Scanning beam medium infra-red interferometry for plasma density measurements

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Abstract. In magnetically confined fusion experiments interferometry is commonly used to measure plasma electron density. This because interferometry is a very reliable technique, not affected by calibration problem. The main drawbacks of interferometers are the integral characteristic of the measurement and the fringe losing problem. Scanning beam interferometry can always overcome the former problem and in some cases the second as well. The advantages of the scanning beam technique can better exploited in two colours vibration compensated medium infra-red (MIR) interferometers. Indeed the short wavelength of the probing beams provide small beam sizes allowing plasma density measurement along many non-overlapping paths, furthermore the vibration compensation system relaxes the requirement of massive interferometer structures embracing the fusion device, actually allowing to install back-reflecting mirror directly attached to the experimental machine.

As an example of application of this technique the two-color medium-infra-red-compensated scanning beam interferometer installed on the Frascati Tokamak Upgrade (FTU) experiment is presented. We present also a preliminary design of a scanning interferometer for the new proposed Fusion Advanced Studies Torus (FAST) experiment. The interferometer uses retroreflectors installed inside the vessel to back reflect the scanning beams; this will allow realizing scanning beams measuring from the plasma edge. This feature in principle can solve the fundamental problem of interferometers: the fringe losing problem.

1. Introduction

Interferometry technique is widely used in magnetically confined nuclear fusion experiments \cite{1, 2, 3, 4, 5} to measure plasma electron density. Interferometers implementing this technique differ in many respects: probing wavelength (ranging from visible light to microwave), detection method (Homodyne or Heterodyne), optical scheme (Michelson or Mach-Zehnder). Though previous differences all interferometers share most of the advantage and disadvantages. On the advantage side can be inscribed an easy data interpretation, no-calibration requirement and a high reliability while on disadvantage side have to enroll the integral nature of measurement and the fringe losing problem \cite{6}. Data interpretation is easy because, with a proper choice of the source wavelength, probing beam phase shift is proportional to the line integral of the electron density along beam path, furthermore since the ratio between the electron density line integral and phase shift depends only from fundamental constants and source wavelength, the measurement does not require any calibration. Finally interferometers have proven to be very reliably thanks to the availability of good laser sources and proper optical and mechanical setup.
The main disadvantage of interferometry is its integral nature: it does not provide a local measurements of density but only an average value. This feature in some cases can indeed be an advantage, for example when interferometer is used for feedback density control line averaging provides a direct evaluation of average particles content avoiding local fluctuation. The integral nature is a real disadvantage in plasma transport studies where a good evaluation of density profiles is required. In this case a high number of channels is required to Abel invert integral measurements, but the required number of channels is so high to be impractical in terms of costs and maintenance effort.

The second disadvantage is related to the differential and periodic nature of the phase shift measurements: to get density phase shift a reference baseline has to be obtained measuring interference phase before or after plasma discharge when density is zero, furthermore interference phase can be measured only within $[0, \pi]$ while phase shift can be much larger involving many fringes $F$ (with fringes number $F = 2\pi$) [6]. For this reason to correctly measure phase shift, $F$ has to be computed starting from (or ending up to) the time of the reference baseline. To get $F$ the interference phase must be fast sampled in order to avoid phase variations larger than $\pi$ between two consecutive samples. If for any reason $F$ is lost, a new reference baseline is needed. Not loosing fringes number is not a problem for short time low density measurements, but can be a hard task in presence of fast transient phenomena (like pellet injection, disruptions) or for long times. To solve this problem two non-conventional interferometers setup have been proposed: dispersion interferometer [7] and differential interferometer [8] but no one up to now is used in medium-large size fusion experiments.

Scanning beam interferometry applied to fusion experiments is a way to overcome previous interferometry disadvantages. In scanning beam interferometer one or more probing beam fast scan plasma cross section, providing in this way a high number of equivalent channels. In all setup scanning beam interferometry provides a fringe loosing immune (except for the starting value) measurement of the integral density profile, sharing in this way the advantage of differential interferometers but with a better signal to noise ratio. Furthermore in some cases vacuum accesses allow to build scanning interferometers with scans spanning from outside to inside plasma cross section, in these cases zero density baseline is performed on each scan allowing an easy recover of incidental fringe loosing. This provides fringes loosing immune interferometers.

