Design of a tangential Phase Contrast Imaging diagnostic for the TCV tokamak

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(Dated: May 4, 2006)

A core density fluctuation imaging diagnostic is being developed for the TCV tokamak, employing a 7-cm wide CO_2 laser beam transmitted through the plasma in a near-toroidal direction. The proposed system employs the phase contrast method, and can resolve wavelengths ranging from 7 down to 0.1 cm, with a minimum measurable line-averaged density $3{\cdot}10^{15}$ m^{-3}/MHz$^{1/2}$. The broad range of microinstabilities that can be at play in the strongly Electron-Cyclotron-Resonance heated TCV plasmas, from ion to electron spatial scale lengths, widely known as ITG, TEM, and ETG modes, would thus be accessible. The use of an imaging technique overcomes the difficulties faced by traditional scattering diagnostics in investigating highly inhomogeneous regions, such as internal transport barriers. Wavelengths and correlation properties can be recovered from the spatial mapping. The tangential configuration, combined with appropriate spatial filtering techniques, provides an excellent spatial resolution, of the order of 1% of the minor radius. In view of the extreme plasma shaping and positioning flexibility of the TCV tokamak, the beam positioning will also be flexible, with translatable mirrors enabling measurements close to the magnetic axis in some configurations.

I. INTRODUCTION

Despite considerable progress in the theoretical understanding of confined plasmas, there is still a need for a detailed description of the fundamental physical parameters playing a role in the processes governing equilibrium, stability, and transport. In particular it is widely known that confined plasmas are subject to a level of heat and particle transport much higher than theoretical predictions based on collisional processes(1); the discrepancy is attributed to turbulent fluctuations. The aim of the project discussed in this paper is to experimentally investigate the physical characteristics of density fluctuations in the core region of the TCV (Tokamak à Configuration Variable) tokamak (major radius R = 0.88 m, minor radius a $\simeq$ 0.25 m, magnetic field on axis $B_0 < 1.5$ T, plasma current $I_p < 1$ MA, auxiliary heating power = 4.3 MW). The project is motivated by the unique characteristics of the TCV tokamak, particularly its very intense electron heating that has been used to study Advanced Tokamak regimes such as electron Internal Transport Barriers(2;3). Depending on the regime of operation, instabilities ranging from Ion-Temperature-Gradient (ITG) to Trapped-Electron (TEM) and possibly to Electron-Temperature-Gradient (ETG) modes are expected to be active. These modes cover a broad range of wavelengths, from the electron to the ion gyroradius scale, presenting a significant challenge for diagnostic coverage.

In the planned diagnostic, fluctuations will be measured by an imaging technique employing a laser beam transmitted through the plasma. Phase constrast is a technique able to image, in real space, the density fluctuations sampled by the probing laser beam; this renders it immune to the problems encountered by other turbulence diagnostics, such as collective scattering(4), reflectometry(5) and cross-polarization Scattering(6) in highly inhomogeneous plasma regions, viz. eITBs. The large density and temperature gradients characterizing these regions cause difficulties to techniques working in the reciprocal wave-number space, such as scattering, since the barrier's narrow spatial extent requires a very high spatial resolution compared to the inhomogeneity scale length for a Fourier representation to remain meaningful. On the other hand, the WKB approximation, upon which the interpretation of the reflectometry and cross-polarization scattering data is based, fails in the high-gradient region. By contrast, the direct spatial mapping afforded by an imaging geometry allows a detailed study of such inhomogeneous regions, provided that good localization can be obtained. In the case of Phase Contrast Imaging (PCI) this can be achieved with a toroidal injection, i.e. in a configuration such that the laser beam wave vector is nearly tangent to the magnetic field line (see Fig. 2).

The remainder of the paper is organized as follows: in section II the basic principles of the PCI are illustrated, in section III the localization recipe is explained, a description of the experimental set-up is given in section IV, and conclusions end the paper.

