A 10-channel far-infrared polarimeter for the TCV tokamak

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A new far-infrared (FIR) polarimeter diagnostic for the TCV tokamak is under construction at CRPP. It uses two FIR lasers at 432.5µm, optically pumped by a 120W continuous wave CO_2 laser. The two FIR cavities will be detuned such that the combination of the beams, using a method proposed by Dodel and Kunz[1], produces a single beam with a linear polarization rotating at the difference frequency (set to 750kHz). For measurements across the minor radius of TCV, this beam will be split into 5 probing beams, each equipped with two Schottky barrier diodes as detectors. Faraday rotation angles will be measured by coherent detection. In order to optimize the sensitivity of the polarimeter for the parameter range of interest ($n_e(0) < 3e19m^{-3}$) , we have chosen to keep it separate from the existing 14-channel interferometer operating at 214µm. This also leads to substantial simplification of the design and signal processing. The design of the system, as well as its expected sensitivity are presented and discussed. The required accuracy to measure profiles of current density and safety factor for typical operating scenarios with internal transport barriers on TCV (including cases with reversed magnetic shear) is assessed by numerical simulations.

I. Introduction

In tokamak research, advanced operating regimes with internal transport barriers (ITB[2]) are of great importance to improve performances towards fusion. In such discharges, non-monotonic current density profile $j(r)$ is generated by bootstrap current[3] and also by additional current drive sources. On the Tokamak à Configuration Variable (TCV[4]), non-inductive current drive is provided by a microwave additional heating system composed of six 0.45MW gyrotrons at the second electron cyclotron frequency (X2) and three 0.47MW gyrotrons at the third harmonic (X3)[5,6]. The launching system has been designed for microwave injection in a large variety of configurations, permitting pure central electron cyclotron heating as well as off-axis current drive (ECCD).

On TCV, to measure poloidal magnetic field B_p and hence $j(r)$ and q profiles, a new far-infrared (FIR) polarimeter is under construction. Since TCV is already equipped with a FIR interferometer[7] at λ=214.6μm which is not optimal for our diagnostic purpose, a separate FIR polarimeter system working at λ=432.5μm is presently proposed without simultaneous interferometric measurements. Its design has been guided by the need to have valid q profile measurements in low plasma current I_p (<100kA) and electron density n_e ($n_e(0)$<3e19m^{-3}) ITB plasmas. In such discharges, the resolution of the diagnostic has to provide distinguishable Faraday rotation profiles $\Psi(r)$ between monotonic and reversed q profile. Since Ψ scales with I_p, the resolution of the diagnostic should not be critical at higher currents while n_e increase will intensify refraction effects.

II. Characteristics of TCV FIR polarimeter

TCV is a medium size tokamak (major radius R=0.88m, minor radius a<0.24m, toroidal magnetic field B_T<1.54T, I_p<1.2MA). Due to the wide range of plasma shapes, positions and sizes accessible on TCV, optimal polarimeter measurements for all possible configurations cannot be fulfilled by one wavelength. The sensitivity of the proposed system is adequate specifically for ECCD and ITB scenarios. Due to density cutoff, X2 ECCD can be driven only in low electron density plasma, typically $n_e(0)$ < 4e19m^{-3} for B_T =1.45T. On the basis of a similar existing system[8], we are expecting a nominal resolution of our detection system of the order of 1 milliradiant.