In this paper we first present the scanning beam interferometer developed for the Frascati Tokamak Upgrade (FTU) experiment, a medium size tokamak device [9, 10] ($R = 0.935\ m$, $a = 0.3\ m$) targeted to high magnetic field operation studies ($B_T = 4 \div 8\ T$, $I_p < 1.6\ MAG$). The FTU scanning solution is similar to that of a previously developed FIR (Far-Infra-Red) interferometer [12] but we implemented it on a two colors vibration compensated MIR (Medium-Infra-Red) interferometer to extend the scanning beam advantages by improving spatial and temporal resolution. Good spatial resolution is obtained by the small size of the probing beams ($\approx 1cm$) such that two parallel scanning beams probing most of the plasma cross section provides more than 30 parallel lines of sight. Good time resolution is obtained using high frequency mechanical scanning devices available for small size beams. Moreover, the short wavelengths can be easily frequency shifted at high speed by Bragg cells for the heterodyne detection, providing a high measurement bandwidth. This allows to correctly measure the highest densities presently reached in FTU (about $7 \div 8 \cdot 10^{20}\ m^{-3}$) and the fastest density changes observed during pellet injection with time slopes as fast as $10^{25}\ m^{-2}s^{-1}$.

Thanks to the high number of equivalent channels, FTU interferometer is able to solve the most important disadvantage of the interferometers, but the vacuum vessel ports do not allow realizing scanning fans going externally to the plasma cross section. This is possible for the interferometer of the new proposed Fusion Advanced Studies Torus (FAST) experiment. In this new device it will be possible to realize scans crossing together and going from inside to outside plasma cross section. That will improve density profile reconstruction and will allow to realize
an interferometer immune to fringe jumps, which is particularly important on a long pulse device as it will be the FAST experiment.

In Sec. 2 we present the main features of the FTU scanning interferometer. In Sec. 3 we present optical setup of the proposed FAST scanning interferometer. Finally in Sec. 4 we summarize main features of scanning interferometry.

2. FTU interferometer

2.1. Diagnostic setup

A detail description of the FTU interferometer can be found elsewhere [13], in this section we summarize its main features.

The optical scheme of the FTU interferometer is a double pass Mach–Zehnder type. To scan plasma cross section it uses two probing beams and two tilting mirrors (Scanner) placed at the focus of an Off-axis Parabolic Mirrors (OPM), see Fig. 1. The OPM convert the Scanner angular beam deflection to a parallel scan, sampling plasma section by parallel channels. On each fan a Roof reflector (RR) send the beam back displaced of 2 cm in the toroidal direction. RR are mounted directly on the FTU mechanical structure.

Considering the beam diameter inside the plasma cross section, the beam movement during a sampling interval and requiring non-overlapping measurements, the FTU scanning interferometer corresponds to a traditional system with more than 30 channels. Furthermore allowing partial beam overlapping and considering the MHz bandwidth of the interferometer more than a two times larger number of lines of sight can be sampled on each scan.

The instrument uses a CO$_2$ laser ($\lambda = 10.6 \, \mu m$) as the main light source, and a CO laser ($\lambda = 5.4 \, \mu m$) as the compensation one. Heterodyne detection at 40 and 30 MHz is obtained by frequency shifting the reference beams with two acousto-optic modulators (Bragg cells). The CO$_2$ and CO lasers beams are sent to two Bragg Cells that split the beams and frequency shift the deflected beams by 40 MHz and 30 MHz. To reduce optical components, the same detector is used for both wavelengths: the CO$_2$ signal is separated from the CO signal electronically thanks to the different modulation frequency.

A crucial part of the scanning interferometer is the beam deflector, to such purpose FTU interferometer uses two 8 kHz Counter Rotating Scanners (CRS) produced by GSI General Scanning whose 7.8x5.5 mm mirror oscillates at 8 kHz with a maximum amplitude of 15°. We preferred a Mechanical Deflector because it simplifies optical scheme though it isn’t the fastest solution [14].

2.2. Results

Scanning interferometer measurements provide good evaluation of density profile evolution in many experimental configurations but the specific features of the MIR interferometry (high time resolution, high diffraction limit) are highlighted in discharges with pellet injection. Indeed pellet
injection produces fast, large and localized density variations [15], these plasma conditions are often hard to account for the long wavelength low frequency modulation FIR interferometers.

