Fluctuations, sheared radial electric fields and transport interplay in fusion plasmas

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\textit{New Journal of Physics} 4 (2002) 51.1–51.12 (http://www.njp.org/)
Received 18 February 2002, in final form 1 May 2002
Published 18 July 2002

Abstract. A view of recent experimental results and progress in the characterization of plasma turbulence in magnetically confined devices is given. An empirical similarity in the scaling properties of the probability distribution function of turbulent transport has been observed in the plasma edge region. This result supports the view that turbulent transport displays universality in fusion plasmas and emphasizes the importance of the statistical description of transport processes in fusion plasmas as an alternative approach to the traditional way of characterizing transport based on the computation of effective transport coefficients. Comparative studies in different magnetically confined plasmas show that fluctuations and sheared poloidal flows organize themselves to be close to marginal stability. This property should be considered as a critical test for improved confinement transition models. Magnetic configuration scan experiments in stellarator devices have shown a complex interplay between transport and sheared radial electric fields in the proximity of rational surfaces. The development of new fluctuation analysis techniques based on the investigation of velocity fluctuations opens a new way to investigate turbulent transport and dynamical electric fields in the plasma core region.

1. Introduction

Understanding the underlying physics of anomalous transport remains the outstanding critical physics issue in magnetic fusion research [1]. It is generally accepted that anomalous transport is due to plasma turbulence. Although the dominant free energy source driving fluctuations has not been identified, one of the important achievements of the fusion community has been the development of techniques to control plasma fluctuations based on the $E \times B$ stabilizing...
mechanism [2]. The generality of this mechanism is based on the fact that the drift of charged particles in the presence of an electric ($E$) and magnetic field ($B$) does not depend on the mass or charge of the particles. When the $E \times B$ shearing rate ($\omega_{E\times B}$) approaches the frequency characteristic of the turbulence ($\Delta \omega_T$), $\omega_{E\times B} \approx \Delta \omega_T$, a reduction in the turbulence amplitude is predicted. The earliest theory of $E \times B$ shear stabilization mechanisms is valid when the time variation of the radial electric field is much slower than the correlation time of the ambient turbulence [3]. Recently the theory of $E \times B$ shear suppression of turbulence has been extended to include time-dependent $E \times B$ flows [4]. The best performance of existing fusion plasma devices has been obtained in plasma conditions where $E \times B$ shear stabilization mechanisms are likely to play a key role [5]: both edge and core transport barriers are related to a large increase in the $E \times B$ sheared flows. Direct measurements of transport and fluctuations during the generation of edge transport barriers show that concurrent changes in turbulence amplitudes, spatial scales and multi-field phase angles lead to a reduction of turbulent particle flux during the formation of the H-mode transport barrier [6]. These results emphasize the importance of clarifying the driven mechanisms of sheared flows in fusion plasmas.

Comparative studies of the structure of plasma turbulence carried out in different magnetic confinement devices have led to insights furthering our understanding of turbulent transport in fusion plasmas [7]. The overall similarity in the structure in the statistical properties of fluctuations has led us to conclude that plasma turbulence in magnetically confined plasmas, as in many other dynamical systems, display universal characteristics [8].

Characterization of fluctuations and fluctuation driven particle and energy fluxes requires experimental techniques for measuring the variations in parameters such as density, temperature and magnetic and electric fields with good temporal and spatial resolution. With the present state of the art in plasma diagnostics this kind of measurement is mostly limited to the plasma edge where material probes can be used [9, 10]. In order to assess the role of both turbulence and $E \times B$ sheared flows on transport in the core of the plasma there is a need for improved diagnostics and analysis tools for fluctuating quantities. Recently wavelet-based cross-correlation analysis has been used to obtain fluctuations of poloidal rotation velocity by means of beam emission spectroscopy and this approach offers some potential for direct measurements of turbulent transport [11]. Measurements of $E \times B$ turbulent fluxes based on the measurement of fluctuations in the phase velocity of fluctuations have been recently reported [12].

This paper reports recent results in the characterization of the statistical properties of turbulence and the physics of $E \times B$ sheared flows in fusion plasmas. The experimental evidence of an empirical similarity in the statistical properties of turbulent transport in the plasma boundary is discussed in section 2. Experimental evidence of sheared flows and fluctuations near marginal stability in the edge region of fusion plasmas is presented in section 3. The influence of magnetic topology (rational surfaces) in the generation of $E \times B$ sheared flows is discussed in section 4. The development of new fluctuation analysis tools based on the measurement of velocity fluctuations is presented in section 5. Finally, conclusions are presented in section 6.

