

## Development and First Result of Phase Contrast Imaging Diagnostic on HL-2A tokamak

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We report the development of Phase Contrast Imaging (PCI) diagnostic on HL-2A tokamak, together with first experimental results. This diagnostic is to measure the phase shift of a CO<sub>2</sub> laser probe when it passes through plasma. This system is designed to diagnose plasma density fluctuations with the maximum wavenumber of 15 cm<sup>-1</sup>. The designed wavenumber resolution is 2cm<sup>-1</sup>, and the time resolution can reach 0.2 μs. The broad kps ranges from 0.2 to 3. The signal series in different PCI channels show a pronounced modulation of incident laser beam by the sound wave. The conversion relationship between the chord integral plasma density fluctuation and the signal intensity is  $2.3 \times 10^{13} \text{ m}^2/\text{mV}$ , indicating a high sensitivity. First experimental results show the ability for turbulence investigation.

### 1. INTRODUCTION

The physical understanding of the turbulent density fluctuations in magnetic confinement plasma is believed to be the key to anomalous transport, which degrades the confinement by two orders of magnitude from the theoretical prediction. The most commonly accepted turbulence theory predicts that the scale length of the turbulent eddies is shortened by the  $E$  cross  $B$  shear flow [1]. Most of the plasma turbulent energy is in the range of low wave number  $k$ , and turbulence can transfer energy from low  $k$  parts to high  $k$  parts by energy cascade. As a result, the turbulent energy spectrum will follow the exponential decay as the increase of  $k$ , which means that we should investigate the turbulence in a wide wave-number range [2]. Keen tools are important to diagnose turbulent parameters in wave-number domain.

The phase contrast imaging (PCI), which was invented by Franz Zernike [3,4] in the 1930s and first employed in fusion plasmas to study turbulence in TCA tokamak

by Henri Weisen [5] in the 1980s, is a kind of keen tool to diagnose the turbulence in a wide  $k$  range. This method allows one to measure small phase shifts in laser waves after passing through plasmas and has been used on many plasma fusion devices, including DIII-D [6], Alcator C-Mod [7], TCV [8], and LHD [9]. Recently, PCI system has been developed on HL-2A tokamak [10].

## 2. PCI DIAGNOSTIC ON HL-2A

PCI diagnostic has recently been developed on HL-2A tokamak. It can diagnose plasma density fluctuation with a maximal wavenumber of  $32 \text{ cm}^{-1}$ , a wavenumber resolution of  $2 \text{ cm}^{-1}$ , and a temporal resolution of  $2 \mu\text{s}$ . The main sketch of this PCI system is shown in figure 1. Two vertically opposite ports with an inner diameter of 30 mm on the bottom and the top of the vacuum vessel at a radial location of  $0.6 < \rho = r/a < 0.725$  are chosen as diagnosing ports. The whole PCI optical path is mainly consist of three parts, i.e. the front expansion and collimation optical path, the path in the vacuum vessel (or in the plasma) highlighted by the blue circle and arrow, and the rear contrast imaging optical path.  $10.6 \mu\text{m}$   $\text{CO}_2$  laser with a diameter of 2 mm and a maximal power of 100 W is used as incident beam. To meet the diameter of ports, this incident beam is evenly expanded to a cylindrical beam with a diameter of 30 mm before injecting into the plasma. A phase plate with a rectangular groove in the center is used in the rear optical path to contrast the unscattered and scattered beams. The width of phase plate is 0.88 mm and the depth is  $\lambda_0/8 = 1.325 \mu\text{m}$ , where  $\lambda_0 = 10.6 \mu\text{m}$  is the wavelength of the laser beam.

