Phase runaway effects on Wendelstein 7-AS


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Abstract. The phase runaway phenomenon has been studied using the W7-AS heterodyne reflectometer. The phase evolution is intermittent, changing rapidly in certain time intervals that show a strong level of amplitude fluctuations. There is a clear dependence of the value of the runaway phase $\langle dp/dt \rangle$ with the local and global plasma parameters. Several authors have proposed that the phase runaway is due to rotation of turbulent structures provided that some asymmetry between these structures and the reflectometer axis exists. The relation between the phase runaway and plasma rotation has been confirmed at W7-AS. The radial profile of the runaway qualitatively corresponds with the plasma poloidal rotation profile. Besides, the observed phase drift can be inverted by inverting the toroidal magnetic field of the stellarator, thus changing the rotation direction of the plasma. This result implies that the necessary asymmetry is independent on the direction of plasma rotation. 2D WKB simulations of the reflection on a poloidally rotating turbulent plasma for the W7-AS reflectometer and plasma parameters reproduce qualitatively the experimental features (intermittent phase drift, relation between phase and amplitude changes) of the measured phase signal.

I. Introduction

Under turbulent plasma conditions a drift of the measured reflectometer phase is observed which cannot be explained by a realistic radial movement of the cut-off layer due to density changes. This so called "phase runaway", that complicates and in occasions impairs completely the density measurements, has been observed for many plasma conditions with almost all reflectometers able to follow such a phase drift [1-6].

The phase runaway can affect the density profile measurements performed by some reflectometry techniques. The relevant magnitude to be measured for obtaining the density profile is the time delay $\tau(F)=1/2\pi (d\phi/dF)$, where $F$ denotes the microwave frequency. Techniques like FM reflectometry measure the time delay from the time derivative of the phase as the frequency is swept with time. Under these conditions the phase runaway directly affects the measurements since it simply adds to the actual phase derivative. The problem can be overcome by sweeping the frequency fast enough or by using techniques like Pulse Radar or Amplitude Modulation (also differential phase techniques) which determine the time delay from simultaneous measurements of the phase at neighboring frequencies.

Concerning the density turbulence measurements, the time scales of the phase excursions that give rise to the phase drift and that of the turbulence induced phase fluctuations are similar. This makes the separation of both parts of the signal very difficult and sometimes impossible. On the other hand, the phase runaway itself is a consequence of the plasma density turbulence. An understanding of this phenomenon is therefore essential for the correct interpretation of the reflectometer signal in terms of plasma density turbulence. With this aim experiments and simulations have been carried out at W7-AS.

It has been suggested that the phase runaway represents the Doppler shift of the probing radiation reflected from rotating cut-off layer disturbances [2,4,5]. Either these disturbances are asymmetric [2,4] or a misalignment of the reflectometer axis with respect to the normal at the cut-off
layer exists [5]. A two dimensional full wave simulation [7] of the interaction between the mm-wave and poloidally propagating oscillatory modes in this situation predicts the appearance of a phase runaway. However, so far no direct comparisons of the runaway phase with an independent plasma rotation measurement have been done.

In this paper we first describe the reflectometer system (section II). Section III deals with the characteristics of the observed phase drift. In section IV the experiments to investigate the relation of the phase runaway with plasma rotation at W7-AS are described. 2D WKB code calculations are presented in section V. The possible origin of the phase runaway at W7-AS is discussed in section VI.

II. System description

W7-AS is a low shear modular stellarator with a major radius R=2 m and an average minor radius a<17 cm. The reflectometer installed at this machine [8,9] uses X-mode propagation in the W-band (75-110 GHz) for probing radial positions corresponding to densities between 1 and 6 $10^{19}$ m$^{-3}$ (for a magnetic field on axis $B_0=2.5$ T) or between 4.5 and 10 $10^{19}$ m$^{-3}$ ($B_0=1.25$ T). Corrugated horns in combination with elliptical mirrors are used as emitting and receiving antennas. Their pattern is characterized by gaussian beams (nearly flat wave front approaching the plasma) with a waist of 2 cm in vacuum at a focal distance of 50 cm. The experimental setup is shown in Fig. 1. The cut-off surfaces are slightly tilted (2.6°) with respect to the probing direction.

Heterodyne detection with a dynamic range of more than 60 dB allows to decouple phase and amplitude fluctuations. The phase is detected by a sin/cos phase meter operating at 60 MHz and the signal amplitude is measured at the input of the phase detector with a wideband detector diode (3 dB bandwidth of 4-5 MHz). An Amplitude Modulation system [9] integrated in the reflectometer provides a time delay measurement which is used to obtain density profile information. All signals: carrier phase, time delay and amplitude, are sampled at 10 MHz.

