Development of an Ultrahigh-bandwidth Phase Contrast Imaging system for detection of electron scale turbulence and Gigahertz RF waves

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Introduction and motivation

The development of a scientific basis for plasma fusion requires diagnostic systems able to accurately measure phenomena at increasingly fine spatio-temporal scales. A wide variety of electron density fluctuation diagnostics has been developed and is operational on various machines worldwide. Commonly used systems include Phase Contrast Imaging (PCI), microwave and CO_2 scattering, and correlation reflectometry. Even though such systems greatly contributed to the advancements of research on plasma micro-instabilities at low or moderate wavenumbers, i.e. $k \leq 10\,\mathrm{cm}^{-1}$, none of them is designed to detect the entire spectrum of fluctuations from ion to electron gyro-radius scales. The reason is twofold: some systems rely on physical principles that do not allow one to detect a large fraction of the spectrum, e.g. reflectometry and back-scattering techniques at high and low wavenumbers, respectively; others, like PCI, suffer from technological limitations such as detector bandwidth and size of collecting optics.

This work presents the development of a new diagnostic that overcomes such difficulties. In particular, by adapting the Phase Contrast method to work at 1.55 μm it would be possible to accurately measure turbulent density fluctuations at ion and electron gyro-radius scales and in the frequency region comprised between kHz and GHz. This would allow to detect the perturbed density produced by radio-frequency waves used for heating and current drive without optical heterodyning techniques, though those were successfully employed for ICRF waves in the past[1]. Such a diagnostic, whose absolutely calibrated measurements would provide unprecedented validation between modeling and experiments, would also meet the need to decrease port allocation requirements in present and future large scale devices as well as overall costs.

Basic principles of the Phase Contrast Imaging technique

Phase contrast imaging is an internal-reference interferometer that is sensitive to the time-varying index of refraction of the plasma which, for Infra-Red laser light, leads to a phase shift in the laser phase fronts proportional to the line integral of the electron density fluctuations[2]. At the heart of a phase contrast measurement is an optical component called *phase plate*, with which the PCI transforms the phase variation in the laser into an amplitude variation to be measured by a detector. The laser is then imaged onto an array of detectors, either linear of quadratic, that are usually photoconductive and maintained at liquid nitrogen temperature for noise reduction purposes and that are typically characterized by a frequency bandwidth of the order of $1-2$ MHz. Therefore, the imaging of the spatial variation of the phase shift across the beam permits to decompose the turbulence, or wave, measurements into a wavenumber spectrum within the frequency bandwidth of the detectors. The smallest detectable wavenumber is controlled by the laser beam size and, on most PCI systems installed on worldwide tokamaks, is in the region $0.5-1$ cm^{-1}. The maximum wavenumber can be arbitrarily chosen by varying the optical magnification of the imaging system, within a range restricted by the size of in- and ex-vessel optics. Indeed, a given fluctuating wavenumber k, propagates at a scattering angles $\theta = \pm k/k_0$ from the probing beam of wavenumber k_0. Too large scattering waves are not collected by optics of finite size which, thus, act as aperture stops in the optical system.

Set-up and initial results

The choice of 1.55 μm as the new probing beam wavelength is dictated by the considerable progress made by research and development programs in the telecommunication and military sectors in the Near-InfraRed (NIR) region. Arrays of tens of room temperature InGaAs detectors with peak sensitivity at 1.55 μm and GHz bandwidth are readily available, thus more than adequate for detecting electron scale fluctuations and most RF waves used for heating and current drive. Additionally, the fact that such detectors do not need to be cooled at 77 K as opposed to HgCdTe detectors used in the MIR, reduces maintenance and operational overhead especially in future reactors, where recirculating liquid nitrogen circuits would have to be installed due to restricted access to the torus hall. A further benefit is that such arrays are one tenth the price of liquid-nitrogen-cooled HgCdTe detectors that are currently used at 10.6 μm. Another advantage of the reduced probing wavelength is the decrease of the scattering angles at which fluctuating components propagate, thus permitting one to collect shorter scattering wavelengths. By operating with a probing beam size of a few cm, so as to retain ion scale fluctuations in the measurements, most of the spectrum of fluctuations expected to be unstable in large scale devices would be accessible to the same diagnostic, thus avoiding cross-calibration issues encountered when comparing measurements from different systems.

