

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 4.2K. 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.

I. 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.

II. 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]

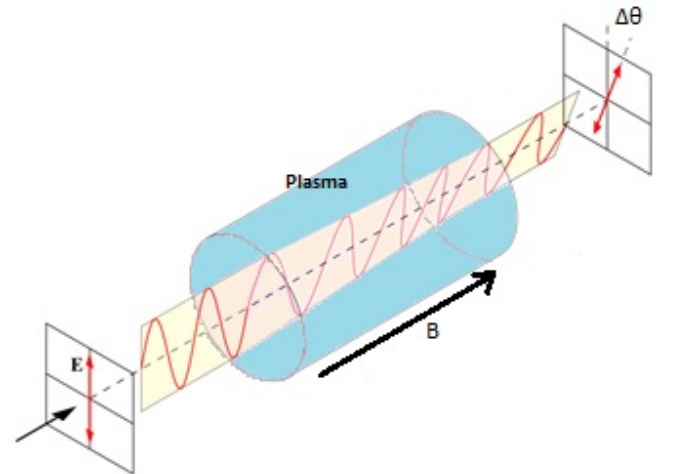


Figure 1 Representation of the Faraday effect

$$\Delta\theta = \frac{e^3}{2\epsilon_0 m_e^2 c \omega^2} \int n_e(z) B_{\parallel}(z) dz \quad (1)$$

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

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

Current polarimetric systems employ gas lasers, typically HCN [8,9,10] @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.

III. 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 were 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.

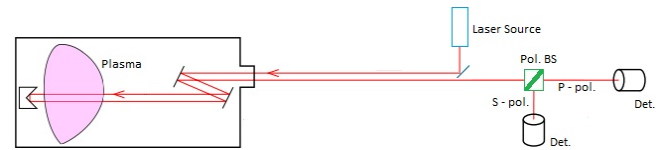


Figure 2 Schematic representation of the double passage dual detector polarimeter

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 \rightarrow 5 THz, roughly 350 \leftarrow 60 μm) with the most common being 2.8 THz (107 μm), capable of ambient temperature operations (Fig.3,4). Such a laser would give us rotations in the range of 0 - 5 $^\circ$ with AUG typical conditions (n_e 3 - 9*10¹⁹ m⁻³, B_{\parallel} \approx 0.2 - 0.4 T, plasma radius \approx 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].

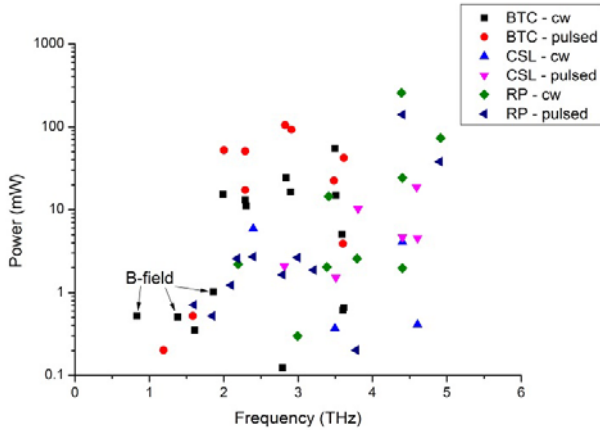


Figure 3 Peak optical power as a function of lasing frequency for different kind QCLs, based on active region design (CSL = Chirped SuperLattice, BTC = Bound - To - Continuum, RP = Resonant Photon) [13]

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 ^4He 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.

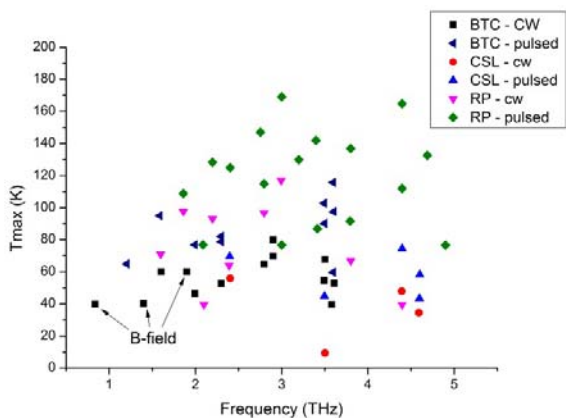


Figure 4 Peak operating temperatures vs lasing frequency for QCLs[13]