Instrumental effects can be excluded to be responsible of the observed phase drift. Phase changes up to at least 5 MHz can be properly measured. Nevertheless, in order to increase the signal/noise ratio, the 3 dB bandwidth of detection was restricted to 1 MHz by a bandpass filter immediately before the phase meter. For the complete reflectometer

![Fig.1: W7-AS reflectometer setup.](image-url)
system, including oscillators, mixers and electronics, the dynamic range is 60 dB and the overall phase noise is around 0.1 rad in all the range of mm-wave frequencies. It has been checked that the electronics, even for very small signal levels, does not introduce any apparent drift of phase.

III. Description of the "phase runaway" at W7-AS

An example of the evolution of the reflectometer phase during stationary plasma conditions of a typical plasma discharge at W7-AS is shown in Fig. 2a. A detail of 10 µs is given in Fig. 2b.

The phase evolution is intermittent. There are time regions without phase drift and small time intervals (5-30% of the time) in which the phase increases or decreases very rapidly $(2\pi)^{-1}\frac{d\varphi}{dt}$ of several hundreds kHz. These phase excursions (between 4 and 15 radians typically) tend to occur preferentially in one direction giving rise to an average phase runaway $(2\pi)^{-1}\langle\frac{d\varphi}{dt}\rangle$ of the order of some tens of kHz. A 10 MHz sampling rate is required to measure properly the fast phase changes. The phase excursions are accompanied by fluctuations in the returned mm-wave power and a clear correspondence exists between the power minima and the fastest phase changes. Typically, all phase increments faster than 2 rad/µs are related to a drop of power of the order of 20 dB. The observed phase fluctuations are often asymmetric (an example is shown in Fig. 2b): the phase increases faster than it decreases, with the minima in the amplitude produced during the fastest phase change. During these periods of low amplitude, the phase shows sometimes excursions of the order of $2\pi$, not recovering to its previous value, causing in the long term a drift in negative direction.

The minimum measured power is around -40 dBm, well above the limit for a correct measurement of the phase detector (the minimum power at the entrance of the phase detector required for a phase measurement with an accuracy of 3° is -70 dBm). When the phase drift is not too strong, amplitude and phase signals are coherent for all frequencies higher than 50 kHz with the phase shift between them very close to $\pi/2$. This agrees with observations at JET and simulation predictions [10,11]. On the other hand, when the phase runaway is large, the phase spectra have a $1/f$ shape and amplitude and phase signals show low coherence in the whole frequency range. The $1/f$ shape of the phase spectrum has also been observed experimentally in TFTR during discharges with high power NBI heating[12] and in ohmic discharges on CCT [13].

Fig. 2: a) Evolution of the reflectometer phase for a constant microwave frequency $(F=85$ GHz, $r_{cut-off}=0.135$ m) during stationary plasma conditions (origin of time trace 0.368 s after beginning of discharge). b) Detail of reflectometer phase (solid line) and reflected power (broken line) signals for the same conditions as in fig 2a.
Although fluctuations in the time delay measured with the AM system are observed, the phase of the AM envelope is typically within a range of 1-2 rad, also during periods which exhibit a drift of the carrier phase. This indicates that the phase evolution is very similar over the radial range probed by the spectral components of the AM wave and thus the drift is canceled by the differential phase measurement.

The magnitude $(2\pi)^{-1}\langle d\phi/dt\rangle$ of the observed runaway shows a characteristic radial profile: it is positive, i.e. the reflected signal is "blue shifted", outside the separatrix, negative within the confinement region with a maximum net frequency shift of a few 100'lds kHz and it decreases towards the plasma centre. This radial dependence has been observed in a wide range of plasma conditions with ECH, NBI, at different heating power and electron densities.

![Graph](image)

**Fig. 3:** Dependence of the phase runaway (black dots) with radial position a) 400 kW ECH heating, $<n_e>$= 3.5 10^19 m^-3 and b) for a high density separatrix-dominated (1.8 MW NBI heating, $<n_e>$=1.2 10^20 m^-3) discharge. The density profiles, obtained using the reflectometer time delay signal during the ramp down following the stepwise sweep and Thomson data, are also included. Position of the LCFS is around 16 cm and 13 cm in Figs. 4a and 4b respectively.

