Optical path design of phase contrast imaging on HL-2A tokamak

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Abstract
A phase contrast imaging (PCI) diagnostic has recently been developed on HL-2A tokamak. It can diagnose plasma density fluctuations with maximum wave number of 15 cm⁻¹ and wave number resolution of 2 cm⁻¹. The time resolution reaches 2 μs. A 10.6 μm CO₂ laser is expanded to a beam with a diameter of 30 mm and injected into the plasma as an incident beam, injecting into plasma. The emerging scattered and unscattered beams are contrasted by a phase plate. The ideas of optical path design are presented in this paper, together with the parameters of the main optical components. The whole optical path of PCI is not only carefully designed, but also constructed on HL-2A. First calibration results show the ability of this system to catch plasma turbulence in a wide frequency domain.

Keywords: phase contrast imaging, plasma laser diagnostic, phase plate

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

1. Introduction
Micro-turbulence is believed to be the key to the anomalous transport in high temperature plasma. Most of the plasma turbulent energy is in the range of low wave number k, and turbulence can transfer energy from low wavenumber parts to high wave number parts by energy cascade. The turbulent energy spectrum will show an exponential decay as the increasing of k, which means that we should investigate not only the turbulence with high k such as the electron temperature gradient mode [1] but also that with low k such as the ion temperature gradient mode [2] and trapped electron mode [3]. The far-forward laser scattering diagnostic [4–6] which can measure density fluctuations with high k, is not suitable for low k circumstances for the limited scattering angle. Phase contrast imaging (PCI) [7], which can diagnose long wave-length density fluctuations, is a keen tool to investigate the wide-spectrum characteristics and is developed in many magnetic confinement devices, such as DIII-D [8], Alcator C-Mod [9], LHD [10], TEXT-U [11].

When a laser beam runs through the turbulent plasma, there will be a small phase shift of the beam. If a phase plate is used on the path of the unscattered beam and delays its phase for π/2, we can contrast the phase shifted unscattered beam and the scattered beam. The intensity I_PCI of the total beam and phase shift Δ caused by the plasma density fluctuation are given by:

\[ I_{PCI} - I_0 \propto \Delta = -\lambda_0 r_e \int n_e dl \ll 1, \]

where \( I_0 \) is the incident light intensity, \( \lambda_0 \) is the wavelength of the incident beam and \( r_e = e^2/(4\pi\varepsilon_0 m_e c^2) \) is the classical electron radius. From this equation, we can get the conclusion that the light intensity fluctuation of PCI is proportional to the density fluctuations of plasma. So, the main idea of PCI
detection is to catch the weak light intensity fluctuations which requires a high-performance and reliable optical path. In recent years, a set of PCI diagnostics has been developed on HL-2A tokamak. It is obvious that one of the key issues of this system is the optical path. In this article, we present the design of the optical path of this PCI system. The rest of this article is organized as follows. The layout and requirements of PCI system on HL-2A are briefly introduced in Section 2. Detailed designs of the front expansion optics and rear imaging optics are presented in Sections 3 and 4, respectively. The simulated optical path and the parameters of main components are listed in Section 5, together with some first calibration results showing the performance of this optical path and the success of the PCI development. In the final Section 6, a brief summary is presented.

2. Design requirements of PCI diagnostic on HL-2A

The optical path, which is shown in Figure 1, is the key issue of the optical diagnostic of PCI. Because PCI is a kind of scattering diagnostic, the beam should pass through the plasma and be collected by the detector array. On HL-2A, and also almost on all of the large tokamaks, there exist no inner ports on the high field side. The most convenient way for PCI optical path is injecting the incident beam from a bottom port of the vacuum vessel and collecting the emerging beam from the top port, especially the opposite port. HL-2A has only one bottom port with a diameter of 30 mm at a radial position of $0.625 < \rho = r/a < 0.7$ labeled as port ‘NO’, with a top port of the same size which is right opposite to it. ACO$_2$ laser with a wavelength of 10.6 $\mu$m is chosen as the incident beam. The diameter of the laser beam is 2 mm, and it should be expanded to 30 mm, limited by the inner diameter of 30 mm diagnostic ports. From the perspective of wave propagation, the diagnostic diameter determines the maximal wavelength of the plasma wave which can passing through the viewing port, or in other words, the minimal wavenumber $k$ of the PCI system. The expanded beam has to be accurately collimated because of the long optical path. To achieve PCI, the focuses of the emerging scattered and unscattered light are required to fall on the specified position on the phase plate. Also, the position of the exit pupil after modulation is required to coincide with the detector plane. Consequently, the design of the entire optics is crucial. The front expansion and collimating optics of PCI (before injecting into the plasma) and the rear emerging imaging optics (after passing through the plasma) should be carefully analyzed and designed to determine the parameters of the alloptical elements.