2. Statistical properties of turbulent transport

Broadband electrostatic and magnetic fluctuations have been observed in the boundary region of magnetically confined devices. The electrostatic fluctuations produce a fluctuating radial velocity given by $\tilde{v}_r = \tilde{E}_\theta / B$, $\tilde{E}_\theta$ being the fluctuating poloidal electric field and $B$ being the toroidal magnetic field. The electrostatic fluctuation driven radial particle flux is given by
Figure 1. Vacuum magnetic flux surfaces for different configurations 100.68.72 (magnetic well 2.5%), 100.68.81 (magnetic well 0.9%) and 100.68.91 (magnetic well 0.2%) in the TJ-II stellarator (a)–(c). (d)–(f) Raw signals of ion saturation current fluctuations measured at \( \rho \approx 0.8 \). An increase in the level of fluctuations (i.e. rms) is clearly seen at the plasma edge when reducing the magnetic well level.

\[ \Gamma_{E \times B}(t) = \tilde{n}(t)\tilde{E}_\theta(t)/B. \] Ignoring poloidal and toroidal asymmetries the total electrostatic fluctuation driven particle fluxes can be computed. It has been experimentally shown that, in some cases, the fluctuating flux can account for an important part of the total particle flux in the edge region [6, 13]. However, it should be noted that, in some cases, fluctuation fluxes appear too high to be consistent with global particle balance [14]. Poloidal asymmetries, large scale convective cells or the possible role of temperature fluctuations may account for these apparent inconsistencies. At present, this disagreement still remains an open question [15].

In order to go deeper into the mechanisms underlying turbulent transport it is important not only to compute the average value of the fluctuation induced transport, but also the statistical properties of the time resolved turbulent flux. A systematic comparison of the statistical properties of turbulence has been investigated in the plasma edge of the TJ-II stellarator.

Previous magnetohydrodynamic (MHD) studies [16] have investigated the stability properties of the TJ-II device. The importance of the magnetic well term for ideal and resistive interchange modes has been studied, and it was found that the magnetic well is the main stabilizing mechanism. Due to the flexibility of the TJ-II configuration, the magnetic well depth may be modified over a broad range of values, i.e. from 0–6 %, while the radial extent of the magnetic well can also be strongly modified. A region having a magnetic well in the bulk of the plasma can coexist with a region having a magnetic hill in the outer region of the plasma. These properties make TJ-II an ideal device to study the onset of fluctuations and related phenomena in a controlled way. Recent experiments [17] have shown that, as expected from the theoretical point of view, the level of edge fluctuations and the degree of intermittency show a significant increase when the magnetic well is reduced in the TJ-II stellarator (figure 1).
In the TJ-II stellarator, as in other devices [18, 19], the probability density function (PDF) of the turbulent transport shows significant non-Gaussian features. The PDFs of the local $E \times B$ turbulent flux are modified when decreasing the magnetic well (figure 2(a)): these changes are mainly an increase in the probability of large amplitude flux transport events. The PDF of $E \times B$ turbulent fluxes can be rescaled using a finite-size scaling law [20]:

$$\text{PDF}(\Gamma_{E \times B}) = L^{-1}g(\Gamma_{E \times B}/L)$$

where $\Gamma_{E \times B}$ is the turbulent $E \times B$ flux and $L$ is an scaling factor (figure 2(b)). In order to identify the relation of the scaling parameter to plasma parameters it is important to keep plasmas with similar properties (magnetic topology, collisionality, etc) but with different magnetic wells (i.e. different levels of fluctuations). This study has shown that the scaling parameter $L$ is directly related to the level of fluctuations. A similar dependence has been recently observed in the JET tokamak [21]. These results are consistent with previous findings which have shown an empirical similarity of frequency spectra of edge plasma fluctuations in different toroidal magnetic confinement devices [8]. Frequency spectra can be re-scaled using the expression $P(\omega) = P_0g(\lambda, \omega)$, where $\lambda$ and $P_0$ are parameters to be determined for each device [8].

The empirical similarity in turbulent fluxes suggests that edge plasma turbulent transport evolves into a state in which the PDFs of transport exhibit the same behaviour over the entire amplitude range of transport events. These results emphasize the importance of the statistical description of transport processes in fusion plasmas as an alternative approach to the study of transport based on the computation of effective transport coefficients.