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 with suitable high sensitivity detectors to account for the decreased intensity of the probing beam. Developed for the use in astrophysics and astronomy ([18,19,20,21]) where power available is in the order of the nano and picowatt, Kinetic Inductance Detectors represent a viable solution for applications in plasma diagnostics. In such detectors photons with energy higher than the gap energy of an absorbing superconductor break Cooper pairs and change the absorber macroscopic electrical properties. The increased density of quasi-particles (conducting electrons) changes the surface reactance of the superconductor (kinetic inductance effect). This effect can be measured efficiently when the absorber is implemented into a superconductor resonator circuit coupled to a transmission line, via the complex transmission scattering parameter S_{21} . The Al KID reaches a NEP of around $10^{-18} \text{ W}\cdot\text{Hz}^{-1/2}$, but requires temperatures in the order of 250-300 mK [22], increasing both the assembly and operating costs. The usage of high T_c materials in the construction of these devices can, nevertheless, solve this problem. Niobium Nitride (NbN) is the material of choice for the production of the KIDs. With a critical temperature around 16 K [23], these thin films transit to the superconducting state at a temperature higher than liquid He (4.2 K), simplifying the characterization of the final product and its operation. The higher critical temperature of the NbN films will determine a decrease of the NEP, to be determined once the first detector prototypes are produced. Production, characterization and testing of the KIDs will represent the biggest part of the project related to the realization of the polarimeter described in this paper.

Once the two polarizations components are recorded by the detectors, the Faraday angle is given by the arc tangent of the amplitude ratio of the two signals.

IV. VALIDATION OF THE FIRST ASSESSMENT

In order to validate the concepts we exposed so far, we ran some calculations using as benchmark reference

the values obtained from actual measurements made at ASDEX Upgrade. The system located at Garching is based on a DCN Laser emitting radiation @ 195 μm . A beam from the DCN system passing through the plasma above the midplane at AUG high density ($\sim 9 \cdot 10^{19} - 10^{20} \text{ m}^{-3}$) should have a rotation of the polarization vector of roughly 10 degrees. Two different density profiles (low $\sim 3 \cdot 10^{19} \text{ m}^{-3}$ MAX and high $\sim 9 \cdot 10^{19} \text{ m}^{-3}$ MAX, Fig.5) were provided by the AUG team,

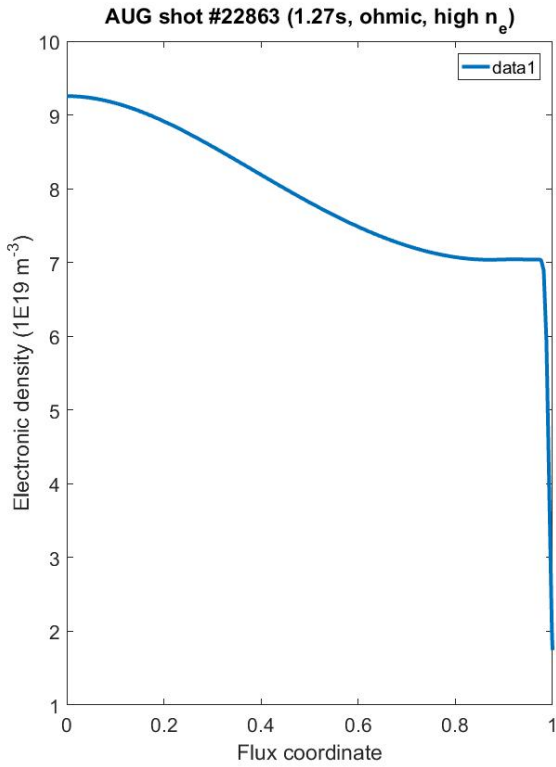


Figure 5 AUG “high” density profile

while a third (medium density) was obtained by averaging the values in the density matrices. Magnetic equilibria (Fig.6) were also provided, completing the datasets necessary to run the calculations via MATLAB script which performs the numerical integration of Eq. (1).

Three different probe beam frequencies were simulated at 1.3, 1.6 and 1.8 THz, corresponding to 230.6, 187.3 and 166.5 μm wavelength. The results are summarized in Table 1. The results are in accordance with our cross reference value of 10 degrees for the AUG DCN polarimeter. Taking into account the considerations made about the dynamic range of the device, the low density regime, where the maximum value is around $3 \cdot 10^{19} \text{ m}^{-3}$ is the lower applicability limit for the two higher frequency sources.

If we are to consider possible applications of the device to machines with higher magnetic fields and larger dimensions than AUG, the 1.3 THz beam can be subject to rotations over $\pm 90^\circ$, requiring complicated phase analysis techniques to discern between partial and complete rotations. 1.6 THz is our candidate frequency for this application (Fig.7). In any case the modularity of the instrument and the size of QCLs allow for easy swapping of the sources to accommodate the operational conditions of the target plasma.