3. Front expansion optics

The PCI diagnostic utilizes the CO$_2$ laser with a wavelength of 10.6 $\mu$m and the beam diameter of 2 mm. To meet the 30 mm diameter of the vertical bottom and top ports for PCI, it is necessary to design the front (before injected to the plasma) expansion and collimating optics. Firstly, we expand the diameter of the laser from 2 to 30 mm. Secondly, because the entire length of the front optics is longer than 8 m from the front platform to the HL-2A bottom port, the divergence of the Gaussian beam is non-negligible and optical path collimation is needed. Zemax is chosen as the main optical simulation software.

The expansion optical path, as shown in Figure 2 in which blue lines indicate the laser beam, is a telescope system consisting of a concave mirror and an off-axis parabolic mirror. Because of the non-negligible divergence of the Gaussian beam, the incident 2 mm laser is firstly focused by two lenses, which will be discussed in detail in Section 3.2. After that the laser is expanded by the concave mirror from the narrow beam to the laser of 30 mm diameter, afterwards collimated by the off-axis parabolic mirror. The entire parabolic mirror is shown in the figure, but in fact only a small part of its edge is actually utilized. After going through the front expansion optics, the parallel laser beam with a diameter of 30 mm is shaped and then injected to the vacuum vessel through the bottom port window of HL-2A.
3.1. Material selection of the optical elements

Since the laser for the PCI diagnostic is infrared with the wavelength of 10.6 μm, so we choose the ZnSe as the lens material, which is nearly transparent for such line. The common choice of reflective material includes aluminum, silver and gold, etc. Considering the wavelength and the reflection coefficients, gold is chosen as coating material for the parabolic mirror and other reflective surfaces. ZnSe is also the only candidate for the bottom and top port windows, although working as sealing glass it is soft and fragile under the air pressure.

3.2. Arrangement of focusing lens

Due to the long optical path, the focus lenses are added in the front expansion optical path. ZnSe lenses (see figure 2) with a focal length of 500 mm work as main focusing lens. The light passing through a single lens is thought to be divergent after propagating more than 1000 mm, which is twice of the focal length. The total optical path length of the front expansion optical path is 2800 mm before expansion in this system. Therefore, two lenses are used. One is placed at a position of 500 mm away from the laser source, and the other is placed 490 mm before the concave mirror. Consequently, the radius of the exit laser given by the simulation of Zemax is 15.0898 mm, which well meets the requirement of an optical path of 30 mm.

3.3. Position optimization of concave and parabolic mirrors

The concave mirror is not an ideal lens, and what is more, it needs to be rotated precisely to a certain angle. To get the parallel emerging beam, suitable placement of the concave mirror and the parabolic mirror is key to the front expansion optical path. The optimization of the relative position of these two mirrors is of prime important. The common used Zemax software is chosen as the main design tool in this article. The optimization of a focal system is not obvious in Zemax, so we change the system into a focal system in the simulation by adding an ideal lens which does not exist in the real optics. The ideal lens with a focal length of 100 mm is added at the end of the front optics, which is placed exactly 100 mm in front of the image plane. Thus if the laser emerging from the parabolic mirror is parallel, it should be focused exactly at the image plane by the ideal lens. Setting the pitch of the concave mirror and the parabolic mirror variable, optimizing the image by using Zemax optimization function, we gain a parallel emerging beam which satisfies PCI requirements. The beam shifts only 0.06 mm downwards after transmitting for 8600 mm. The off-axis parabolic mirror is a part of a paraboloid. When we choose the paraboloid with zonal radius of 176 mm (8°) and the radius of 32 mm, the parabolic mirror actually utilizes the edge part from 112 to 208 mm off the axis of the paraboloid. Because the expansion optics must ensure the coincidence of the focus both of the concave mirror and the off-axis parabolic mirror, the rotation of the concave mirror will introduce a large off-axis distance due to the

4. Rear imaging optics

For many reasons, such as reducing the divergence, the influence from other surrounding machines and vibrations, the optical length should be short. The rear optical path is located right on top of the tokamak to reduce the optical length as short as possible. It is not wise to construct a big optical platform on top of HL-2A. It is hard to find enough space and suitable supporters for the platform. Together with shielding and safety reasons, the size of the rear optical platform is restricted. The rear optical path should be compact.

The rear optics is a PCI system composed of an off-axis parabolic mirror, reflecting mirrors, a phase plate, lens groups and a filter. The details of the design are shown in figure 3. The green and the red lines represent the two scattered light beams exiting from the plasma, and the blue lines indicate unscattered light. The black circles and the corresponding black arrows in the figure work here just as marks of zooming into show the local magnified optical paths near the reflecting mirror, phase plate, and filter. The scattered and the unscattered beams are collected and focused by the off-axis parabolic mirror, and two Fourier planes are formed before and after the lens groups. The first Fourier plane is used for modulating the emerging beams by placing the phase plate right there to realize phase contrasting, and the second one is for spatial filtering. At the end of the rear optics, the detector
array is placed at the exact location of the exit pupil to detect the signals.