The phase plate is an optical component that enables the functioning of the Phase Contrast method. Its role is to dephase the unscattered from the scattered radiation and can be of a reflective or refractive nature. Phase plates currently employed on most PCI systems worldwide are made of a reflecting surface, essentially a flat mirror, in which a phase groove is engraved. The phase groove depth is approximately equal to $\lambda_0/8$ such that the relative dephase is equal to $\pi/2$. The width of the groove has to be wide enough to accommodate the focused unscattered beam whose diameter D_f at focus, in the case of a collimated Gaussian beam focused by an *ideal* lens, is given by $D_f = \frac{4M^2\lambda f}{\pi D}$, where M^2 is the beam mode parameter, λ_0 the wavelength of the probing beam, f the focal length of the lens, and D the diameter of the collimated beam in front of the lens. If the phase groove is too narrow part of the unscattered beam will be phase shifted while, if the phase groove is too large, radiation scattered by long wavelengths in the plasma will also be phase shifted and the system will lose information at the low end of the spectrum. To avoid signal loss the optical system needs to be appropriately designed in such a way that the undiffracted beam component has a Gaussian width comparable to the size of the groove.

Figure 1: Phase plate fabricated by masking a one inch diameter NBK-7 substrate with a flat ribbon 0.254 mm wide.

The reduced wavelength makes the manufacturing of the phase groove complex and tolerances more stringent. Although plasma etching processes are theoretically able to manufacture grooves suitable for the NIR, they usually entail high cost due to the charge of Non Recurring Engineering. In the initial phase of this work we decided to follow a cheaper option that allows a proof of principles of the new diagnostic, leaving the procurement of more accurate phase plates as an option for future work. The methodology we set out was similar to that used by H. Weisen when he pioneered the Phase Contrast method on the TCA tokamak and is detailed below. Flat ribbons made of 0.254 mm and 0.762 mm wide 304V stainless steel were used to cover a number of uncoated substrates made of various materials that were placed in a recess in a custom made holder. The ribbons were stretched across the substrate by attaching them, on each side, to springs with suitable elastic constant. The coating itself was done by vacuum deposition of Aluminium in a standard evaporator. The depth requirement for a 1.55 µm light is about 200 nm which, being about twice the standard thickness of coating layers in precision grade mirrors, results in appropriate reflectivity and is achievable by professional optical coaters. Additionally, the required thickness does not affect the flatness of the reflecting surface, therefore excluding artificial effects that would be deleterious for the correct functioning of the phase plate. This procedure resulted in about eight usable phase plates, one of which is showed in Fig. 1, including representatives of all substrates and widths. Two distinct measurements with an interferometer and a confocal microscope indicated groove widths nearly equal to those of the ribbons, as expected, while depths are in the range 125 – 150 nm, depending on the sample, corresponding to degradation of the PCI signal amplitude between 8% and 18%.

Before installing the new system on an actual device, it was decided to carry out initial testing on a bench-top which, lacking vacuum-plasma interface windows, does not entail large power losses. A low-power fiber-coupled laser was thus procured, along with an appropriate controller of the laser-diode bias current and temperature that is used to enhance beam quality and lasing stability by side mode suppression of the various longitudinal modes. The laser power can be continuously increased from zero up to 120 mW by varying the diode current, which allows testing at various input powers without the need for beam splitters and dumps. The laser light is coupled from the diode to free space via a single-mode, polarization-maintaining fiber with FC/APC output connection. The beam half-divergence is 4.65°, which is more than an order of magnitude larger than that of scientific grade CO_2 lasers used in 10.6 µm PCI systems installed in tokamaks worldwide. The highly divergent beam was collimated to a desirable size via a two-lens system.

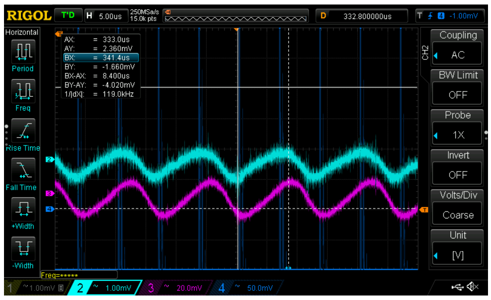

Figure 2: Phase contrast signal of sounds waves from two detector channels (magenta and light blue) and timer signal from the 75 kHz transducer (dark blue).

The PCI technique is sufficiently sensitive to measure the change in index of refraction caused by a sound wave propagating in air. Two configurations with transverse optical magnification of 1.0 and 0.4 were aligned and tested using an ultra-sound speaker at 75 kHz and 125 kHz, which is the system commonly used for calibration of the 10.6 µm PCI system installed on worldwide tokamaks. In Fig. 2 we display a 75 kHz calibration sound wave detected as a PCI signal by two non-neighboring elements; the slight phase shift is due to the spatial propagation of the sound wave imaged by the linear array.

Future work will focus on determining the signal to noise ratio of this diagnostic to determine whether it can be successfully operated on a large scale fusion device, as well as the manufacturing of more precise phase grooves.

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References

[1] N. Tsujii *et al., AIP Conference Proceedings* **1689** (2015) 040005

[2] H. Weisen *et al., Plasma Phys. Controll. Fusion* **28** (1986) 1147