II. PHASE CONTRAST

When the spatial scales of fluctuations are in the so-called Raman-Nath regime, i.e. they are sufficiently large compared to the size of the sampled plasma, it can be

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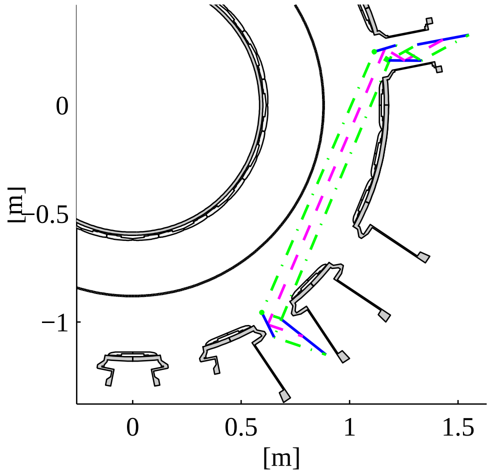

FIG. 1 (Colors on line) Top view of the TCV tokamak showing the in-vessel mirrors (full •), the laser beam center (dashed •) and its end-points (dashed-dotted •)

shown that the following formula describes the phase shift experienced by the laser beam transmitted through the plasma[7]

$$\Delta\Phi(\vec{x}) \simeq r_e \lambda_0 \int_{\vec{x_1}}^{\vec{x_2}} dl\ n_e(\vec{x}) \tag{1}$$

where λ_0 is the wavelength of the probing beam, r_e is the classical electron radius, n_e is the electron density and the integral is calculated along the beam path. The aim of the phase contrast technique is to measure this phase relative to a reference one, as in an interferometer. The technique relies on the $\pi/2$ phase shift between the unscattered and scattered components of the beam, expressed by the following expansion of the wave field up to the Maclaurin first order

$$E(\vec{x}, t) \simeq E_0 e^{i(\vec{k}_0 \cdot \vec{x} - \omega_0 t)}[1 + i\Delta\Phi(\vec{x}, t)] \tag{2}$$

which holds when $\Delta\Phi \ll 1$ (generally true in the case of fluctuations). These two components are separated on a focal plane, where an additional $\pi/2$ shift is introduced by a spatial filter (phase plate), resulting now in a measurable intensity variation at the image plane:

$$I(\vec{x}, t) \simeq |E_0|^2 [1 \pm 2\Delta\Phi(\vec{x}, t)] \tag{3}$$

Thus, while a standard interferometric measurement relies on a reference beam external to the plasma, in the case of phase contrast the reference beam is also transmitted through the plasma itself. The advantage of this scheme is a much reduced sensitivity to mechanical vibrations. The main limitation is the impossibility of measuring the absolute phase shift or, equivalently, the capability of measuring only fluctuations whose wavelength is shorter than the beam width. Among all these so-called internal reference techniques, phase contrast is the only one that provides a true image of the fluctuations since its spectral response is uniform above a given wavenumber cut-off[8].

III. LOCALIZATION RECIPE

A. Basic principle

It is widely accepted, in view also of some experimental evidence[9], that in magnetized plasmas fluctuations are aligned along the magnetic field, i.e. the parallel wave vector is much smaller than the perpendicular one. Thus, since the measurement, being line-integrated, is sensitive only to fluctuations perpendicular to the laser beam, one can only measure fluctuations which lie in a plane perpendicular to both the magnetic field line and to the beam direction. This identifies, at each location along the beam path, a precise angle formed by the measured fluctuation wave vector with a given reference vector in the beam wave-front plane[10]. Since this angle can be selected by spatial filtering on a focal plane, if it is a single-valued, monotonic and steep function of a linear coordinate along the laser beam path, it is indeed possible to select an effective integration length which is much shorter than the whole path sampled by the laser inside the plasma (Figure 2). The steepness of the angle function is a consequence of the near-tangential launching.

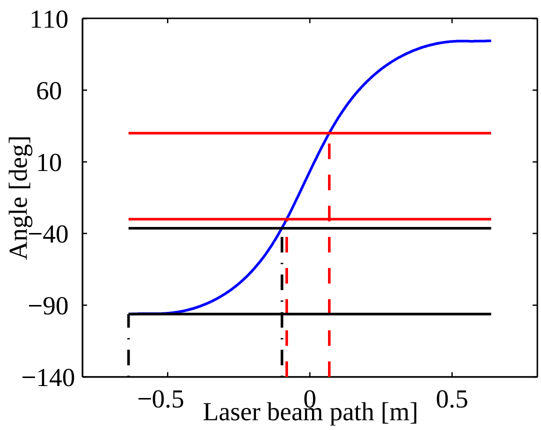

FIG. 2 (Colors on line) Selected fluctuating direction, with respect to the horizontal one, as a function of the beam path. The two boxes delimited by the dash-dotted and dashed vertical lines show, respectively, an example of poor and good spatial resolution. The width of each region is limited by diffraction.