3. Sheared poloidal flows and transport near marginal stability

The structure of plasma profiles in the proximity of the last closed flux surface (LCFS) has been investigated in tokamaks, stellarators and reversed-field pinches by using Langmuir probes [22]–[26]. Typically, the ion saturation current increases and the floating potential becomes more negative when the probe is inserted into the plasma edge. From the wavenumber and frequency spectra $S(k, \omega)$, computed from the two-points correlation technique [26], we define the poloidal phase velocity of fluctuations as

$$v_{\text{phase}} = \sum S(k, \omega)(\omega/k) / \sum S(k, \omega).$$
A reversal in the phase velocity of fluctuations (shear layer) has been observed in the proximity of the LCFS (usually ±1–2 cm) in magnetic fusion devices. The shear layer location provides a convenient reference point for the characterization of the structure of fluctuations. The maximum in the fluctuation flux appears to be linked to the location of the velocity shear layer (which acts as an effective confinement radius).

Experiments carried out in the TJ-II stellarator show that the resulting radial gradient \( \frac{dv_{\text{phase}}}{dr} \) is in the range of \( 10^{5} \, \text{s}^{-1} \), which turns out to be comparable to the inverse of the correlation time of fluctuations, in the range of 10 \( \mu \text{s} \) (figure 3). This result suggests that \( E \times B \) flows and fluctuations organized themselves closed to marginal stability (i.e. the shearing rate is close to the critical value to modify plasma turbulence).

It is interesting to compare the results obtained in the TJ-II stellarator with those previously reported in other devices (figure 4). In stellarator plasmas such as ATF [22] a reversal in the phase velocity of fluctuations has been observed. The position of the shear depends on the magnetic configuration and the resulting radial gradient \( \frac{dv_{\text{phase}}}{dr} \) was in the range of \( 10^{5} \, \text{s}^{-1} \), as in the TJ-II stellarator. It is remarkable that similar results have been obtained in tokamak plasmas. In particular, experiments carried out in JET [12] show that the resulting shearing rate in the poloidal phase velocity of fluctuations is also in the range of \( 10^{5} \, \text{s}^{-1} \). Similar results were found in the plasma edge of the TEXT tokamak [23]. Large \( E \times B \) sheared flows have also been reported in reversed field pinches [13]. These changes in the poloidal phase velocity of fluctuations can be explained, or at least are consistent, in terms of \( E \times B \) drifts.

These findings show that the presence of sheared flows with shearing rates close to the critical value modify plasma turbulence in the plasma boundary of magnetically confined plasmas. This result implies that there is not a continuous increase of the \( E \times B \) flow shear when approaching the critical power threshold for the transition from low confinement to improved confinement regimes (i.e. L–H transition) [5]. On the contrary, sheared flows with decorrelation rates close to the critical value to reduce turbulence are already developed well below the L–H power threshold. This property should be considered as an important ingredient in the modelling of the L–H transition. It should be noted that core turbulence simulations have shown that the picture of turbulence as a self-regulating system consisting of sheared flows and ambient turbulence seems consistent only when the reduction in the random shearing effect due to time-dependent flow is taken into account [4].
Figure 4. Radial profile of the poloidal phase velocity of fluctuations in the proximity of the LCFS in stellarator (ATF) and tokamak (JET) devices. Shaded areas indicate the location of the velocity shear layer. The probe is moving radially inwards from the Scrape Off Layer (SOL) to the plasma edge region. The position of the LCFS was determined by the equilibrium code EFIT in the JET tokamak [45].

Understanding the mechanisms which drive \( E \times B \) sheared flows is a key issue to understanding the transition to improved confinement regimes. There are different sources of radial electric fields in plasmas [1]. From the radial force balance it follows that the radial electric field can be generated via poloidal and toroidal flows and by pressure gradients. Concerning the physics of poloidal flows several driving mechanisms have been proposed [1]: ion temperature gradients, Stringer spin-up, ion orbit losses and Reynolds stress. From this perspective, an open question is the following: which mechanism allows fluctuations and poloidal flows to organize themselves to be close to marginal stability?