Fig. 3a shows the runaway radial profile during an ECH discharge. As an example of the positive values of the phase runaway observed outside the LCFS, Fig. 3b shows the runaway and electron density profiles during a discharge with high density ($<n_e>$ 1.2 10^20 m^-3) and heating power (1.8 MW NBI), for which the radial positions accessible for the reflectometer are more external with respect to the separatrix.

For a given microwave frequency, the phase runaway strongly depends on variations of plasma conditions such as the heating scenario or fuelling. Changes in the value and sign of the runaway phase drift are observed a few tens of ms after the ECH or NBI heating are switched on or off. These variations are associated with the change of the electron density profile that results in a shift of the probed radial position. For some plasmas with balanced NBI heating no runaway was observed while it was present with co or counter injection alone. The most striking effect is the sudden disappearance of the phase runaway at the transition to the H-mode[14,15]. This can be seen in Fig. 4a, which shows the phase of the signal reflected at a position within the transport barrier together with the H_e signal for comparison. Figs. 4b and 4c show the Fourier spectra of the carrier phase and power signals in time windows corresponding to L and H-mode respectively. The
phase spectrum during L-mode shows the typical 1/f behaviour and the phase and power fluctuations are incoherent. When going into the H-mode, a decrease of fluctuations in the phase and power signals is observed for the full frequency range. During this regime, amplitude and phase fluctuations are coherent, being the phase shift between them very close to π/2 for all fluctuation frequencies.

![Graph showing phase spectrum during L-mode and H-mode.](image)

Fig. 4: (a) Reflectometer phase and H_α signals during an L-H transition. Probing frequency is 86.8 GHz and corresponds to a position r=0.16 m, inside the transport barrier. Power spectra of (b) carrier phase and (c) signal power in L and H-mode.

The disappearance of the runaway is observed at all radii except for the most external ones, outside the transport barrier. ELMs and dithers are accompanied again by rapid phase excursions.

**IV. Experiments on plasma rotation**

The correlation between the phase runaway and poloidal plasma rotation of the electrons has been investigated at W7-AS. The observed change of sign of the runaway at a position close to the LCFS (and to the velocity shear layer) suggests a relation between these parameters. This has been studied in detail in two types of discharges which display different rotation profiles (Fig. 5): (5a) ECRH heating 400 kW off-axis + 400 kW on-axis and (5b) ECRH 400 kW off-axis only. The poloidal plasma rotation was obtained as a sum of the ExB and diamagnetic drifts. The radial electric field has been measured from the Doppler shift of impurity emission lines (boron IV) and the pressure profile has been obtained from Thomson scattering data. Fig. 5 shows that for the two plasma conditions the radial profile of the phase drift qualitatively corresponds with the poloidal plasma rotation profile. The electron density and temperature profiles are also displayed in this figure. For the case of pure off-axis heating (Fig. 5b) the electron temperature and its gradient have moderate values inside the heating position (r≈0.1 m). Therefore the diamagnetic contribution to plasma rotation in this region is very low, a feature that is also observed in the phase runaway values. In this
experiment positions outside the LCFS could not be reached with the reflectometer and no positive
values of the runaway were found.

![Graphs showing electron density, temperature, and poloidal rotation](image)

**Fig. 5**: Radial profiles of electron density and temperature, electron poloidal rotation and phase runaway. (a) ECRH heating 400 kW off axis + 400 kW on axis, (b) ECRH 400 kW off axis only. For each case, the values of the runaway in two identical discharges are shown.

To confirm the relation between the phase runaway and plasma rotation, the stellarator magnetic field has been inverted for a series of ECRH heated discharges keeping all other plasma parameters constant.

The electron density profile (measured with Thomson scattering, reflectometry and Li-beam) and the electron temperature profile (measured with Thomson scattering and ECE), do not change as the magnetic field is reversed. Impurity rotation changes sign confirming the inversion of the ExB velocity.

**Fig. 6**: $\text{d} \varphi/\text{d}t$ as a function of radius in two symmetrical plasma configurations. All plasma parameters are kept constant while magnetic field and rotation have opposite sign in both.

Fig. 6 shows the radial profile of the phase drift for positive and negative magnetic field: for all probed radial positions the drift is inverted as the plasma rotation is reversed. Nevertheless, for some
discharges, the absolute values of the drift differ by up to a factor of two, specially for the lower microwave frequencies. A detailed observation of the phase signal shows that not only the runaway but also the shape of the temporal behavior of the phase fluctuations is inverted. This can be observed in Fig. 7, that represents a detail of the phase and amplitude of the reflected microwave signal for two discharges with different magnetic field directions.

