Recent Progress in the Development of Phase Contrast Imaging Techniques to Measure GHz RF Waves in Fusion Grade Plasmas

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Background

The Phase Contrast Imaging (PCI) diagnostic has been successfully deployed on tokamaks as well as stellarators to measure low frequency turbulent waves and MHD phenomena with frequencies up to 1 MHz and perpendicular wavelengths from a few mm to up to 10 cm [1,2]. In addition, beam modulation with Acousto-Optical Modulators (AOM) has allowed the successful heterodyne detection of ICRF waves at 80 MHz on Alcator C-Mod [3].

PCI, an imaging interferometer, measures the wavelength and wave amplitudes of density fluctuations. Recently interest has arisen in extending the PCI method up to the GHz range, e.g. to measure helicon waves at 476 MHz in DIII–D [4]. The efficiency of the Helicon as a driver of plasma current will depend on the coupling of wave power to the core plasma and the propagation of the wave in the plasma, and measurements of the wave amplitude and structure in the core plasma are required to validate the predictive models. Both current drive and the density perturbation due to the helicon at the PCI location (120° toroidally from the Helicon antenna) can be computed with the All ORders Spectral Algorithm (AORSA) [5]. Stacking multiple 2D AORSA calculations provides resolution in 3D (see Fig. 1) and allows the computation of synthetic PCI measurements. A discharge under development will optimize the plasma current and density and Helicon launch direction for PCI detection and model validation.

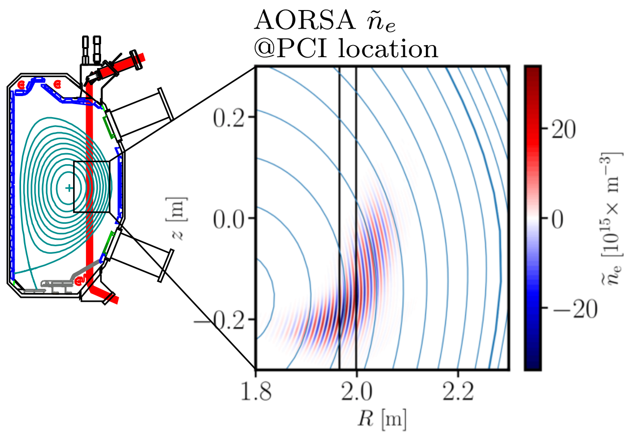

Figure 1: In a scenario under development, AORSA shows the helicon intersecting the PCI beam path with an optimal wave pattern.

This work describes two approaches to extend the PCI method up to 1 GHz. In the first approach we describe the development of an Electro-Optical Modulator (EOM) at frequencies close to that of the helicon frequency so that a heterodyne technique can be used to detect the

(a) (b)

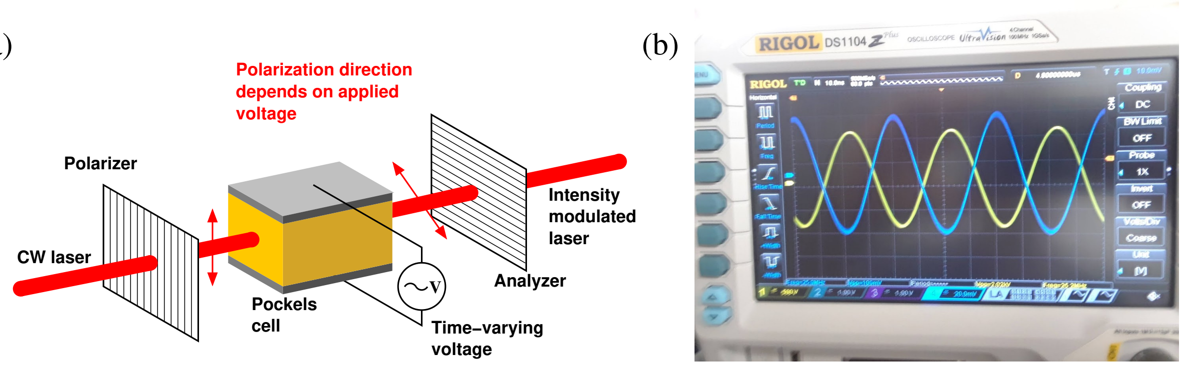

Figure 2: (a) High voltage on the EOM crystal changes the polarization of the laser, which becomes intensity modulation after the polarizer. (b) Qualification testing for the EOM at 25.2 MHz frequency. (Yellow) 2 kV peak-peak voltage drive delivered to the Pockels cell, (blue) resulting modulation of the intensity of a CO_2 *laser beam as detected by a Photovoltaic detector.*

beat wave with a MHz response cryogenically cooled detector array.

The second independent approach uses a 1.55 µm laser to form a beam suitable for scientific-grade interferometric imaging for PCI where detectors with 1 GHz bandwidth are commercially available. New phase plates with $1/8$ of laser wavelength have been manufactured successfully both with a masked coating method, as well as semiconductor micro-fabrication technique.

