area twice is:

\[ \alpha \approx \theta_1 + 2\varepsilon \]  

(2.8)

The result shows that the deflection angle could increase by \( \varepsilon \) each time when the light passes through the test area. It should be noted that the deflection angle is small which makes the reflected light still almost parallel to the incident light. Thus, the forward light reflected by the mirror for \( l \) times, the deflection angle is:

\[ \varepsilon_{2l-1} = (2l - 1)\varepsilon \]  

(2.9)
According to this idea, two splitters are added to the original Z-type system parallel to the view windows of the main vacuum chamber on both sides as shown in figure 2. The reflection coefficients for the first beam splitter and the second beam splitter are \( r_1 \) and \( r_2 \), respectively. \( t_M \) is the transmission coefficient across the light pass. Thus, the contrast of the system is described as following:

\[
C = \frac{f}{a} \left[ \sum_{l=1}^{\infty} (r_1 r_2 t_M^2)^{l-1} e^{2l-1} \right] / \left[ \sum_{l=1}^{\infty} (r_1 r_2 t_M^2)^{l-1} \right]
\]  \hspace{1cm} (2.10)

Neglecting the transmission loss during the light path donates the \( t_M = 100\% \).

Figure 2. Schematic of the multi-pass schlieren system for SMB visualization based on the normal zigzag schlieren system. The red and blue splitters are added to the normal schlieren system to create a multi-pass system.

3 System testing and the initial result

As described above, the multi-pass system is installed on the testing platform. To simplify the testing process, the background pressure is set as the level of \( 10^4 \) Pa to obtain a clear beam structure. In addition, the working gas is chosen to be carbon dioxide (CO\(_2\)) for convenience and safety reason. This system is then carefully adjusted to ensure the secondary schlieren image would be captured, since a small aberration on the first image can be amplified in this optical system. Figure 3 clearly shows two separate schlieren images by adjusting the mirrors. The direct measurement of the schlieren images captured by high-speed camera is shown in figure 3(a). It could be observed that these two images are deliberately separated to show the first and the second schlieren images. The first schlieren image, which is obtained by the light directly passing through the mirrors, has the deflection angle to be. The second schlieren image is obtained by the light reflected twice by the second and the first splitters with the deflection angle. In addition, the intensity of the second schlieren image is less than the first schlieren image, which means the improvement of the contrast or the sensitivity is limited by the performance of the mirrors and the camera. Instead of many schlieren images in theory, several schlieren images can be obtained in practice due to the attenuation of the intensity and the growing of the aberration. The misplaced first schlieren image and the second schlieren image are aligned to be in the same place to form a superposition schlieren image by adjusting the direction of schlieren mirror 2 and the reflector 2.
The reflection coefficients for both beam splitters are 50%. According to equation (2.10), the superposition of these two schlieren images makes the contrast of the twice-pass superposition schlieren image to be 1.25, which is about 0.25 (25%) higher than the single-pass image. Figure 4 shows the comparison of the contrast of the twice-pass superposition image and the normal single-pass image. The contrast of the image is defined in equation (2.4), which is practically calculated by the captured schlieren images as follows:

\[
C \equiv \frac{\Delta E}{E} = \frac{|I(x, y) - I_0|}{I_0}
\]  

(3.1)

Where \(I(x, y)\) is the schlieren image with the SMB captured by high-speed camera, and \(I_0\) is the background image without SMB.

The contrast of the twice-pass superposition image \(C_1\) and the normal single-passing image \(C_2\) is shown in figure 4(a) and figure 4(b) respectively. The comparison of the contrast is shown in figure 4(c), which is obtained by subtracting the contrast \(C_2\) from \(C_1\). It could be observed that the contrast of the twice-pass superposition image is higher.

The background noise and small structure turbulence in the figures should be omitted, which is normally in random distribution and is not repeatable with relatively low contrast (lower than 0.12) in
these cases. The distinguish structure of the main stream, which is considered to be repeatable under the same working condition, is illustrated in figure 5 from superposition image in figure 4(a). Only the data in the main stream region is used, which is \( x = [0 \text{ mm}, 40 \text{ mm}] \) and \( y = [-1.5 \text{ mm}, 1.5 \text{ mm}] \) within about \( 16 \times 230 \) pixels as marked by the dashed red box in figure 5, the data in this region is used. The intersection of the main stream structures from all the images in this region can further figure out a more accurate boundary of the main stream structure. The averaged increase of the contrast from figure 4(c) is then calculated with this accurate main stream structure, which is about 21.0%. This value is close to the value based on the theoretical estimation.

**Figure 5.** The structure of the main stream of the superposition image in figure 4(a) by omitting the part of the image with the contrast lower than 0.12 where the randomly distributed background noise and small turbulence dominate.

### 4 Summary

The supersonic molecular beam injection is widely used in fusion plasma fueling and physical studies. The visualization of the beam is essential for its optimization and further quantitative investigation in related physical studies. A multi-pass schlieren system is designed and investigated for the low gas density working environment, which is expected to have higher sensitivity than the normal system. Usually, the improvement of the sensitivity of the schlieren system is to enlarge the schlieren mirrors to acquire a larger focal length, dramatically changing almost the whole system. Unlike the common approaches, this multi-pass system only simply adds two beam splitters. The testing result shows this multi-pass system improves the sensitivity to be 21.0% higher with the superposition of only two schlieren images. The performance of this system could be better with more superposition images once appropriate reflection coefficients of the beam splitters are chosen. The system will be dedicated to the optimization of the SMB in the low gas density working environment.

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