B. Spatial filter

Figure 2 illustrates how it is possible to localize measurements by selecting a particular range of fluctuation directions. This is done by placing a spatial filter on a focal plane which allows only part of the radiation to reach the detector plane (Figure 3). According to the direction along which the filter is aligned, one obtains the desired angle and thus the location from which the signal originates. Because of the finite dimensions of the focal spot, dictated by diffraction, the spatial filter must have a finite width, which translates into the angular range illustrated in Figure 2. This angular width is a function of the wave number and is the angle subtended, on the focal plane, by the diffraction spot centered on that wave number as seen from the focal point (filter center). In case of a gaussian beam with half-width w_0 calculated at the e^{-2} point, the resulting resolution angle is given by $2\arctan(\frac{2}{kw_0})$. Thus, the achievable resolution improves with k; the worst-case scenario is given by the lower-cutoff wave number, which in an optimized configuration is given by $\mathrm{k}_{\mathrm{cutoff}} \simeq 3/w_0^{(8)}$, giving a resolution of approximately 67 degrees. Two possible configurations may be considered for the spatial filter, as depicted in Figure 3. In the first one, the resolution is optimized for all wave numbers, thus is not uniform over the spectral range since it shrinks for higher k values. This in effect distorts the spectral response since the interaction region is different for different wave numbers. With the second configuration, where the achievable resolution is artificially decreased linearly with k, the angle bandwidth, and thus the integration length, is constant over the whole spectral range.

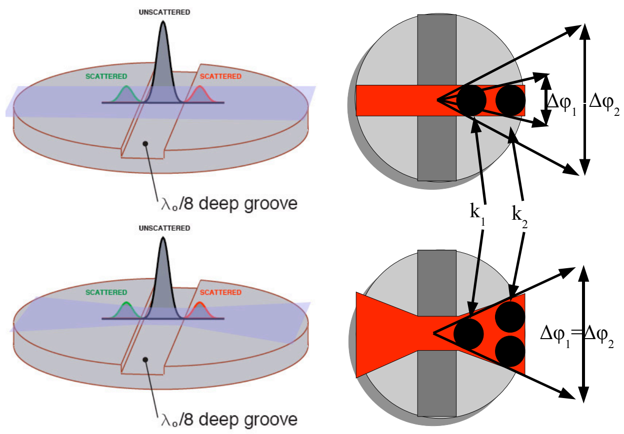

FIG. 3 (Colors on line) Fluctuation direction selection by means of a spatial filter, depicted as a horizontal band, superimposed on the phase-contrast phase plate. At the top the first non-uniform configuration, at the bottom the optimized one. Top and bottom left pictures have been adapted with permission from A. Mazurenko, *Ph.D. Thesis* (Massachussets Institute of Technology)

C. Expected localization in TCV

The actual localization is better understood in terms of a plasma coordinate, normally some form of normalized minor radius; in this paper our coordinate ρ is defined as the normalized square root of the plasma volume. In addition to the steepness of the angle as a function of the linear beam coordinate, a second effect contributes to the localization of the measurement: at the tangency point between magnetic surface and laser wave vector, a significant fraction of the laser beam path stays close to the tangency flux surface; in other words, the linear

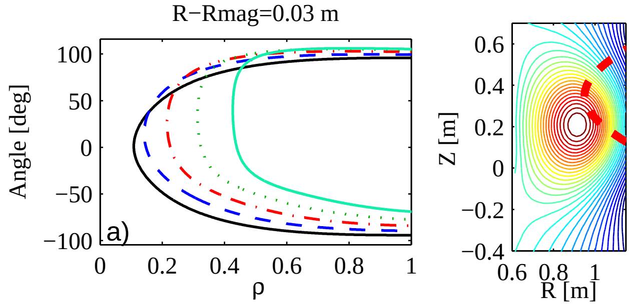

FIG. 4 (Colors on line) (Left) Direction of possible measurable fluctuations, expressed as an angle relative to a fixed direction in the laser wave-front plane, as a function of ρ for a vertical scan in the poloidal section. The laser beam passes through the magnetic axis at the mid-path point (full •) and vertically shifted by 5 (dashed •), 10 (dash-dotted •), 15 (points •) and 20 (full •) cm. (Right) Projection of the laser beam in the plasma poloidal plane, for a given vertical position, and poloidal flux surfaces.

