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FTU Diagnostic System based on THz Time-Domain Spectroscopy

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Abstract

We present the state of development of a THz-based Time-Domain Spectroscopy (TDS) system for FTU Tokamak. TDS is ideal to measure plasma characteristics that are non-uniform and/or evolve during the discharge: THz pulses (0.1-2 THz) produced with femtosecond mode-locked lasers (790 nm) conveniently span the spectrum above and below the plasma frequency and, thus, can be used as very sensitive and versatile probes of widely varying plasma parameters. This work is based on an existing collaboration between ENEA Frascati and the Photonics Group at Clarendon Laboratory, Oxford University, where a THz-TDS experimental apparatus has been assembled and characterised. The spectral response of diagnostic-relevant components and materials has been tested. The instrument is now being equipped with fiber-optics to guide the laser beam to the THz Emitter and Receiver to ease access through the Tokamak ports. Broadband THz pulse propagation in plasma has been simulated using a simple, yet effective Fourier Transform-based model. In the Tokamak environment, THz TDS can be used in conjunction with other diagnostic techniques, such as, interferometry and ECE, for the simultaneous measurement of dispersion and absorption to launch a bridge between major areas of research in the science landscape.

Keywords: THz; broad spectrum; time-domain spectroscopy; plasma diagnostics; Tokamak plasma diagnostics.

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1. Introduction

The Terahertz (THz) band of the electromagnetic spectrum is defined as the frequency range between microwaves and mid-infrared light. This region has recently been the object of a great deal of research for numerous applications bridging electronic and optical processes since THz photons encompass the characteristic energies of many physical processes [Tonouchi 2002], [Johnston 2007]. THz Time-domain Spectroscopy is now being successfully used in various fields of application and is promising for plasma diagnostics, [Parkinson 2009], [Crooker 2002], [Kolner 2004]. The short pulse duration permits time resolving plasma characteristics while the large frequency span permits the analysis of a wide range of plasma parameters. The focus of this work is to present preliminary experimental and simulation results demonstrating that THz TDS can be realistically adapted as a versatile Tokamak plasma diagnostic technique. This work is based on a collaboration between ENEA Frascati and the Photonics Group at Clarendon Laboratory at Oxford University where THz devices based on the interaction between femtosecond IR laser pulses (Infrared, 790 nm) and a photoconductive GaAs plate are routinely in operation [http://www.fusione.enea.it/EVENTS/THz-2011].

2. Experimental results and simulations

THz radiation can be generated exploiting the interaction process between a femtosecond infrared laser pulse (790 nm) and a photoconductive GaAs plate [Castro-Camus 2007]. When the laser induced photocurrent flows in the plate, it emits a broad THz spectrum (100GHz to 30THz); conversely, if the plate is exposed to THz radiation, a detectable current will be generated. THz pulses can be detected coherently with high sensitivity and used for TDS, by measuring the arrival time of an electric field pulse after it has interacted with the sample and taking the Fourier transform of the time-domain waveform. The THz time-domain spectrometer developed at Clarendon is depicted in Fig. 1(a). The main elements are the femtosecond diode-pumped (4 W beam at 532 nm) Ti:Sapphire laser source (10 fs pulses, 790 nm operating wavelength, 700 KW peak power), the THz pulse transmitter and the THz receiver based on electro-optic sampling. The resulting 5ps THz pulse is characterized by a broad band (0.2-4 THz), 0.5 mW average power, at 75 MHz repetition rate. The delay between probe and gate pulses is linearly scanned by varying the path difference at a speed chosen to optimize the measurement temporal resolution and the signal to noise ratio.

The layout of Fig. 1(a) has been suitably modified to satisfy Tokamak operating requirements, Fig. 1(b). Optical fibers will be used to guide the laser beam to the THz Emitter and Receiver, [Ellrich 2011], to ease access through the Tokamak ports. At the same time, a long-range THz optics system will be developed to illuminate the plasma and collect reflected/transmitted radiation. The optical fiber is a dispersive optical component which means that each wavelength component of the fs laser pulse travels at different velocities, thus broadening the pulse (material dispersion). Femtosecond pulses have a high bandwidth that makes the effect relevant. Therefore, the initially compact input pulse significantly broadens after only a few meters in a single-mode commercial optical fibre and THz TDS measurement becomes impossible without a proper compensation of this Group Velocity Delay (GVD) [Treacy 1969]. This aspect has been properly taken into account in the design of the experimental apparatus, Fig. 1(c). The fiber length is 2 m and 15 m. The distance between the two gratings of the compressor will be tuned to optimise compression. The compressor was designed by assuming 18 deg incidence angle, corresponding to approximately 60% intrinsic power loss, thus ensuring sufficient remaining power to drive receiver and emitter with the Femtosource laser, while still operating in linearity region. In preliminary tests with a 5 m fiber, corresponding to 60000 fs pulse spread, the output pulse was successfully re-compressed to 420 fs (over 140 compression factor), already sufficient for THz operation. By fine-tuning and minimization of non-linear effects, alignment and power reduction, further compression is expected, thus extending the useful THz spectral range.