Opposite MIR interferometer perform very well as can see in Fig. 2 which shows the time evolution of the line electron density along some chords of the scanning interferometer. The scanning interferometer can follow the fast density rise for all the five injected pellets.

2.3. Roof mirror real time tilt feed-back

The main problem of the FTU scanning interferometer was related to the RR tilts: being directly attached to the FTU vessel it suffers large displacements and tilts during discharge operation, mainly due to the strong force applied from the high toroidal field. Thanks to the two-color compensation system the RR displacement do not affect density measurements but tilts along scanning direction does it. Indeed, at the first order of approximation, the RR two-mirrors 90° set-up compensates RR rotations along its longitudinal axis in such a way that they does not produce any deflection or path length variation on the reflected beams. Opposite tilts of the RR along scanning direction produce two effects: reduce interference amplitude changing the direction of the reflected beams, introduce a measurement error when the CO$_2$ and CO beams are not exactly superimposed.

The measurement error is proportional to the RR tilt and is due to the different path length variations of CO$_2$ and CO beams, the largest residual errors of the FTU interferometer were due to RR tilts.

To reduce error an off-line procedure has been implemented based on the measurement of ratio between residual error and RR tilt after each discharge. This is possible because the compensated interferometer can measured both the line integral density and the path length variation, then tilt amplitude can be estimated evaluating path length variation on a scan. The measured error-tilt ratio can be applied to correct the tilt error. Such computation was routinely performed and it allowed to reduce the residual error to the lowest values.

To improve the situation and to solve also the reduction of interference amplitude problem we developed a feed-back system to cancel in real time RR tilt angle. We installed on the RR a piezo translator by which we can

**Figure 2.** Line density measures on a 500 kA discharge where 3 big pellets were injected from equatorial port ($t=0.3, 0.7$ and $1.0$ s) and two small pellet were injected from vertical port ($t=0.5$ and $0.9$ s).

**Figure 3.** Comparison of RR tilt angle on two plasma discharges with (# 32061) and without (# 32062) tilt feedback control.
remotely control vertical angle. To compute the tilt angle with a $10^{-3}$ mrad resolution we sample the same interferometric signals that are also stored to compute after pulse line densities. Sampling is synchronized to beam scans by the zero crossing of the CRSs angular position signals. In this way RR tilts are computed every 4 ms, an usual proportional–integral–derivative controller (PID controller) has been implemented as the feedback mechanism. In Fig. 3 is shown a comparison between tilts measured on a scanning channel when feedback control is on or off, the comparison is performed on two identical plasma discharges. Feedback action starts at -0.5 s and in a very short time is able to cancel slow time variation RR tilt, some residual tilt is only present at beginning and at the end of the discharge when fast and large tilt variations are present.

3. FAST Interferometer

The FAST [16] experiment has been proposed as an European ITER [17] satellite facility with the aim of preparing ITER operation scenarios and helping early DEMO [18] design and R&D. FAST should also serve as test bed for the development of compatible ITER and DEMO diagnostics.

Following the good results of FTU interferometer a MIR scanning interferometer sharing most of its characteristics has been also proposed for FAST. Based on FAST reference design the proposed scanning interferometer tries to take advantage of vacuum vessel assembly features and to overcome some limitation of ports setup. In particular two good opportunities are the large free volume available behind the limiter on vacuum vessel bottom side and the large horizontal port. On the other side a strong limitation is the low portion of plasma that could be sampled by two ports passing line of sights. To improve the reliability of the system the interferometer has been divided in two independent modules: a vertical interferometer and an horizontal one. The vertical interferometer uses the top vertical port to measure the density on two fans and one fixed line of sight. The horizontal interferometer enter through the horizontal port to sample the plasma on three horizontal fans. To send back the beams to the scanners two different solutions for retro-reflectors have been proposed: spherical mirrors for the vertical fans and flat mirrors for horizontal fans. Spherical mirrors reduces the overall dimensions required to realize a scan, flat mirrors have been selected for the horizontal interferometer due to the small size available between limiter surface and vacuum vessel, to reduce mirrors damage they are installed 10 mm behind limiter shadow and only a small slice of the mirrors, having a toroidal length of 20 mm, is exposed to the plasma. The drawback of the spherical and flat mirrors retro-reflector compared to roof mirrors is the possible interferometer misalignment caused by toroidal mirrors tilt. To overcome this problem we will apply the mirror position feedback technique both to the scan direction and to the perpendicular direction. The scan direction will be controlled at sub-micron precision by the same interferometric method used on FTU, while the perpendicular direction will be controlled by quadrant detectors measuring returned beam positions. To ensure a line density measurement also in case of mirrors feedback failure, a vertical channels using a corner cube as retro reflector
One of the nice features of the designed FAST interferometer is that the edge vertical fan scans the plasma cross section starting from outside LCFS where plasma density reasonably will be zero. This, beside providing a very good edge profile measurements, will allow to recover also fringe counts in case of interferometer failure.

