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The comparison between near-infrared and traditional CO_2 phase contrast imaging on HL-2A tokamak

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ABSTRACT

The main idea of developing Near Infrared Phase Contrast Imaging (NI-PCI) diagnostic on HL-2A tokamak is presented. Compared to the traditional PCI diagnostic which injects CO_2 laser beam with a wavelength of 10.6 μm into plasma, NI-PCI using 1.55 μm laser has more advantages in measuring plasma density fluctuations due to shorter wavelength. This novel diagnostic is designed to detect plasma density perturbations with a wavenumber ranging from 2 cm^{-1} to over 30 cm^{-1} without significant phase scintillation effect. Comparison of diffraction effects between 10.6 μm and 1.55 μm laser beam shows that NI-PCI has a better response than PCI with a size-limited diagnostic window on HL-2A.

1. Introduction

Micro-turbulence is believed to be the key for understanding the anomalous transport in fusion plasma [1–4]. Theoretical and experimental investigations on turbulence show evidence of energy transfer in a wide range of turbulence wavenumber through energy cascade. In tokamak plasmas, the turbulence scale ranges from the size of minor radii such as magnetic fluctuation to electron cyclotron radii such as electron temperature gradient mode (ETG). ETG will also couple with even larger scaled turbulence. This multi-scale character of turbulence requires keen tools which can diagnose plasma in a wide wavenumber domain.

Most of the plasma density fluctuation diagnostics can only catch low wavenumber turbulent signal, such as Doppler Reflectometer [5], Beam Emission Spectroscopy [6,7] and Gas Puffing Imaging [8]. Far-forward laser scattering [9,10] diagnoses fluctuations with a relative large wavenumber, but it loses application in low wavenumber range because of the limitation of scattering angle. Phase Contrast Imaging, which can diagnose plasma density fluctuations in a wide wavenumber range, works as a keen tool to investigate multi-scale turbulence both in core and edge on many tokamaks [11–16].

A traditional PCI diagnostic based on 10.6 μm CO_2 laser beam has been recently developed on HL-2A tokamak [17]. The probe beams of traditional PCIs on tokamaks to diagnose density fluctuation are usually CO_2 laser with a wavelength of 10.6 μm. This comes partly from the high power and technical maturity of CO_2 laser. Some unsolvable defections of this PCI diagnostic have troubled researchers for decades since the first application on tokamak in the 80 s last century [12]. One of the fatal flaws which strongly restricts the wavenumber measurement of PCI is the phase scintillation effect [18]. For an incident beam with a much shorter wavelength, this unwanted nonlinear effect can be effectively weakened. However, the principle of PCI introduced in Section 2 provides a lower limit that the laser wavelength can't be infinitely small. Longer wavelength of the beam probe will ensure a higher signal noise ratio. As the progress in laser technology, the high power fiber lasers of 1.55 μm wavelength with feedback system can promise a power stability better than 0.05%. Therefore, we need make a compromise among signal output, physical response, technological level and market when deciding the optimal laser wavelength.

In this article, we present a novel kind of Near Infrared Phase Contrast Imaging (NI-PCI) diagnostic based on 1.55 μm fiber laser, which is under development on HL-2A tokamak. The rest of this article is organized as follows. The principle of PCI is briefly introduced in Section 2. Detailed design of NI-PCI system on HL-2A is presented in Section 3 and Section 4 represents some results and discussion. Finally, a summary is given in Section 5.

2. PCI diagnostic on HL-2A

The phase plate, which is the key component in the contrast optical path of PCI system, can delay the phase of the unscattered light by $\pi/2$ [19]. After phase contrast, the total collected light intensity of PCI

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diagnostic is:

$$I_{PCI} \propto \frac{|E_{PCI}|^2}{2\mu_0 c} = I_0(1 + 2\Delta\cos k_p x) \tag{1}$$

where I_0 means the incident light intensity, $\Delta = -\lambda_0 r_e \int n_e dl \ll 1$ represents the phase shift caused by plasma density fluctuations, k_p stands for the wavenumber of density fluctuation perpendicular to scattered direction, $\lambda_0 = 10.6\,\mu m$ or $1.55\,\mu m$ is the wavelength of incident laser for PCI or NI-PCI diagnostic and $r_e = e^2/(4\pi\varepsilon_0 m_e c^2)$ is the classical electron radius. By measuring the light intensities *I(R,t)* using the detector array, we can obtain the frequency-wavenumber spectrum of fluctuations by two dimensional Fourier transformation:

$$S(k_p, f) = \left| \frac{1}{\sqrt{\Delta t}} \frac{1}{\sqrt{\Delta R}} \int_{R_1}^{R_N} \left[\int_{t_1}^{t_2} I(R, t) e^{-i2\pi ft} dt \right] e^{ik_p R} dR \right|^2 \tag{2}$$

where ΔR stands for the distance between the detectors, $\Delta t = t_2 - t_1$ represents the integral time and *N* is the number of detecting elements.

A traditional PCI diagnostic has been developed on HL-2A and located at two vertically opposite ports labeled as 'NO, 45′. These ports are one of the only two pairs of vertical ports of HL-2A with an inner diameter of 35 mm at $0.625 < r/a < 0.7$. The system is designed to diagnose plasma density fluctuations with the maximum wavenumber of about $15\,cm^{-1}$, taking phase scintillation effect into consideration. The wavenumber resolution is $2\,cm^{-1}$, which is restricted by the size of ports. The time resolution is better than $2\,\mu s$, limited by the time response of HgCdTe detectors.

