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THz multi line-of-sight polarimeter for fusion reactors

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ABSTRACT

In this paper we present the first preliminary study of a new polarimetry diagnostic system. The device foresees multiple lines of sight, so that the measure of the plasma parameters can be performed at different chords along the poloidal plane, parallel to the equatorial direction, in a single acquisition cycle. Considering the typical plasma conditions (i.e. ASDEX Upgrade) of the actual magnetic confinement machines, we need to employ sources in the range of the low (< 3) THz to have appreciable rotation angles. As source, the diagnostic foresees the use of Quantum Cascade Lasers (QCL) which represents a very promising solution, given their ability to operate at the expected frequency of 1.6 THz at 4.2 K. Since the power of the probe beam is in the order of tenths microwatts, a cryo-detector, such as kinetic inductance detector (KID), is required. This opens the field for a very compact modular machine, composed by a single cryogenic cooler encasing source, detector and the optical section. The assessment study has been performed taking into account the performances, reliability and adaptability to multiple machines, and enriched with estimates of the Faraday rotation at different conditions, using as base data coming from the ASDEX Upgrade (AUG) tokamak located at IPP in Garching.

1. Introduction

In nuclear fusion research, polarimetry is a well-established technique to measure fundamental plasma parameters, such as the electronic density and the poloidal field [1]. By measuring the Faraday rotation angle, the path integral of these two quantities can be obtained. When coupled with the line integrated density measurement along the same chord coming from another instrument (i.e. interferometer), the plasma current density can be estimated. [2]. Innovative calibration methods, such as Complex Amplitude Ratio (CAR) method, can be used to evaluate the line integrated density independently from interferometric data, via the Cotton − Mouton effect induced ellipticity [3]. Additionally, polarimetric data has been also employed in the past in the determination of the q-profiles [4,5]. Finally, an evaluation of the electronic temperature can be obtained by considering the electronic kinetic effects at high temperatures, and a new model for a more precise evaluation in the upcoming ITER has been recently presented [6]. The knowledge of these and other parameters is fundamental to determine the confinement properties of different plasma scenario and ignition criteria fulfillment. By measuring along different cords, this diagnostic is able to characterize the plasma along the whole poloidal plane. In this document, the concepts for a multiple line of sight polarimeter are presented. We present a first assessment on this topic, taking into consideration the state of the art for sources and detectors currently commercially available.

2. Theoretical background

Polarimetry is the measure of the Faraday rotation angle of an electromagnetic wave when it propagates through a magnetized media (Fig. 1). Consider an electromagnetic wave with frequency ν propagating into a plasma along the z direction. The Faraday rotation for small angles is given by [7]

$$\Delta\partial = \frac{e^3}{2\varepsilon_0 m_e^2 c}\frac{1}{\omega^2}\int n_e(z)B_{\parallel}(z)dz \quad (1)$$

Where $B_{\parallel}$ (z) is the longitudinal magnetic field along the line of sight, n_e is the electron density. This formula is valid for non relativistic electron motion inside the plasma. The phenomenon arises from the fact that the presence of a magnetic field disrupts the symmetry between the plasma dielectric constant for right and left handed circular polarization components of the original beam, given the different response electrons have to the two components. The result of such asymmetry is the rotation of the polarization vector. The rotation is a function of the inverse square of the frequency, of the electron density and magnetic field. Once coupled with the additional information about the electron density given by an interferometric system, the estimation of both magnetic field and current density can be obtained, given that

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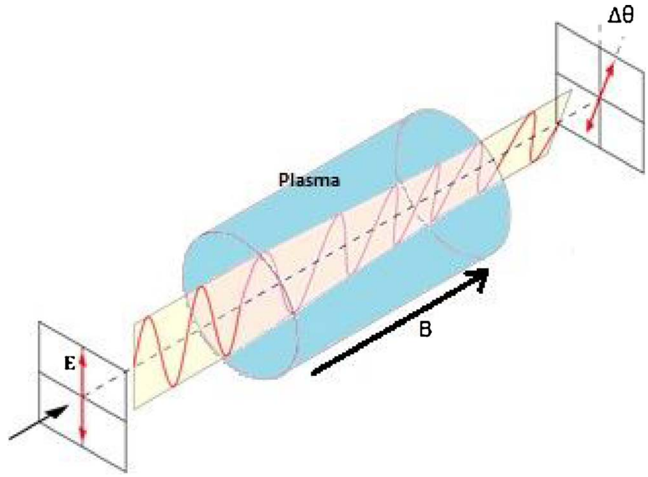

Fig. 1. Representation of the Faraday effect.

$$\int n_e(z)B_{\parallel}(z)dz \approx J \quad (2)$$

Current polarimetric systems employ gas lasers, typically HCN [8–10] @337 μm, HCOOH @ 433 μm [11] and DCN @195 μm [12,13], all needing

- large space
- stabilization in both power and wavelengths
- frequent maintenance and gas refill
- safety measures related to the high voltage

The next generations of fusion plants will require more instruments with high reliability, minimal maintenance downtime and a small footprint.