For the data of Fig. 7, that correspond to an internal position (r~0.1 m), the coherence between phase and amplitude signals is high in the range 50 kHz < f < 2 MHz, and the phase shift between both signals is ±π/2 for positive and negative magnetic field respectively.

Note that in base of these experiments, a Doppler shift induced by radially moving density bursts can be excluded to be the main origin of the phase runaway.

To find out whether the use of two poloidally separated horns had any influence in the phase runaway, emitting and receiving transmission lines were interchanged between reproducible discharges by means of waveguide switches. This was done for a wide range of plasma conditions (toroidal magnetic field of 1.25 / +/-2.5 T, heating with 400/800 kW ECH and 1/2 MW NBI, average density between 2 and 14 10^{19} m^{-3}, rotational transform 0.3/0.5). No change in the magnitude and sign of the runaway phase was observed when using the upper or the lower antenna for launching the microwaves.

V. Simulation

To analyze the possible effects of poloidally propagating density structures, a two dimensional WKB simulation has been carried out for the W7-AS plasma and reflectometer parameters (antenna aperture=2.3', distance antenna-plasma=50 cm, microwave wavelegth λ=2.7-4 mm). Previous 1D calculations [16] have shown that for the microwave wavelengths used and the expected fluctuation wavelengths (1.5 cm at the plasma edge, 3 cm at the most internal probed positions) the WKB method can be considered a good approximation to the full wave treatment. Diffraction effects are not taken into account in the WKB approximation. However, given the high directivity of the antenna-mirror arrangement, for a probing direction close to perpendicular most of the diffracted signal should not return to the receiving horn and thus reflected components should dominate the measured signal. For the turbulence, a simple model consisting of a series of hills and valleys superimposed to the average density distribution is used [17,18]. The amplitude A_s of each hill or depression and the distance between them vary randomly in both radial and poloidal directions within 50% of their mean
values. The average size $\Lambda_s$ of the turbulence is the average distance between tops of the hills. Calculations were made for a range of $\Lambda_s$ corresponding to $n/\bar{n} \sim 0.1-6\%$ (typical $n/\bar{n}$ measured at W7-AS from phase signals that presented no runaway are 1-6% ) and for $\Lambda_s \sim 0.1-20$ cm.

In accordance with the experimental findings, the simulated phase signal shows sudden phase changes combined with drops in the signal amplitude. This occurs when 1) the amplitude of the density turbulence $\Lambda_s$ is greater than some threshold $\Lambda_{\text{thr}}$, where $\Lambda_{\text{thr}} \sim \lambda/8 \times \text{grad} \nu$ and 2) the average poloidal size of the turbulence is comparable to the spot size. These two conditions imply that phase shifts of the order of $\pi$ can exist between rays that are reflected at different poloidal positions in the antenna pattern. These rays interfere at the receiving antenna giving rise to strong amplitude fluctuations and rapid phase changes of the resulting signal. The coherently reflected signal is lost and the phase of the resulting wave is not related linearly with the density fluctuations. In this situation, a net drift of the phase appears if the geometry of the emitting horn, the rotating cut-off layer and the receiving horn is not symmetric. The asymmetry may be present in the turbulent structures or may be caused by non perpendicular probing with respect to the cut-off layer. It must be mentioned that a method has been proposed recently to extract the density turbulence characteristics from the ratio of the coherent and incoherent parts of the reflected signal\[19].

As an example, Fig. 8 shows the simulated phase and amplitude fluctuations and the corresponding density signal when the antenna axis is misaligned by $2^\circ$ in the poloidal plane. Large phase and amplitude variations are observed. In the long run the phase changes are unbalanced and lead to phase runaway. In agreement with the experimental results presented in section III, the minima in the amplitude correspond to the fastest phase changes.

If the average size of the turbulence is much smaller than the spot size the probability of completely destructive interference decreases and so does the resulting phase runaway (but note that if $\Lambda_s > \Lambda_{\text{thr}}$ reflection is incoherent and phase and density fluctuations can not be related). No phase runaway occurs either in the other limit, when the spot includes only a small fraction of an average

Fig. 8: Results of 2D WKB simulation with the horn axis $11^\circ$ misaligned from the equatorial plane. Turbulence parameters used: $n/\bar{n} = 0.8\%$, $\Lambda_\theta = 3\text{cm}$. a) Density fluctuations. b) Reflectometer phase and amplitude.