4.1. Determination of off-axis distance

The off-axis parabolic mirror in the rear optics cannot rotate, otherwise the incident light will not be parallel to the symmetry axis of the paraboloid, causing the incident parallel light is not normal incidence and cannot be strictly focused at the focus, which result in producing an aberration similar to the concave mirror. The deviation angle of the light reflected by the parabolic mirror is completely determined by the off-axis distance. It is necessary to select an appropriate off-axis parabolic mirror in order to avoid the blocking of the optical path. The radius of the reflecting mirror we used is 25.4 mm. The distance from the parabolic mirror to the first reflecting mirror is 400 mm. The traces of the light with different off-axis angle from 5° to 10° are simulated, taking the total radius of the reflecting mirror 30 mm. The results indicate that the optical path is blocked at 5°, and the light is separated from the reflecting mirror obviously at 7°. However, the size of the paraboloid significantly increases when the off-axis angle is more than 9°. Considering the processing technology, finally we choose the off-axis parabolic mirror of 8°. Thus, the scattering angle can be allowed to reach 0.15° without blocking. According to the Bragg conditions \( \sin(\theta) = \frac{k_0}{2l} \), where \( k_0 \) is the wave number of laser, the maximal wave number \( k_p \) that can be measured is about 15.52 cm\(^{-1}\).

4.2. Focus at Fourier planes

4.2.1. Phase plate. After being scattered by the plasma, the emerging light can be seen as three beams of parallel light as shown in figure 3, given a scattering angle of 0.15°. The focal spots of the scattered and the unscattered light on phase plate are simulated by Zemax. Focused by the off-axis parabolic mirror, as shown in figure 4, the unscattered light is nearly an ideal circle spot (figure 4(A)), but the scattered lights form a deviation due to the scattered angle (figures 4(B) and (C)). When the waist of the Gaussian beam is 4600 mm before the parabolic mirror, with the radius of 15 mm, the diameter of the focal spot of unscattered light is 0.56 mm, and it is 0.62 mm for the scattered light. They are clearly separated from each other because the distance between the centers of the focal spots is \( s = 3.587 \) mm. The groove size of the phase plate can also be determined. Taking into account the actual process capacity of technology, the width of the groove in the phase plate is designed to be 0.88 mm. This groove width is determined by the viewing port size, the wavelength of the incident beam and the focal length of the off-axis parabolic mirrors \( F_1 \). A more detailed theoretic derivation of groove width can be consulted in [12]. To avoid the scattered beams falling partly into the groove, the groove width follows \( w \ll 2s = \frac{2\lambda_0}{k_0}F_1 \), where \( \lambda_0 \) is the diagnosed plasma wavelength. Since the phase delay of the unscattered beam to the scattered beams is expected to be \( \pi/2 \), the depth of the groove is designed to be \( \frac{\lambda_0}{s} = 1.325 \) µm, where \( \lambda_0 = 10.6 \) µm is the wavelength of the CO\(_2\) laser.

4.2.2. Filter plane. Nonlinear effect will cause signal distortion of plasma waves with very large wavenumbers. Spatial filtering should be designed in the PCI optical path to filter it out.

When the three parallel lights are given a scattered angle of 0.15°, with the incidence from 4600 mm before the off-axis parabolic mirror, the filter plane is at 127 mm after the f150 lens (focal length \( f = 150 \) mm ZnSe lens). Since the ZnSe lenses are not ideal lenses, the focus spots are different from before, as shown in figure 5. Assuming the waist of the Gaussian beams is 4600 mm before the parabolic mirror, the diameter of the unscattered light is 0.12 mm (figure 5(A)). The diameter of the scattering light is 0.12 mm as well (figures 5(B) and (C)). The distance between the spots of scattered light and the unscattered light is 0.70 mm, so the spots are separated.