The free-space THz-TDS system of Fig. 1(a) was used to obtain initial experimental data from Tokamak-relevant devices and components. The experimental data was interpreted using a simple, yet effective Fourier Transform-based model simulating THz pulse propagation. In the model, the input THz pulse and spectrum are represented as follows:
The output pulse is obtained by propagating the input pulse in the medium of interest:

\[ E_p(t) = \frac{1}{2\pi} \int E_i(t) \exp(-i\omega t) dt \]

while the reference pulse is obtained by propagating the input pulse through an equivalent distance in free space:

\[ E_r(t) = \frac{1}{2\pi} \int E_i(\omega) \exp(i(\omega t - k_o L)) d\omega \]

In the previous expressions \( n_r \) and \( n_i \) are, respectively, the real and imaginary parts of the plasma complex refractive index. The transfer function:

\[ H(\omega) = \frac{E_p(\omega)}{E_r(\omega)} \]

is used to retrieve material parameters, in conjunction with suitable error-minimisation routines, as necessary, [Kolner 2008]. Tokamak-relevant materials and components have been characterized in the laboratory. The results of the transmission ratio obtained experimentally are presented in Fig. 2. The ECE devices characterized in the laboratory include wire-grid polarisers, TPX and quartz lenses, and a quartz window. From those results it is observed that the 290 GHz low-pass filter behaves almost ideally. The wire-grid polariser, supposed to be a radiation stop for long-wavelength electromagnetic waves polarized parallel to the wires, shows the expected increase in transmission when the spectral wavelength decreases. The TPX lens becomes opaque at few hundred GHz frequency, The model was validated against the experimental data acquired from the tests on a Quartz window, Fig. 2 for the transmission curves and Fig. 3 for the pulse characteristics. The agreement is excellent between the simulated, Fig. 3(a), and experimental data, Fig. 3(b), showing the characteristic etalon response of the quartz slab.

The model was then used to simulate THz pulse propagation in a high-density cold magnetized plasma. The WKB method was used to simulate a flat-top density distribution, with a peak value representing typical fusion plasmas in the FTU Tokamak \( (0.5-1.8 \times 10^{20} \text{ m}^{-3}) \). The calculated spectra, Fig. 4, clearly show the resonances and stop bands expected when exciting the O- and X- waves (perpendicular propagation) in this type of plasma. The same information can be obtained from the complex refractive index calculated using the transfer function. These preliminary simulation results are promising and indicate that an appropriately designed THz-based TDS system can be used to probe a fusion plasma in Tokamaks. THz-based TDS is a versatile technique when applied to plasma diagnostics because it permits the investigation of several parameters simultaneously, for instance characteristic resonances and stop bands, and time-dependent density variations.
Fig. 1. (a) Free-space laboratory apparatus; (b) layout of the experimental set up for use in FTU and (c) detail of the GVD compensation system using a grating pair for pulse pre-compression.
Fig. 2. Measured transmission coefficients for Tokamak-relevant ECE components.

Fig. 3. Measured (left) and simulated (right) THz-TDS pulses (blue: reference; red: after propagation) obtained for a 7.15 mm quartz window; the corresponding (measured and simulated) transmission curves are included in Fig. 2.
Fig. 4. Computed magnetized plasma spectral response to THz pulse perpendicular propagation, calculated using WKB approximation for a flat-top density profile for O-wave (left) and X-wave (right): reference spectrum (blue, continuous curve) and spectrum after propagation in plasma (red, dashed curve). Input parameters: plasma density = $10^{20}$ m$^{-3}$; $B_0 = 5.3$ T; $L = 60$ cm.

4. Conclusions

All mm-wave techniques, from radiometry to reflectometry, from interferometry to polarimetry can in principle make use of THz-TDS solid state devices, with the advantage that these are cheaper, more stable and more compact than conventional mm-wave components and operate at room temperature. Optical components can be easily connected using optical fibers rather than waveguides or coaxial cables, making them suitable for harsh environments and adding further compatibility with the tokamak environment (in particular, exposure to neutrons and X-rays). Further, all components are external to the vessel and no dedicated port is necessary. The proposed diagnostic only needs a small portion of a port, compatible with optical fibers installation. First foreseeable plasma measurements are reflectometry (single port) and interferometry (two ports).

There is potential for further evolution of the diagnostic capability, beyond routine plasma density & temperature measurements, moving towards the measurement of fluctuations, charge density and conductivity, with unprecedented resolution. This will lead to the creation of a completely new concept of plasma diagnostics, enabling multiple measurements with one device.

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