Recent numerical simulations have shown that a turbulent driven fluctuating radial electric field via Reynolds stress has the property to make \( \omega E \times B \) critical [27]. From the experimental point of view, a quantitative estimation of the importance of fluctuation induced driven flows in the plasma boundary region has been done [28]. The \( \langle \tilde{v}_r \tilde{v}_\theta \rangle \) term of the Reynolds stress tensor can be computed as \( \langle \tilde{v}_r \tilde{v}_\theta \rangle \approx \langle \tilde{E}_r \tilde{E}_\theta \rangle / B^2 \), \( \tilde{E}_r \) and \( \tilde{E}_\theta \) being the fluctuating radial and poloidal electric fields. The radial and poloidal electric fields were estimated from floating potential signals measured by radially and poloidally separated probes, respectively. With these approximations the electrostatic component of the Reynolds stress has been computed in the proximity of the velocity shear layer in tokamaks. The measured radial gradient of \( \langle \tilde{v}_r \tilde{v}_\theta \rangle \) is in the range of \( 10^7 \)–\( 10^8 \) m s\(^{-2}\). The damping term due to magnetic pumping [29, 30] in the plasma boundary region can be estimated as \( \gamma_{mp} v_{i\theta} \), where \( v_{i\theta} \) is the ion poloidal velocity. Assuming an ion poloidal velocity of the order of the phase velocity of fluctuations (about 1 km s\(^{-1}\)) and for typical edge plasma conditions, \( \gamma_{mp} \approx 10^4 \) s\(^{-1}\), it follows that the contribution of the magnetic pumping to the time evolution of the poloidal flow is about \( 10^7 \) m s\(^{-2}\). This finding shows that the radial gradient in \( \langle \tilde{v}_r \tilde{v}_\theta \rangle \) is high enough to play a significant role in the physics of poloidal flows in the plasma boundary region. Recent experiments indicate that the turbulence-induced Reynolds stress might be the dominant mechanism to create the sheared poloidal flow in the edge region of tokamak plasmas [31].

It is easy to understand why Reynolds stress driven flows allows poloidal flows and fluctuations to reach the condition \( \omega E \times B \approx \Delta \omega_T \). The Reynolds stress measures the degree of
anisotropy in the structure of fluctuations. Radially varying Reynolds stress allows the turbulence to rearrange the profile of poloidal momentum, generating sheared poloidal flows. In the plasma boundary region, strong gradients in the level of fluctuations can provide a modification in the degree of anisotropy in the radial–poloidal structure of fluctuations. Once the Reynolds stress driven sheared flows reach the critical value to modify fluctuations a negative feedback mechanism will be established which will keep the plasma near the condition $\omega_{E \times B}$ critical. On the other hand, it is less obvious to understand in which way other mechanisms, like those based on the role of ion orbit losses, can allow the sheared poloidal flows and fluctuations to self-organize to reach the condition $\omega_{E \times B}$ critical.

4. Rational surfaces, radial electric fields and transport

The generation of internal and edge transport barriers is linked to plasma regions with a unique magnetic topology [32]. In configurations with low or negative magnetic shear, internal transport barriers (ITBs) are formed close to the location of a minimum in the safety factor ($q_{\text{min}}$) and in the proximity of low-order rational surfaces [33, 34]. Edge transport barriers are located close to the boundary between the region with open and closed magnetic field lines, and in this plasma region there are strong gradients in the level of fluctuations.

The operational flexibility and control of the magnetic topology in stellarator devices make them useful tools to investigate the role of rational surfaces on transport [35] (figure 5). The presence of natural resonances has clearly been observed as a flattening in the edge plasma profiles in the TJ-II [35] and LHD [36] stellarators. Structures in plasma profiles have been observed in the case of low-order rational surfaces ($n = 8$, $m = 5$; $n = 4$, $m = 2$) in the TJ-II stellarator (figure 6), with significant variation in plasma potential just outside the flattening region (figure 7). These results have been interpreted as an increase of the sheared $E \times B$ flow linked to the radial location of rational surfaces. In the TJ-II stellarator the resulting radial gradient $(dE_r/dr)B^{-1}$ can reach values of about $10^5$ s$^{-1}$. Because the plasma edge radial and poloidal correlations are typically of the same order [23] and TJ-II is a low magnetic shear stellarator, this can be considered to be a rough estimate of the shear decorrelation rate [37]. This value turns out to be comparable to the inverse of the decorrelation time of fluctuations usually measured in the TJ-II device (figure 3).

These experimental results illustrate the impact of rational surfaces in the generation of $E \times B$ sheared flows. These results look very similar to recent experiments carried out in the JET tokamak, which have shown flattening in plasma profiles and evidence of $E \times B$ sheared flows linked to rational surfaces [38]. This similarity suggests that $E \times B$ sheared flows are connected to

![Figure 5. TJ-II vacuum configuration (a) without and (b) with a medium size island ($n/m = 4/2$) in the plasma boundary region.](http://www.njp.org/)

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Figure 6. Radial profiles of the ion saturation current measured by Langmuir probes (a) without and (b) with the $n = 4$, $m = 2$ rational surface inside the LCFS in the TJ-II stellarator.