a) Technical layout

In the proposed scheme, the technique used to measure the Faraday rotation Ψ is based on a technique first proposed by Dodel and Kunz[1] in which the polarization of the probing beam is modulated. This technique requires only one detector per line of sight and Ψ is obtained as a result of a phase shift measurement, independent of signal amplitude. A schematic view of the beam setup is shown on Fig.1: two cavities of our FIR laser system are used to produce the probing beams. The cavity lengths are set to such that the difference in frequency between the first and the second cavity is around ω_m=750kHz. Directly from the cavities output, the two beams will be transported up to the tokamak by separate dielectric waveguides. Polarization selection with wire grids at the waveguide output will be done to suppress any polarization changes (rotation, elliptisation …) occurring inside the waveguide path. At the waveguide output, a half-wave plate first rotates the vertical polarization of the first probing beam into horizontal. Then the two beams are superimposed and passed through a single quarter-wave plate which converts their polarizations to counter-rotating circular. The combination results in a single beam with a linear polarization rotating at ω_m. As shown on Fig.2, a fraction of the beam is split off and is directed to a reference detector while the main part propagates towards the entrance port. This probing beam is divided into five separate beams and distributed across the minor radius of TCV. The entrance port situated at a vertical position Z=-0.98m (Z=0m being the midplane of the torus) is equipped with Z-cut crystal quartz windows of 7.285mm thickness. Due to different physical constraints, the maximum beam diameter at the quartz window is 57mm. The beam waist ω_0 (1/*e* of the electric field) of the middle beam is situated in the midplane of the torus at Z=0m and can be estimated as 15.8mm[10]. Polarization insensitive meshes are used as beam splitters. Even splitting is achieved by the use of 50%/50% and 70%/30% beam splitting ratios are used. At the output of the torus, a wire grid analyzer first selects one polarization. The detection is then done using an array of 10 Schottky diode mixers, each of the beam being sampled by 2 detectors.

b) Laser wavelength selection

The upper limit for the wavelength selection is set by refraction effects due to density gradients perpendicular to the probing beams. The lower limit is defined by the minimum amplitude resolution. The Faraday rotation is given by the relation

$$\psi = 2.62\times10^{-13}\lambda^2\int n_e(z)B_{//}(z)dz \qquad (1)$$

where λ is the laser wavelength, $B_{//}$ is the component of the magnetic field parallel to the laser beam and the integration is done along the ray path into the plasma. Since ψ scales with λ^2, the larger wavelength, the better in term of resolution. On Fig.3, we represent the

Faraday rotation amplitude on a typical low n_e, low I_p ITB discharge for a laser wavelength of 432.5μm. For our FIR interferometer wavelength of 214.6μm, ψ would then be about 4 times lower. With an expected resolution of 1 milliradiant, it is obvious that a higher wavelength than the 214.6μm from the existing FIR interferometer system is needed to obtain Ψ that can be measured with sufficient accuracy. On Fig.4 top, using equation 1, we compare the Faraday rotation for three different plasma types with different electron densities and plasma currents. While, as just mentioned, for low n_e, low I_p plasmas the accuracy could be an issue, it appears clearly that for typical ECCD conditions and H modes where I_p and n_e are higher, the Ψ resolution is expected to be far from marginal.

On the other side, refraction effects scale with λ^2 as well. Since the detectors position is fixed and since the windows through which the probing beams enter and exit the vacuum chamber are limited in size, these refractive effects have to be kept as small as possible. On Fig.4 bottom, we can see the effect of refraction on the laser beam trajectories in 3 different plasma types. The refraction has been calculated using the ray tracing code TORAY-GA[11, 12] using electron density profiles measured by Thomson scattering. For the ITB case, refraction effects are small and should not affect the measurements. For the ECCD case, the maximum deviation is about 9mm at the edge. This should still be acceptable since our scheme is insensitive to amplitude variation in the signal. Although strongly undesirable, such displacements could be corrected for by incorporating a ray-tracing code in the inversion procedure. In the H-mode case, where the density gradients are large, the deviation is much higher (up to 40mm). This would result in the loss of some edge channels. The most central channels should however still be usable.

With regard to the preceding analysis, on TCV, a single high-power (~120W) CO_2 laser will be used to pump two far-infrared (FIR) laser cavities (30mW/cavity). The FIR lasing medium is chosen to be formic acid (HCOOH). Its 432.5μm line is pumped by the CO_2 laser beam tuned to the 9.27R20 line (λ=9.27μm).

c) Detection and signal processing

After passing through the plasma, the beams will pass through a polarizer before being focused onto the Schottky barrier diode detectors at close distance (~20 cm) from the quartz windows. After detection, the signals will first be amplified, then band-pass filtered around the IF frequency ω_m and then mixed. ADC up to 250 kHz is then planned.