4.3. Size and position of exit pupil

The size of one element of the 32-channel linear detector array of PCI is 0.2 mm × 1 mm with 0.05 mm gap between the adjacent two, which will be presented in the 5th section of this article. This array is not well suited for detecting plasma density fluctuations with \( \lambda_0 \gg 8 \) mm. Therefore it requires a zooming out collection optical lens group with a magnification coefficient \( M < 1 \). This collection optics can greatly enhance the light intensity by a factor of \( 1/M^2 \). The position of the Gaussian waist will affect the magnification and the position of the exit pupil. When the waist is given at the position of 4600 mm before the parabolic mirror, the exit
pupil is 166 mm after the f150 lens. The diameter of the exit pupil is 3.996 mm, and the magnification is 0.133. If the relative position of the two lenses of the rear optics is changed, i.e. 833 mm changes to 450, 354–315 mm, and the diameter of the exit pupil will change to 11 mm. The exit pupil is now 296 mm after f150 lens, which is nearly at the position of twice of the focal length, and the magnification becomes 0.37. The filter plane is also changed, which is now at 127 mm after the f150 lens. The diameters of both the scattered and unscattered light are 0.18 mm. The spots are still separated since the distance between them is 1.05 mm.

5. Development of optical path on HL-2A

Basing on the discussion and simulation of the front expansion optics and the rear imaging optics, the whole optical design of PCI diagnostic on HL-2A is determined, as shown in figure 6. Similar to that in figure 3, the optical path is locally zoomed in marked by black circles and arrows. The blue lines shown the path of the laser beam, and the short red line segments indicates optical components numbered from 1 to 15. The primary parameters of all of these 15 optical components are shown in table 1. Some main parameters of the key component of phase plate numbered 10 in figure 6 are not shown in table 1. The diameter of the phase plate is 30 mm. The width of the rectangular groove in the center of phase plate is 0.88 mm with a designed 1.325 μm thick gold coating on both sides. Due to the limitation and error of processing, the actual coating thickness is 1.3 μm.

The optical path of PCI has recently been developed on HL-2A tokamak. Figure 7 shows a photo of the front optical path. It is to be noted that in this photo, a red helium–neon gas laser beam, instead of the 10.6 μm CO₂ laser which is invisible, is used as the test signal to check the optical path. One can clearly see the fairly good collimation of this optical system.

To get reliable diagnostic data, absolute calibration of PCI system is carried out by means of using sound waves from a loudspeaker. The method of calibration is out of the range of this article and will be discussed elsewhere. Here we will present parts of the calibration results to show the success of the optical design.

Table 1. Main parameters of the optical elements of PCI diagnostic.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Radius (mm)</th>
<th>Focal length (mm)</th>
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<tbody>
<tr>
<td>1, 4, 12</td>
<td>ZnSe lens</td>
<td>25.4</td>
<td>500</td>
</tr>
<tr>
<td>14</td>
<td>ZnSe lens</td>
<td>25.4</td>
<td>150</td>
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<tr>
<td>2, 3</td>
<td>Reflecting mirror</td>
<td>12.7</td>
<td>/</td>
</tr>
<tr>
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<td>Concave mirror</td>
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<td>125</td>
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<td>Off-axis parabolic mirror</td>
<td>32</td>
<td>1250</td>
</tr>
<tr>
<td>8, 9, 11, 13, 15</td>
<td>Reflecting mirror</td>
<td>25.4</td>
<td>/</td>
</tr>
<tr>
<td>10</td>
<td>Phase plate</td>
<td>15</td>
<td>/</td>
</tr>
</tbody>
</table>

Figure 5. The focal spots of the scattered and the unscattered light on filter plate. (A) Unscattered; (B) and (C) scattered.

Figure 6. The final optical path of PCI diagnostic on HL-2A tokamak.

Figure 7. Parts of the optical path of developed PCI diagnostic (front expansion optics).
A 32-channel photo conductive HgCdTe detector line array with preamplifiers and nitrogen cooling is chosen as the detector of the PCI system. Every element has a size of $0.2 \, \text{mm} \times 1 \, \text{mm}$ with a gap of 0.05 mm between two adjacent elements. Figure 8 shows the power spectrum of signals from one PCI HgCdTe detector channel Ch9. In this calibration, a 10.6 $\mu\text{m}$ laser is used as the incident beam. Sound waves at the frequency of 10, 20 and 15 kHz are used to simulate plasma turbulent waves. After the modulation of the PCI laser beam by these sound waves at different frequencies, we can clearly see three pronounced peaks in the spectrum in figure 8. This means that this PCI system can efficiently catch the modulation of the PCI laser beam by the plasma waves in frequency domain. A more detailed absolute calibration is out of the scope of this article and will be carefully discussed elsewhere.

6. Summary

The optical design of the PCI diagnostic on HL-2A has been finalized. Main parameters of all of the optical elements are carefully validated and the whole optical path has been developed. Sound wave calibration shows the success of not only this optical design but also an acceptable technical process of the optical elements. The PCI system can diagnose plasma density fluctuations with maximum wavenumber of $15 \, \text{cm}^{-1}$, wavenumber resolution of $2 \, \text{cm}^{-1}$ and time resolution of $2 \, \mu\text{s}$. The broad $k_p$ ranging from 0.2 to 3 makes it a keen tool for turbulence investigation [12].

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