3. Assessment study

The assessment study we performed can be divided into the following steps:

1. Definition of the system specifications, assuming a set of design guidelines. More specifically, the polarimetric system shall have high reliability and availability, simplicity, ease of service and wide angular dynamic range, to maximize the angular resolution and therefore the precision of measurement. Performance − wise, ITER requirements for polarimetric systems have been taken as guidelines. Some of the desired key characteristics include:
   - Pump − probe type of input: by monitoring the input power, the device can be equipped with an automatic feedback power control and stabilization system
   - Compact: plug and play, ready to measure boxed system
   - Reliability and low maintenance
   - Multiple line-of-sight
2. Identification of possible solutions: multiple options for both the source and the detector are actually available as state of the art technologies. The assessment of the devices has been carried on under the performances, system specifications and costs points of view.
3. Definition of the configuration of the device: polarimeters can be built in a variety of configurations. The parameters that influenced the assessment on the configuration are the same ones used in the devices evaluation.

In analogy to the interferometric systems, polarimeters may come in a wide variety of configurations [14]. In an effort to keep the system as simple as possible and to avoid issues deriving from laser stability, vibrations and alignment, the Dodel-Kunz method and a JET-like interferometer – polarimeter where excluded. In order to improve the reliability of the system and minimize maintenance issues, we devised a solution that avoids moving parts, as in the rotating waveplate and dual PEM methods.

Our iteration of the polarimeter foresees the use of dual detectors, one for each polarization plane of the probe beam (Fig. 2). The laser beam enters the plasma, is reflected by retroreflectors placed on the first wall at the high field side, passes through a polarizing beamsplitter, which separates the ordinary and extraordinary components, whose intensities are recorded by the detectors.

Using Quantum Cascade Lasers (QCLs) in place of gas lasers, costs and space footprint can be greatly reduced while power stability and reliability increase. QCLs have a wide frequency range (0.85 → 5 THz, roughly 350 ⟵ 60 μm) with the most common being 2.8 THz (107 μm), capable of ambient temperature operations (Figs. 3 and 4). Such a laser would give us rotations in the range of 0–5° with AUG typical conditions (n_e 3–9*10^{19} m^{-3}, $B_{\parallel}$ ≈ 0.2–0.4 T, plasma radius ≈ 1 m), therefore a laser with a lower frequency would be better suited. Prototypes of 1.2 THz (250 μm) are being tested and applying a strong magnetic field would decrease the frequency to 0.85 THz (350 μm). The problem in this case resides in the fact that, at these frequencies, the laser transitions are in the energy range of few meV. At ambient temperature or during CW operation, the raise in thermal activity of the device can lead to longitudinal optical phonons scattering between lasing levels, resulting in a degradation of the population inversion. These devices therefore require cooling at liquid helium temperature levels in order to work properly [15,16].

Ideally, a QCL laser source for a double pass configuration would be characterized by a wavelength around 200 μm (1.5/1.6 THz) and able to emit 100 mW power level at temperatures in the order of 250 K, enabling the use of Peltier cells as cooling system.

The current state of the art for QCLs at 1.6 THz sits around 0.3 mW for the maximum power extracted at liquid ^{4}He temperatures [17]. The system will therefore require a cryostat, in the form of a pulse tube refrigerator, given that as per ITER specifications He bath cryocoolers are to be avoided.

The inherent advantages of QCLs are their extremely compact size, ruggedness, and much cheaper price. They require minimal maintenance and the sources can be easily swapped in case of need. Their cheap price allows also to design multiple sources machines for multiple lines of sight at a fraction of the cost of a single gas laser operating at THz frequencies.

Whereas the gas lasers classically employed in polarimetric diagnostics have powers in the order of hundreds of milliwatts [10], commercially available QCL emitting at analogous wavelengths scale down to tenths of milliwatts. The polarimeter must be therefore equipped

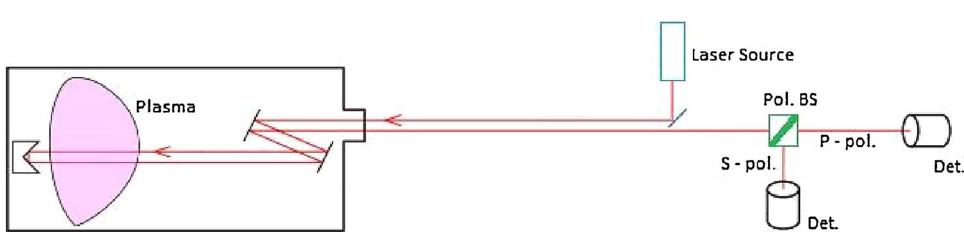

Fig. 2. Schematic representation of the double passage dual detector polarimeter.