II. Simulations

Since the purpose of the diagnostic is to measure the current density profiles in plasmas with internal transport barriers, high bootstrap fraction and reversed magnetic shear profiles, it will be important to detect differences in the Faraday rotation between monotonic q profiles, reversed magnetic shear profiles and current hole plasmas. On fig 5, using equation 1, we calculated the Faraday rotation angle for a plasma with constant total current I_p=80kA, electron density profile $n_e(0)$=1.1e19m^{-3} and shape but with three different q profiles. These are the lowest plasma current and electron density of interest on TCV. It is clear that in this low current, low density discharge where the Faraday rotation is expected to be small. With a maximum Ψ value of 10, the resolution of the system in this extreme discharge is going to be close to marginal. Distinction between the two reversed shear q profiles will be hard to do. The slope of Ψ around the plasma axis being proportional to the central current density, the central value of q should however still be both measurable and distinguishable in between the different q profiles.

Acknowledgments

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Figure captions

FIG. 1. Schematic description of the polarimeter technique used on TCV. Two laser beams slightly detuned by the frequency ω_m are made counterrotating circular using a quarter-wave plate. The combination of the two beams results in a laser beam with a linear polarization rotating at ω_m

FIG. 2. Polarimeter setup on TCV. The grey beams are Gaussian beams. We show the full beam size ie. its diameter $D=\pi w$, where w is the beam width

FIG. 3. ψ calculation for TCV shot # 25013 at 0.95s with central density $n_e(0)$=1.8e19m$^{-3,}$ plasma current I_p=120kA, elongation κ=1.46, triangularity δ=0.26, as a function of the plasma major axis R. We have considered beam propagation in the vertical direction and λ = 432.5μm

FIG. 4. **Top**:For three typical TCV plasmas, we represent, as a function of the radial position R, ψ calculated for a laser wavelength λ=432.5μm. The pulses characteristics are: • ITB: pulse # 25013, $n_e(0)$=1.8e19m^{-3}, Z_{axis}=0.12m, I_p=115kA; • ECCD : pulse # 25588, $n_e(0)$=3.5e19m^{-3}, Z_{axis}=0.23m, I_p=240kA; • H mode : pulse # 29883, $n_e(0)$=6.5e19m^{-3}, Z_{axis}=0.23m, I_p=400kA. **Bottom**: For the same plasmas, we represent the laser beam's displacement due to refraction effects at the detector position (Z=1.2m) with respect to ideal non-refracted beams

FIG. 5. For three different types of q profile (full= monotonic, dashed = reversed shear, dashed-dotted=strong reversed shear) we represent the calculated Faraday rotation angle as a function of the radial position R. We have considered vertical lines of sight. The small vertical bars indicate the position of the detectors. Their height of the bars represents the expected resolution of 1 mrad of the detection system. The main plasma parameters are I_p=80kA; $n_e(0)$=1.1e19m-3, elongation κ=1.4, triangularity δ=0.25

Figures

Fig 1:

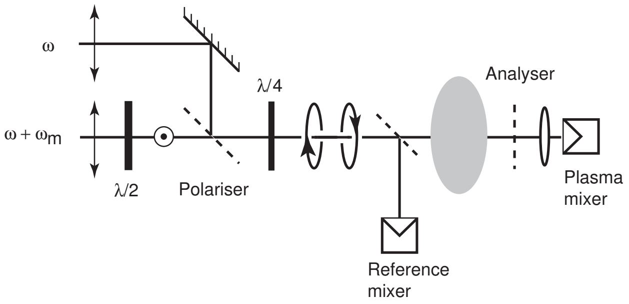


Fig 2.

