Data analysis and effect corrections of Phase Contrast Imaging diagnostic on HL-2A tokamak

Y.Yu¹, S.B.Gong¹,², M.Xu², C.J.Xiao³, W.Jiang¹, W.L.Zhong², Z.B.Shi², H.J.Wang¹, Y.F.Wu¹,², B.D.Yuan¹,², T.Lan⁴, M.Y.Ye¹, X.R.Duan², and HL-2A team

¹School of Nuclear Science and Technology, USTC
²Southwestern Institute of Physics
³State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University
⁴Department of Modern Physics, USTC

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• Background
• PCI on HL-2A
• Data processing, validation, analysis and calibration
• NIR PCI on HL-2A
- Magnetic island
  - Magnetic fluctuations
- Ion temperature gradient mode (ITG) $k \rho_i < 1$
  - Electromagnetic mode with limited beta
- Trapped electron mode (TEM) $k \rho_i \geq 1$
- Electron temperature gradient mode (ETG) $k \rho_e < 1$ and $k \rho_i > 20$
  - Electrostatic mode
- Coupling between ETG and larger scale turbulence

Turbulence can transfer energy from low $k$ parts to high $k$ parts by energy cascade.
Invented by Dutch scientist Frits Zernike in 1930s.

First employed in fusion plasmas to study turbulence in TCA tokamak by Henri Weisen in the 1980s.

\[
E = E_0 e^{i\Phi} \approx E_0 (1 + i\Phi)
\]
\[
I = \frac{|E|^2}{2\mu_0 c} \approx I_0 (1 + \Phi^2)
\]
\[
E_{PCI} \approx E_0 (i + i\Phi)
\]
\[
I_{PCI} \approx I_0 (1 + 2\Phi)
\]

\(\Phi = 0.09\text{rad}\)

- \(\lambda_0 = 10.6\text{um}\)
- \(r_e = 2.8 \times 10^{-15}\text{ m}\)
- \(l = 30\text{cm}\)
- \(\bar{n}_e = 10^{18}\text{m}^{-3}\)

Time resolution: higher than 2 \(\mu\text{s}\)
Wavenumber range: 2\text{cm}^{-1}\text{~}30\text{cm}^{-1}
Frequency range: 2kHz\text{~}500kHz
• Background

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Sketch panorama of PCI on HL-2A

- 10.6 μm CO2 laser
- Front expansion and collimating optics
- Optical path in HL-2A plasma
- Rear imaging optics
- Detector and data acquisition system

Some parameters for PCI on HL-2A

- Port: ‘NO’, the only vertical port with a diameter of 30 mm
- Spatial position: 0.625 < ρ < 0.7
- A maximum wavenumber of 32 cm⁻¹
- A wave-number resolution of 2 cm⁻¹
- A time resolution can reach 0.2 μs

\[ k\rho_s = 0.2 \sim 6.4 \]
Front optics

Front expansion and collimating optics

Optical simulation of front optics

Sketch of front optical path

CO2 laser

long laser tube
Optics in plasma

Optical path in plasma

Vacuum port

Britle ZnSe
Where $L_0=460\text{cm}$ and $F_1=125\text{cm}$, designed.

$M$ is the magnification coefficient.

We finally decide $F_1=125\text{cm}$, $F_2=50\text{cm}$, $F_3=15\text{cm}$.

The resulted magnification factor is 0.37.

The ideal maximal wavenumber is about $32\text{cm}^{-1}$, with a wavenumber resolution of $2\text{cm}^{-1}$.
Rear imaging optics
➢ Off-axis parabolic mirror
➢ Reflect mirror
➢ Phase plate
➢ Lens groups
➢ Filter plane

light faculas on phase plate

light faculas on filter plane
The width of phase plate is 0.88 mm and the depth is 1.325 um.