Electro-Optic Modulation

PCI systems typically use Photo-Conductive or Photo-Voltaic detector arrays whose 3dB points are within 1 MHz and 10 MHz, respectively. Although suitable for broadband turbulence and low frequency waves, such narrow bandwidths preclude the study of faster phenomena, whose detection requires the use of suitable heterodyning techniques. By modulating the intensity of the probing laser beam at a frequency close to that of the wave of interest the heterodyne beat frequency falls within the PCI detector bandwidth, thus making the imaging method applicable at higher frequencies. Such technique was implemented on the Alcator C-Mod tokamak using Acousto-Optic-Modulators (AOM), and successfully detected for the first time mode-converted Ion Cyclotron slow waves [6]. Further, by employing the absolute calibration of the PCI system, it also yielded the first quantitative experimental validation of full-wave models [3]. Nevertheless, laser power modulation near the Helicon frequency is not feasible using AOMs because they are available only in the frequency range 40–100 MHz. Instead, we opted to develop a novel heterodyning technique using an Electro-Optic-Modulator (EOM) made of a liquid cooled CdTe Pockels cell, which is expected to respond uniformly up to frequencies close to 1 GHz (see Fig. 2(a)). The flat frequency response of the EOM is leveraged to measure other frequency ranges of interests, such as that corresponding to Ion Cyclotron Emission (ICE), by

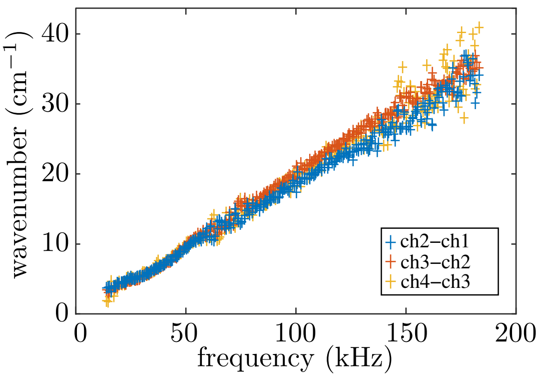

Figure 3: Wavenumber measured with prototype 1.55 µm PCI as audio wave frequency is swept demonstrates functionality.

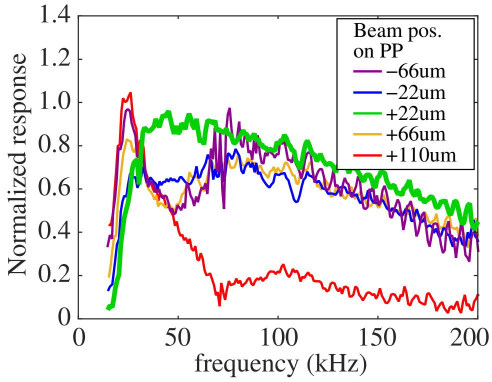

Figure 4: PCI response vs. frequency as focal spot is shifted from center of phase plate quantifies sensitivity to mechanical vibrations.

merely replacing the driver of the Pockels cell with one able to drive it in the appropriate frequency range. In particular, a variable frequency driver for the frequency range 20–50 MHz has been developed and passed qualification testing, being able to deliver to the Pockels cell the design voltage of 2 kV peak-peak in the desired frequency range. The Pockels cell is observed to appropriately modulate a CO_2 laser beam, as displayed in Fig. 2(b). The development of an appropriate driver delivering the same voltage at 475 MHz is currently underway.

PCI at 1.55 µm

Development of a PCI system using a 1.55 µm laser beam is in progress, which will provide two major benefits. First, low-noise detector arrays are commercially available that operate at room temperature, and thus have a bandwidth measured in GHz, much higher than the 10 MHz detectors for 10.6 µm. Second, decreasing the wavelength decreases scattering angles and hence the effect of apertures, increasing $k_{\max}$ by a factor of seven.

First, the phase plate, the custom optic that creates the phase contrast [7], must be rescaled for the shorter wavelength. Reflective phase plates consist of a substrate with a reflective coating of thickness $\lambda/8$ except in a gap in the center. Two techniques have been explored for fabricating new phase plates. A masking and coating method, similar to that used in the past, has produced good phase plates with a gap size of 200 µm and thickness of 190 nm (compared to the 1 mm gap and 1.3 µm coating used at 10.6 µm). High quality was achieved by iterating with the coating company directly. Additionally, an extremely high quality phase plate was produced by a nanofabrication lab, at a more competitive price than was possible in the recent past. With these phase plates, a prototype PCI was constructed at 1.55 µm which was capable of high-accuracy wavenumber measurements, as shown in Fig. 3.

Additional challenges arise from the increased sensitivity to various deleterious effects. Large tokamaks suffer from mechanical vibrations that deflect the PCI beam by several mm, which must be reduced by feedback-controlled active steering [7]. The effect of uncorrected vibrations on PCI response was studied, showing large distortions in the wavenumber response, as shown in Fig. 4, and indicating that beam motion must be reduced to below 10 µrad, about ten times smaller than that required with a 10.6 µm PCI. Studies of noise and aberrations confirm that a 1.55 µm PCI on a large tokamak will provide a good signal-to-noise ratio.

Discussion

Each of the two upgrades being explored to extend PCI to the GHz range has distinct strengths. The EOM allows current low-frequency turbulence measurements to continue unchanged, as the EOM with no bias voltage allows the beam to pass through unmodified. Heterodyne detection also reduces data storage requirements, as data is acquired at a reduced frequency. On the contrary, a 1.55 µm PCI system will directly record the measured wave. This will allow the system to record multiple waves simultaneously, which is especially useful in the study of instabilities and parametric decay waves [8], but will allow even the simultaneous capture of e.g. ion-scale electrostatic turbulence and RF waves, a capability that may prove valuable in the study of the effect of edge turbulence in Helicon wave coupling [9].

Acknowledgments

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