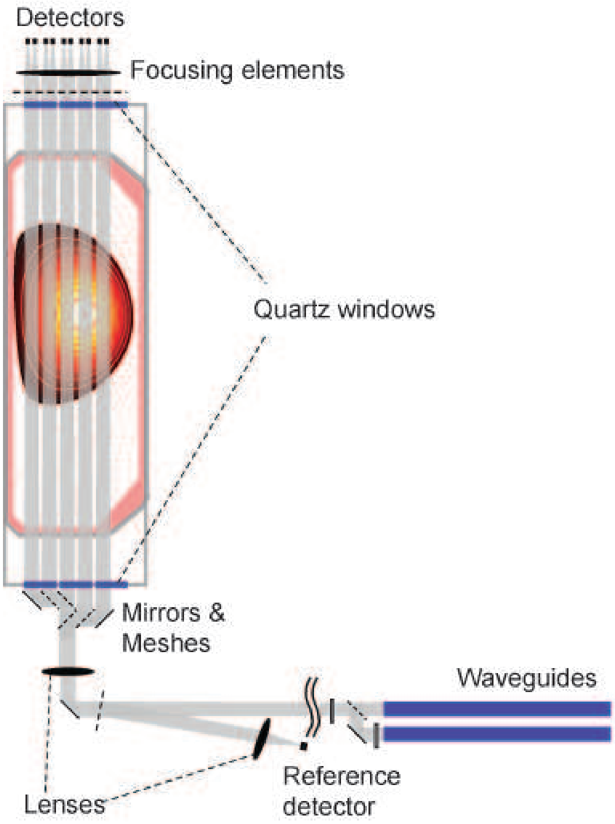

Detectors
Focusing elements
Quartz windows
Mirrors &
Meshes
Waveguides
Reference
detector
Lenses

Fig.3:

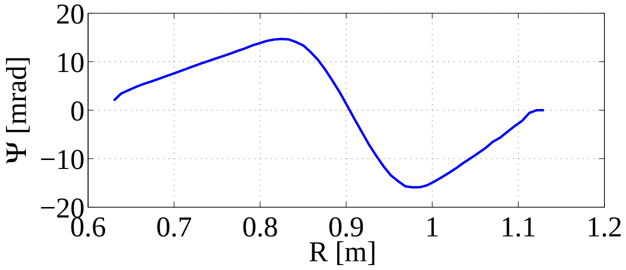


Fig.4:

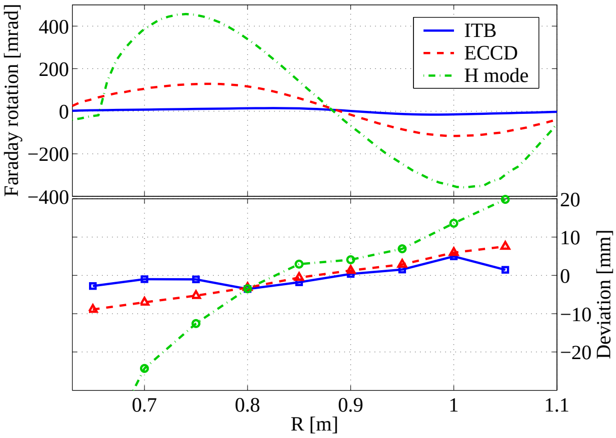
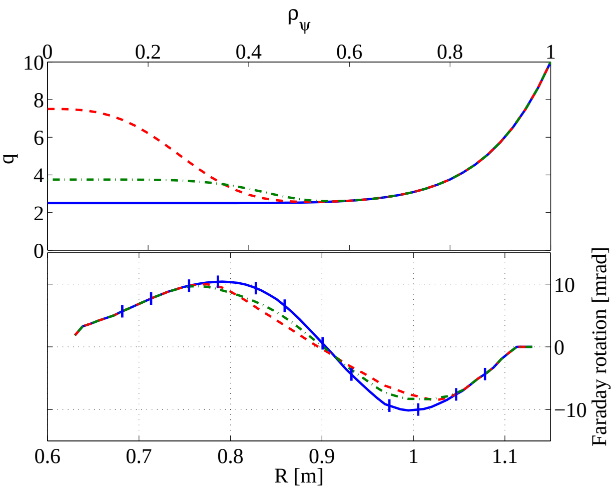

Faraday rotation [mrad]
400
200
0
−200
−400
ITB
ECCD
H mode
20
10
0
−10
−20
Deviation [mm]
0.7
0.8
0.9
1
1.1
R [m]

Fig.5


ρ_ψ
0
0.2
0.4
0.6
0.8
1
10
8
6
4
2
0
q
10
0
−10
Faraday rotation [mrad]
0.6
0.7
0.8
0.9
1
1.1
R [m]