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<td>10</td>
<td>Phase plate</td>
<td>15</td>
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Rear optical platform
➢ On right top of HL-2A
➢ Inductive currents analysis
➢ Inductive heating analysis
➢ Electrical and vibration analysis
Data systems

32-channel high-quality liquid nitrogen cooled multi-element photoconductive HgCdTe detector line array (Model number: MCT-3200)
• Background
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Electromagnetic Interaction

Meshed model of TF coils, PCI platform and vacuum chamber

Meshed model of the air sphere and the infinite element layer

Inductive current density

Absolute error and relative error of magnetic field

electromagnetic force acting on the steel platform

EM force acting on platform during plasma current disruption
Wavenumber Response

- Response of low k limitation: the weakly scattered component may fall within the groove of the phase plate.

\[ R_{\text{low}}(k_p) \approx 1 - \frac{f(k_p) + f(-k_p)}{2} \]

\[ f(k_p) = -\frac{1}{2} \left[ \text{erf} \left( \frac{k_p - k_2}{k_w} \right) - \text{erf} \left( \frac{k_p - k_1}{k_w} \right) \right] \]

\[ k_w = \frac{2}{w} \]

- Response of high k limitation: plasma turbulence with high wavenumber will result in intensity variations on the detector smaller than the detector elements.

\[ R_{\text{high}}(k_p) \approx \frac{2J_1(k_p b)}{k_p b} \]

\[ b = l/2M = 0.03\text{cm} \]
Scintillation effect

For a plane wave,

\[ I_{L+PCI} \sim \left| E_{L+PCI} \right|^2 \approx E_0^2 \left[ 1 + 2 \Delta \cos \frac{\pi \zeta_0 L}{\lambda_P^2} \cos \left( k_p x + \omega_p t \right) \right] \]

Where \( L \) is chord integral length, and \( \Delta = -\lambda_0 r_e \int n_e dl \)

The term \( \cos \frac{\pi \zeta_0 L}{\lambda_P^2} \) will bring significant scintillation effect, and the wavenumber response needs corrections.

Phase scintillation effect:

\[ \cos \left( \frac{k_{\perp}^2}{2k_0} (z - z') \right) \]
PCI diagnostic can achieve frequency-wavenumber spectrum of turbulence as:

\[
S(k_p, f) = \left| \frac{1}{\sqrt{\Delta t}} \frac{1}{\sqrt{\Delta R}} \int_{t_1}^{t_2} \int_{R_1}^{R_2} I(R, t) e^{-i2\pi ft} dt \right|^2 e^{ik_p R} dR
\]

where \( \Delta R \) is the distance between the detectors, \( \Delta t = t_2 - t_1 \) is the integral time, \( I \) is the signal intensity at time \( t \) and \( N \) is the number of detecting elements.

PCI calibration using sound waves launched by a loudspeaker
The signals caught by two detecting channels in four independent tests

The power spectra of detected signals in different channels with a 20 kHz sound wave modulation

The power spectra of detected signals with different sound wave modulations in Ch9
Raw signals from twenty detecting channels with a modulating sound wave frequency of 20 kHz

- 15~25 kHz band-pass filter;
- Absolute calibration of the HgCdTe detector line array with pre-amplifiers: moderate-temperature blackbody furnace.

The time slices of signals from detecting channels after filtering and absolute magnitude calibration

M validation:
- Designed: 0.37;
- Calibrated: 0.35.
The frequency-wave number spectrum of the signals from the 32-channel detector array after calibration:

- Wavenumber calibration (20kHz):
  - Theoretically calculated: 3.65/cm;
  - Calibrated: 3.6/cm.

The relation between wavenumber $k$ and the sound wave frequency $f$:

- Bandwidth of the loudspeaker limited the calibration of PCI:
  - 12/cm (32/cm designed)
The phase fluctuation of the laser beam caused by the sound wave in the air:

$$\tilde{\phi}(x_\perp) = k_0 \int \tilde{N}(x_\perp, z) \, dz$$

where $\tilde{N} = k_{GD} \tilde{\rho}$ is the fluctuation of refractive index caused by sound wave,

where $\tilde{\rho} = \frac{\tilde{P}}{C_s^2}$ is the fluctuation of air density, $k_{GD} = 0.22 \text{ cm}^3 / \text{g}$ is a constant in the mid-infrared wave range and $\tilde{P}$ is the fluctuation of pressure.