3. Design of NI-PCI system

A suitable collimated monochromatic laser beam with a near infrared wavelength of $1.55\,\mu m$ is chosen to work as the beam probe for NI-PCI system. In order to achieve a high power stability, feeding back system is applied. As mentioned above, the incident beam width is limited by the diagnostic window at location 'NO, 45′ on HL-2A with an inner diameter of 35 mm. So the incident beam from the NI-laser, which has a width of 2.0 mm should be expanded to 30 mm (< 35 mm) by a factor of 15. The expansion of the beam is achieved by a pair of focusing mirrors, i.e. a small concave spherical mirror with a focal length of 200 mm and a large off-axis parabolic (OAP) mirror with a focal length of 1500 mm as shown in Fig. 1. A couple of lenses with focal lengths of 500 mm are used to prevent the beam from expanding too early and to control the initial beam diameter when it enters the two-mirror system. Multispectral ZnS is finally chosen as the material of these lenses. Multispectral ZnS has a better transmission at the wavelength of $1.55\,\mu m$ than ZnSe, which is a common material for CO_2 laser.

The phase plate is the most critical element among NI-PCI components. Fig. 2 shows the design of phase plate. $\lambda_0/8 = 194$nm thick gold coating (yellow parts in Fig. 2) is deposited on the ZnS substrate. The $\lambda_0/8$ coating introduces $\pi/2$ phase shift for contrast between scattered

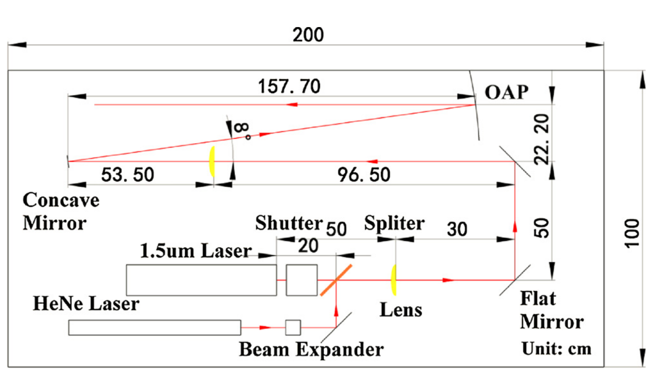

Fig. 1. Layout of the optical components of the NI-PCI expanding optical path.

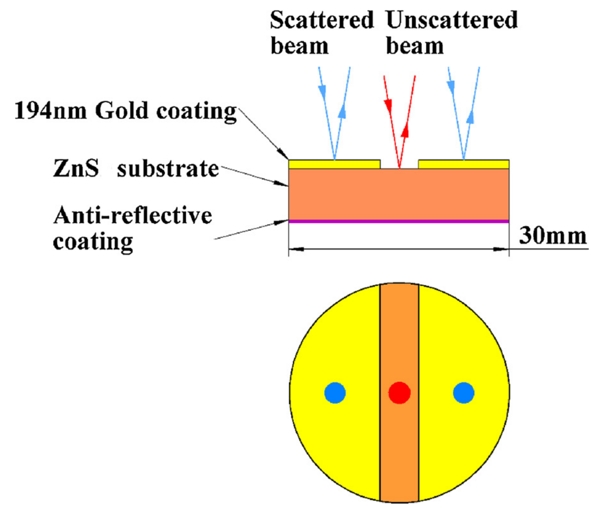

Fig. 2. Phase plate of NI-PCI system. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

and unscattered beams after passing through plasma. The detailed optical path is shown in Fig. 3. ZnS is applied here because of its low absorption of infrared light. A narrow strip with a width of *w* is left uncoated as a phase plate groove. All of the scattered beams are reflected on the gold surface. Overwhelming majority of the unscattered beam is reflected on the ZnS surface and then contrasts the scattered beams.

To get a good response from the phase plate, 100% of the center focal spot should fall within the phase plate groove (red spot in Fig. 2). At the same time, the side spots should be as completely as possible beyond the groove (blue spots in Fig. 2). As a result, the groove width *w* should meet [17]:

$$d = \frac{4F_1\lambda_0}{\pi D} \ll w \ll 2s = \frac{2\lambda_0}{\lambda_p} F_1 \tag{3}$$

where *d* represents the diameter of the Gaussian-distribution focal spot, $D = 30$ mm represents the diameter of the Gaussian beam, $F_1 = 1500$ mm stands for the focal length of off-axis parabolic mirror and *s* is the separation between the centers of the unscattered and scattered spots. Here *w* and *D* are both defined by $1/e^2$ of light intensity. We can easily get $w^{optimal} = 150\,\mu m$ and the high cutoff wavelength for detectable plasma fluctuations $\lambda_{p,max} = 3$ cm [18]. Consequently, the minimal wavenumber is $k_{p,min} = 2\,cm^{-1}$. Compared to the traditional PCI diagnostic, NI-PCI system keeps the same minimal wavenumber measurement of plasma density fluctuations, while the main parameters of phase plate listed in Table 1 change a lot due to different laser source in order to get $\pi/2$ phase shift.

Note that all our calculations including diffraction effects in Fig. 7 assume the Gaussian beam because the beam profile that we use is TEM00 [21]. To confirm how much the laser is different from the Gaussian beam, we need to analyze the beam after finishing the construction on HL-2A.

The detector for NI-PCI is InGaAs with linear arrangement, 64 channels. The temporal resolution is better than 0.1 us which is enough for the research of plasma turbulent transport. But we need to confirm the practical bandwidth on the tokamak since the electromagnetic environment is too complicated. The size of detector element is 0.2×1.0 mm with 0.05 mm separation between each two adjacent elements. Therefore we need to construct an optical system which would reduce the image size to some manageable value. The rear contrast optical path is shown in Fig. 3. Red and blue lines show the unscattered and scattered beams, respectively. The image dimensions are reduced by $1/M$ and the overall image intensity goes up by a factor of $1/M^2$, where *M* is the magnification coefficient of the lenses.