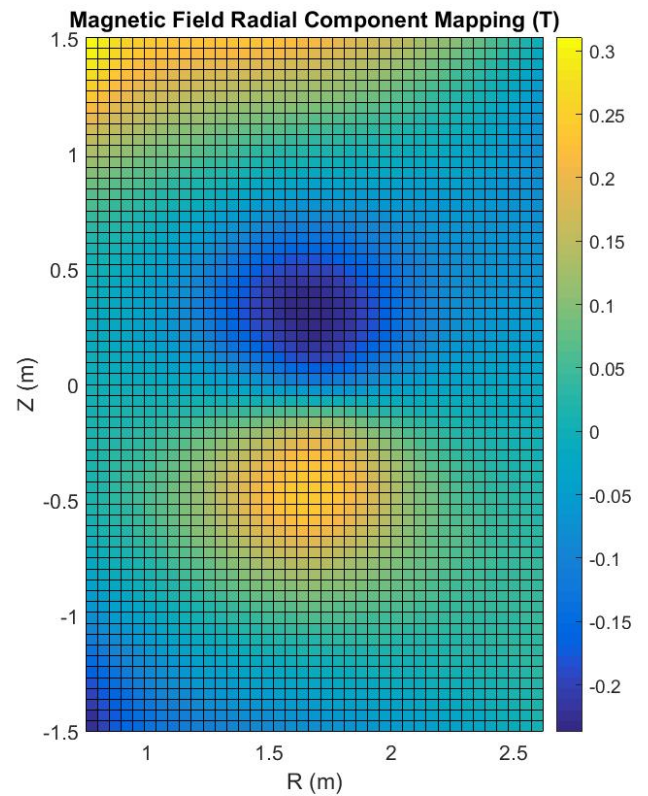


Figure 6 AUG magnetic field (radial component) equilibria

	Low Dens.	Mid. Dens.	High Dens.
1.3 THz (230 μm)	6.5/-7.3	13/-14	19.6/-22
1.6 THz (187 μm)	4.3/-4.8	8.6/-9.7	12.9/-14.6
1.8 THz (166 μm)	3.4/-3.8	6.8/-7.7	10.2/-11.5

Table.1 Rotation values (in degs) for the Faraday effects, at the maximum field points

Theta_r vs line of sight, 1.6 THz (low, medium and high density

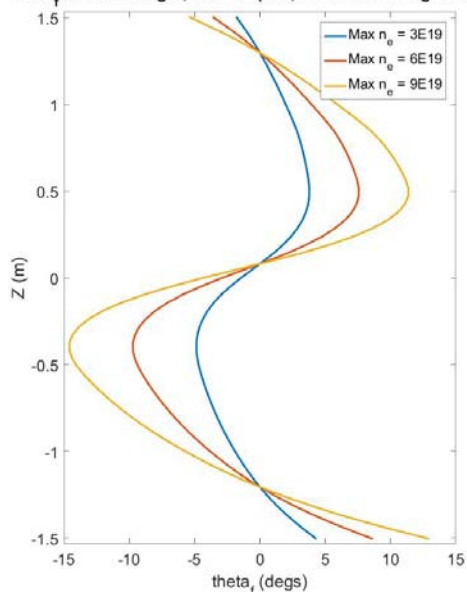


Figure 7 Faraday rotation angle, calculated at the three density profiles for a 1.6 THz probe beam

V. FUTURE STUDY REFINEMENTS

The calculations presented above are just a first step into a more refined assessment to be carried out in the next future. Improvements will include

- Re-modelization of the Faraday rotation using solutions to the Stokes equations, as presented in [24,25,26]
- Evaluation of the impact of Cotton - Mouton and electronic kinetic effects over the polarization measurements for data correction [3]
- Better definition of the required optical system and modelling for calibration purposes [3]
- Evaluation of the applicability of the final instrument to temperature measurements and q-profile extrapolation

VI. SUMMARY

We presented a first assessment about a possible innovative solution for polarimetric measurements in the future fusion reactors. The rationale takes into account key properties such as compact size, low maintenance, low cost, stability, flexibility and robustness, with multiple line of sight. The combination of devices that best suites our needs is a cryogenic system, based on a pulsed tube refrigerator containing the QCL source @1.6 THz, optics and the detectors. A first set of calculations were performed, to validate the applicability of the concepts exposed, returning promising results for the device to be. A

more refined assessments that takes into consideration a better model and additional phenomena occurring to the beam in the plasma is foreseen for the immediate future.

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