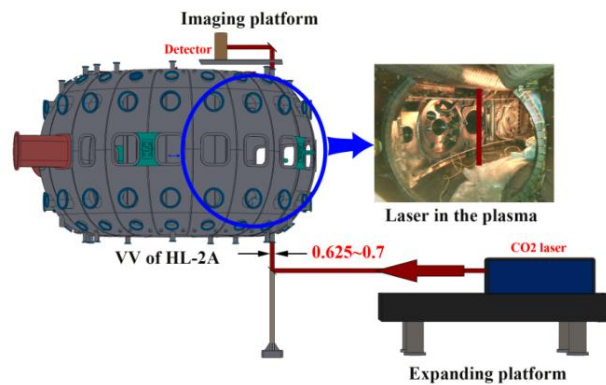


Figure 1, PCI diagnostic on HL-2A. The red line shows the laser path and arrow shows beam direction. The whole PCI optical path consists of three parts, i.e. the front optical path on the expanding

platform, the laser path in the plasma and the rear optical path on the imaging platform. Finally, the laser beam is detected by the detector array on the imaging platform.

32-channel high-quality liquid nitrogen cooled multi-element photoconductive HgCdTe detector line array (Model number: MCT-3200) with preamplifiers is chosen as the main detector. The 32-channel preamplifier is specifically designed to operate with photoconductive MCT detectors. The electrical bandwidth is internally set from 2 kHz to 5 MHz with different gain values. The size of every MCT element is  $0.2 \times 1.0$  mm with a 0.05 mm separation between each other. The array is fully submerged in liquid nitrogen to reduce noise as much as possible. The data from detector array are collected by a 32-channel digitizer with a sampling rate of 1 MHz and finally stored in the HL-2A database.

### 3. FIRST RESULTS

Electron density fluctuations in HL-2A shot #32841 are measured by PCI diagnostic. The magnetic field is  $\sim 1.3$  T, the electron density is  $\sim 1.0 \times 10^{19} \text{ m}^{-3}$ , the plasma current is  $\sim 150$  kA and the plasma lasting time is  $\sim 2000$  ms. The PCI sampling rate is 1 MHz and the sampling time is 2200 ms. Low hybrid wave (LHW) is injected during 0.8~0.9 s with a power of 250 kW and 0.9~1.2 s with a decreased power of 60 kW. Strong MHD phenomena confirmed by magnetic probes and soft X-ray arrays are observed. Thus it is convincing to validate the PCI signal through the MHD instabilities.

As is shown in figure 2, the time frequency spectrum of PCI data detected by channel 15 is compatible with that of magnetic probe. Both the frequency and the modulation of TMs are almost the same, which clarifies the validity of PCI signals. In addition, the electron density fluctuations are enhanced on a large scale during the injection of LHW. High-order harmonic-frequency TMs seem to be drowned in the background turbulence spectrum. It is likely that the magnetic fluctuations and density fluctuations behave in different ways before and after 0.8 s. It is inspiring that higher order harmonics can be observed obviously in PCI data during LHW heating, while it is not so clear in magnetic signals. PCI is turned out to but not limited to be a good supplement for MHD instability research.

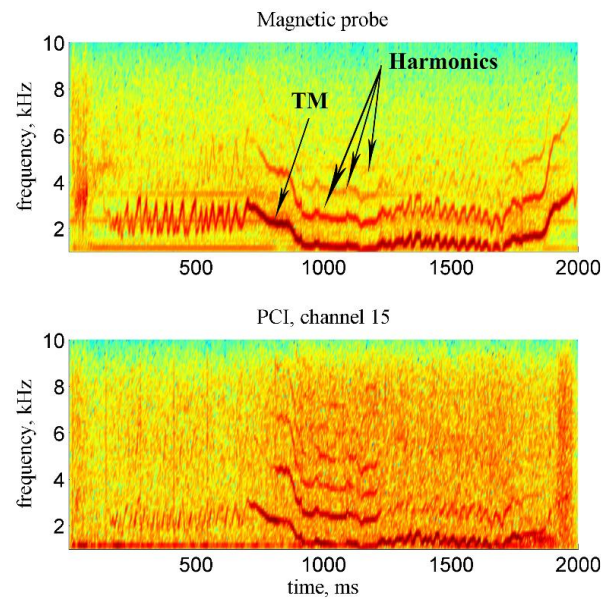


Figure 2, Comparison of time-frequency spectrum between magnetic probe and PCI. Filter bandwidth: 1kHz to 10kHz.

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