$$\tilde{\phi}(x_\perp) = C_0 \int \tilde{P}(x_\perp, z) \, dz$$

where constant $C_0$ is $1.1 \times 10^{-11} \frac{\text{rad}}{\mu \text{Pa} \cdot \text{cm}}$. 20 $\mu \text{Pa}$ is always treated as 0dB

$$\tilde{P}(r) = r_0 \tilde{P}_0 \left( \cos \left( kr - \alpha t \right) \right) \frac{1}{r}$$

where $r_0 \tilde{P}_0$ is a constant and $r = \sqrt{x_\perp^2 + z^2}$

$$\tilde{\phi}(x_\perp) = \left( \frac{2\pi}{k |x_\perp|} \right)^{1/2} C_0 r_0 \tilde{P}_0 \cos \left( k \frac{|x_\perp|}{x_\perp} - \alpha t + \pi / 4 \right)$$
The frequency response of the loudspeaker (model L400)

\[ |\tilde{\phi}(x_\perp)| = \left( \frac{2\pi}{k|x_\perp|} \right)^{1/2} C_0 r_0 \tilde{P}_0 = 2.9 \times 10^{-5} \times \frac{1}{\sqrt{|x_\perp|}} \]

\[ |x_\perp| = 15 \text{ cm} \]

\[ |\tilde{\phi}(x_\perp)| = 7.4 \times 10^{-6} \text{ rad} \]

For a PCI system \( \tilde{\phi} = -\lambda r_e \int \tilde{n}_e dz \)

where \( r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} \) is the electron radii.

\[ \int \tilde{n}_e dz = 2.5 \times 10^{14} \text{ m}^{-2} \]

The 20 kHz sound wave is the equivalent of a chord integral density fluctuation of \( 2.5 \times 10^{14} \text{ m}^{-2} \).

The signal intensity of the first MCT element is 10.7 mV.

The relation between the signal intensity and the chord integral plasma density fluctuation is \( 2.3 \times 10^{13} \text{ m}^{-2} / \text{mV} \).

For typical HL-2A plasma, \( n_e \sim 2 \times 10^{19} \text{ m}^{-3} \), \( \tilde{n}_e / n_e \sim 0.01 \), \( dz \sim 0.5 \text{ m} \).

A 4V signal for data acquisition system!
content

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1.5 um near infra-red (NIR) fiber laser works as a substitute of CO2 10.6 um laser.

- Wavelength: 1.5 um;
- Power: 20W;
- Diameter: 2mm;
- Divergence angle: 7mrad;
- Groove width of phase plate: >96um;
- Groove depth: 0.1875um.

Phase plate

Collimated and expansion optical path
Designed parameters:

- $L_0 = 4600\text{mm}$
- $F_1 = 1500\text{mm}$
- $F_2 = 500\text{mm}$
- $F_3 = 150\text{mm}$
- $L_1 = 465\text{mm}$
- $L_2 = 170\text{mm}$
- $S_2 = 2F_3 = 300\text{mm}$
- $M = 0.38$.

Magnification lenses in rear contrast optical path

\[ L_2 = \left[ \frac{1}{F_2} + \frac{L_0 - F_1}{F_1^2 - L_1(L_0 - F_1)} \right]^{-1} \]

\[ M = \frac{L_1}{F_1} \left[ 1 - \left( \frac{1}{F_2} - \frac{1}{L_1} \right) L_2 \right] \]

$L_2$ vs. $L_1$ and $M$ vs. $L_1$ for four different values of $F_2$
◆ Phase scintillation effect:

\[ R_{PCI}(k_R) = \left[ 1 - \frac{f(k_R) + f(-k_R)}{2} \right] \text{sinc} \left( \frac{k_R}{\pi k_z} \right) \cos \left( \frac{k_R^2}{2k_0}(z - z') \right) \]

- For 10.6um HL-2A PCI: ~66.7m;
- Optical length: >10m;
- For 1.5um HL-2A PCI: ~471>>10m.

◆ Rayleigh lengt\( Z_R = \frac{k_0 W_0^2}{2} \)

- For 10.6um HL-2A PCI: ~66.7m;
- Optical length: >10m;
- For 1.5um HL-2A PCI: ~471>>10m.

◆ Scattering: \( L \ll \frac{k_0 W_0}{k_\perp} \)

\( L \) is the chord integral length.

◆ Wavelength limit:

\( \omega_0 \gg \omega_{ce} = \frac{eB}{(m_e c)} \)

For typical HL-2A plasma PCI requires \( \lambda_0 \ll 7\text{mm} \)

1.5um laser is better.
**Diffraction effect.** $a=40$ mm is the PCI port on HL-2M.
Thank you.