4. Summary

MIR scanning interferometry can be effectively applied to fusion device experiments to provide good reliable measurements of electron density profile time evolution. Providing a high number of equivalent measurement channels with minimum experimental effort, the scanning technique overcome the limitations of traditional interferometry. This is confirmed from the operation of the FTU scanning interferometer.

Scanning technique extends the good features of interferometry but to get the best it has to be optimized to the experimental device peculiarities. An example of this optimization are the different optical schemes adopted for the FTU interferometer and for the proposed FAST interferometer. To improve measurement quality and reliability, feedback technique have also to be implemented to control interferometer alignment before and during plasma discharge. On this direction we have shown the fast feedback method used to control roof reflector tilt during discharges.

Acknowledgments

This work was supported by the European Communities under the contract of Association between EURATOM/ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Braithwaite G, Gottardi N, Magyar G, O’Rourke J, Ryan J and Veron D 1989 Rev. Sci. Instrum. 60 2825
[2] Mansfield DK, Park HK, Johnson LC, Anderson HM, Chouinard R, Foote VS, Ma CH and Clifton BJ 1987 Appl. Opt. 26 4469
[3] Carlstrom TN, Ahlgren DR and Crosbie J 1988 Rev. Sci. Instrum. 59 1063
[4] Innocente P and Martini S 1992 Rev. Sci. Instrum. 63 4996
[5] Deng BH, Brower DL, Ding WX, Wyman MD, Chapman BE and Sarff J S 2006 Rev. Sci. Instrum. 77 10F108
[6] Brower DL, Ding W X, Mirnov VV, Van Zeeland MA and Carlstrom TN 2008 AIP Conf. Proc. 988 92
[7] Bagryanasky PA, Khilchenko AD, Khashin AN, Lizunov AA, Voskoboinikov RV, Solomakhin AL, Kosowski HR and TEXTOR team 2006 Rev. Sci. Instrum. 77 053501
[8] Ding WX, Brower DL, Deng BH, and Yates T 2006 Rev. Sci. Instrum. 77 10F105
[9] Pizzuto A, Amino C, Baldarelli M, Bettinardi L, Brogatti G, Crescenzi C, Maddaluno G, Riccardi B, Righetti B G, Roccella M and Semeraro L 2004 Fusion Sci. and Tech. 45 422
[10] Angelini BM, Apicella ML, Bucetti G, Centioli C, Crisanti F, Iannone F, Mazza G, Mazzitelli G, Panella M, Vitale V and The FTU Team 2004 Fusion Sci. and Tech. 45 427
[11] Krug PA, Stümson PA and Falconer IS 1987 J. Phys. E: Sci. Instrum. 20 1249
[12] Warr GB, Blackwell BD, Wach J and Howard J 1997 Fusion Eng. Des. 34-35 387
[13] Canton A, Innocente P and Tudisco O 2006 Appl. Optics 45 9103
[14] Canton A, Innocente P, Martini S, Tasinato L and Tudisco O 2001 Rev. Sci. Instrum. 72 1085
[15] Mazzotta C, Tudisco O, Canton A, Innocente P, DeBenedetti M, Giovanni Z, Marocco D, Micozzi P, Monari G and Rocchi G 2006 Phys. Scr. T123 79
[16] Calabro G et al. 2009 Nucl. Fusion 49 055002
[17] Holtkamp N 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland 2008) (IAEA: Vienna) CD-ROM file OY/2-1 and http://www-naweb.iaea.org/nfpc/physics/FEC/FEC2008/papers/oy_2-1.pdf
[18] Nishitani T, et al 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland 2008) (IAEA: Vienna) CD-ROM file FT/1-3 and http://www-naweb.iaea.org/nfpc/physics/FEC/FEC2008/papers/ft_1-3.pdf