beam coordinate is also a steep function of ρ. The two effects combined result in the angle being an extremely steep function of ρ at this location, as shown in Figure 4. Here, the different curves refer to different vertical plasma positions in the vacuum vessel; it is clear that by displacing the plasma good resolution can be achieved at virtually all values of ρ. Note that even the coarse angular resolution ($\simeq$60 degrees) that can be obtained near the cutoff wave number results in good resolution in terms of ρ, as shown in Figure 5(a). The resolution $\Delta\rho$ at the tangency point is in the range $0.01 \div 0.05$.
While the spatial filter selects a given wave-number direction in the laboratory frame, its poloidal projection onto the physically meaningful radial and poloidal directions will generally change at different locations along the beam. This direction is always purely radial at the tangency point, as shown in Figure 5(b). The finite residual integration length also results in some degree of wave-number mixing, depicted as an uncertainty in Fig. 5(c); this is calculated as the difference between the maximal and minimal component of k_ρ along the integration length corresponding to each point.

IV. EXPERIMENTAL SET-UP

The experimental arrangements will consist of an array of 24 photoconductive detectors with 1-MHz bandwidth which will allow the spatial reconstruction of fluctuations. A one element photovoltaic detector with 10 MHz bandwidth will be used to investigate the possible presence of high frequency modes. The present design is configured for the use of an 8W CO_2 laser beam (10.6 μm wavelength) whose full-width, equal to 7 cm at the e^{-2} points, will allow the detection of fluctuations with a minimum wave number of about 0.9 cm^{-1}. The maximum measurable fluctuating k is about 40 cm^{-1}; in some selected configurations, the integration length can be reduced further and thus the maximum k can be increased

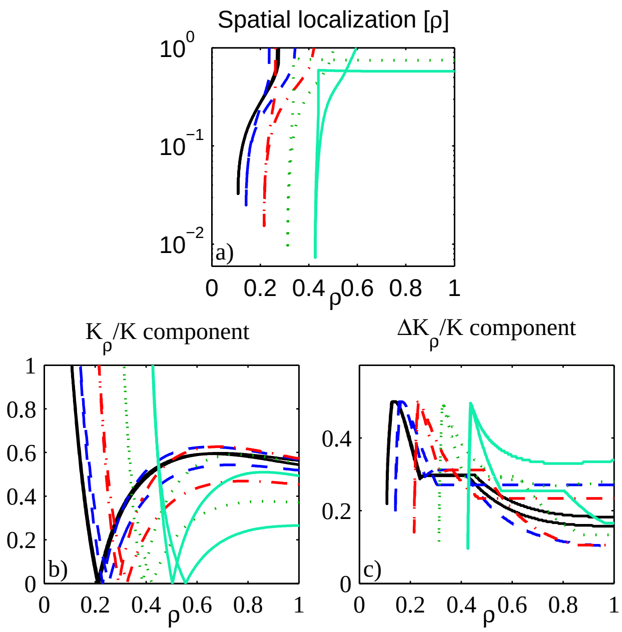

FIG. 5 (Colors on line) a) Radial resolution expressed as ρ as a function of ρ itself. b) Expected ρ component of the fluctuating k measured and (c)its uncertainity. The color coding is the same as in Figure 4.

to 60 cm^{-1} without violating the Raman-Nath validity condition. The breadth of the accessible range will thus make it possible to observe the different ion and electron instabilities discussed at the outset. Signal-to-noise considerations yield a minimum detectable line-averaged density variation of $3 \cdot 10^{15} \mathrm{m}^{-3}/\mathrm{MHz}^{1/2}$. In order to inject the laser beam in the vacuum vessel in the toroidal direction and to retrieve it, five in-vessel mirrors will be required. As TCV is a very flexible machine in terms of plasma shape and positioning, the whole set of mirrors in both ports will be translatable so that, in some extreme configurations, mirrors can be placed beyond the plasma-facing first wall tiles, thus allowing measurements close to the magnetic axis. The two mirrors closest to the plasma will also have an adjustable inclination for optimum alignment control.

V. CONCLUSIONS

The phase constrast technique is a very versatile and sensitive tool to investigate plasma fluctuations with a broad range in both wave numbers and frequencies. The toroidal injection allows an excellent spatial resolution down to one-hundredth of the minor radius by making use of an additional spatial filtering technique.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Y.Andrèbe for valuable help. This work was partly supported by the Swiss National Science Foundation.

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