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wavelength. For intermediate values of $A_s$ and provided the necessary condition $A_s > A_{thr}$ is fulfilled, the resulting runaway is larger the larger is the amplitude of the density turbulence $A_s$. For large $A_s$, strong fluctuations in the signal amplitude that are incoherent with the phase oscillations appear and the phase spectra have a $1/f$ behaviour. (even when no asymmetry exists[18]). For low values of $A_s$ the phase runaway $<d\phi/dt>$ is lower, phase fluctuations correlated with density fluctuations can be distinguished from the phase of the incoherent signal and the phase spectra are different from $1/f$. This is consistent with the experimental observations that were described in section III and coincides also with the predictions of the random phase screen model [12,20] for low and high turbulence cases when the measurement takes place beyond the diffraction scale length for the phase screen.

The wavelengths of the fluctuations are supposed to be much larger in toroidal than in poloidal direction [21]. If this is the case, the effect of the toroidal pattern of the cut-off layer on the resulting amplitude and phase signals should be much smaller than the effect of the poloidal pattern. This is the reason why the toroidal rotation has not been considered in the simulation.

In conclusion, the simulations confirm that a drift in the phase can appear when there are poloidally rotating structures in the plasma provided some asymmetry exists. The drift is due to the existence of a rough cut-off surface ($A > A_{thr}$) and the finite spot size. Recently, a 2D full wave code has been developed [16] and its predictions will be compared to the ones of the WKB code.

VI. Conclusions

The reflectometry system at W7-AS has been used to investigate the phase runaway effect observed at most reflectometer devices. Due to the dynamic range and bandwidth of the system an instrumental origin of the phenomenon, e.g. due to intermittent loss of the reflected signal, can be excluded. Besides, the measured phase runaway strongly depends on plasma conditions.

It has been proposed [7,2,4,5] that the phase runaway can be explained by a Doppler shift of the reflected radiation caused e.g. by plasma rotation and either a non-perpendicular line of sight or poloidally asymmetric density structures at the cut-off layer. The relation of the phase runaway with plasma rotation in W7-AS has been confirmed by a comparison of the runaway radial profile with the plasma poloidal rotation profile as obtained from impurity spectroscopy. In addition, it has been demonstrated that the direction of the phase drift can be inverted by inverting plasma rotation. Therefore, an explanation based on the existence of asymmetric density structures would require that the asymmetry be independent on the rotation direction. For example, velocity shear induced asymmetries should be excluded. The most plausible explanation of the asymmetry in W7-AS would then be a tilt of the antenna axis with respect to the plasma.

2D WKB simulations of reflection on a rotating plasma made for the W7-AS plasma and reflectometer parameters show that for the expected turbulence conditions a phase runaway can appear due to the slight tilt of the antennas ($2.6^\circ$) with respect to the normal to the cut-off surfaces. Moreover, the simulations reproduce qualitatively some of the experimentally observed features of the phase runaway: the $1/f$ phase spectra and the correspondence between minima in the amplitude of reflected signal and the fastest phase changes. Quantitative results cannot be deduced from these
simulations as the phase response is very sensitive to the particular parameters of plasma turbulence and the antenna-plasma geometry. In particular the orientation of the cut-off surfaces at the plasma edge of the low shear stellarator W7-AS can change due to the neighbourhood of island structures and thus depends on the edge rotational transform.

It is difficult to extract information about the plasma rotation velocity from the mean phase runaway measurements, as the phase drift depends on turbulence parameters (amplitude and wavelengths) which are usually unknown. Besides, the observed intermittent phase evolution complicates even more the interpretation of the phase runaway in terms of plasma rotation. This behaviour can in principle be explained by the non-linear response of the phase measurement to the local density fluctuations at the reflecting layer (small changes in the amplitude and wavelength characteristics can produce a completely different phase response). However, the intermittency could also be the result of a real intermittent behaviour of the plasma: the appearance and disappearance of small turbulent structures or a sudden change in their characteristics. It is worth to be mentioned that given the high instantaneous $d\varphi/dt$, great care must be taken when measuring the profiles with FM techniques.

Based on the comparison between the experimental results and the 2D WKB simulation we can state that the observation of a phase runaway is a consequence of the 2-dimensionality of the reflection process (which under turbulent plasma conditions is modified by refraction, diffraction and scattering phenomena). The absence of the phase runaway is a necessary but nevertheless not sufficient condition to state that 2D effects do not affect the fluctuation measurement (e.g. runaway is not present in cases without asymmetry or with very broad antenna pattern). However, for plasma regimes where the phase signal shows no runaway and fluctuations of the reflected signal amplitude are low - like in the H-mode - the measured phase can be related with the density at the cut-off layer following a 1D scheme.

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**References**

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