Figure 7. Sheared $E \times B$ flows linked to rational surfaces ($m = 8$, $n = 5$) in TJ-II.

the magnetic topology (rationals) both in tokamaks and stellarators. The presence of $E \times B$ shear flow at the boundary of the magnetic island is a candidate to explain the observed link between the location of transport barriers and low-order rational surfaces in fusion devices [33, 34].

A possible explanation of the flow structure near rational surfaces is the coupling of flow generation and turbulence [27] (i.e. sheared flows driven by fluctuations via Reynolds stress). In the absence of $E \times B$ sheared flows, fluctuations are expected to show maximum amplitude at the rational surface [39]. The corresponding instability mode width will depend on the nature of the instability and on the magnetic shear scale length. As a consequence, a modification in
On the other hand, the presence of rational surfaces can also cause the formation of island or magnetic ergodic regions, which in some cases can degrade the quality of confinement in magnetically confined plasmas. Low-order resonances are often associated with ‘hard’ MHD events, such as disruptions, or ‘soft’ MHD events, which limit the plasma performance in tokamaks. MHD (ELM-like) activity has recently been observed in TJ-II [41]. This MHD mode is linked to the presence of the $m = 2, n = 3$ resonant mode interacting with a resistive ballooning instability. In the TJ-II stellarator this ELM-like instability modifies transport properties in the region where it is developed and the outward particle flux is enhanced. These results show the direct impact of rational surfaces on transport in the TJ-II stellarator. The control of the influence of magnetic island on transport is an active area of research due to the influence of neoclassical tearing modes on confinement [42].

Recent experiments in the TJ-II stellarator have shown that the local $E \times B$ fluctuation induced fluxes are significantly modified in the proximity of rational surfaces [43]. In the case of measurements taken in the proximity of the $n = 4, m = 2$ resonant surface, located near the plasma boundary, the local $E \times B$ fluctuation particle flux shows a reverse direction (from outwards to inwards). This modification is due to a change in the phase relation between density and electric field fluctuations. As shown in figure 8, the absolute value of the measured local $E \times B$ transport is similar in both cases, with (inward transport) and without (outward transport) the presence of the $n = 4, m = 2$ rational surface. At present, the mechanism responsible of the observed inward transport has not been identified. The fact that no significant differences were found in the global confinement strongly suggests a local nature of the measured turbulent transport. Simultaneous measurements at different poloidal and toroidal locations are needed to clarify this question.

**Figure 8.** Radial profile of the turbulent particle flux measured in a configuration-free or low-order rational surface (a) and with a low-order resonance $(4/2)$ located near the plasma boundary (b) in the TJ-II stellarator.
Figure 9. Comparative study of the PDF of transport computed from the correlation between density and poloidal electric field fluctuations and from the correlation between velocity and density fluctuations. Measurements were carried in the JET tokamak plasma boundary region.

5. Velocity fluctuations and transport

A new approach for the measurement of turbulent fluxes and time-dependent $E \times B$ sheared flows has been recently investigated. It is based on the measurement of fluctuations in the phase velocity of fluctuations [11, 12]. Wavelet-based cross-correlation analysis has been used to obtain fluctuations of poloidal rotation velocity by means of beam emission spectroscopy and this approach offers some potential for direct measurements of turbulent transport in the plasma core region [11]. Recently, fluctuations in the radial phase velocity ($\tilde{v}_{\text{phase}}^r$) have been computed from plasma density signals using Langmuir probe arrays in the plasma boundary region [12].

Experiments to test this approach were carried out in the JET plasma boundary region using a fast reciprocating Langmuir probe system located on top of the device [12]. The experimental set-up allows the investigation of the radial structure of fluctuations and electrostatic driven turbulent transport using two radially separated probe arrays. The $E \times B$ turbulent flux was measured using two different approaches:

(a) From the correlation between density and poloidal electric field fluctuations, neglecting the influence of electron temperature fluctuations, and using the standard probe techniques [9, 10]. The electrostatic driven radial transport is given by, $\Gamma_{E \times B}(t) = \tilde{n}(t) \tilde{E}_\theta(t)/B$.

(b) From the correlation between density fluctuations and fluctuations in the radial phase velocity of fluctuations using the expression $\Gamma_{\text{phase}}(t) = \tilde{n}(t) \tilde{v}_{\text{phase}}^r(t)$. The radial velocity $\tilde{v}_{\text{phase}}^r$ is given by $\Delta x/\Delta t$, $\Delta t$ being the time delay between two ion saturation current ($I_s$) signals radially separated by $\Delta x = 0.5$ cm. The time delay was computed using 200 $\mu$s time window realizations.

Figure 9 shows the probability distribution function of the time-resolved radial turbulent flux ($\Gamma_{E \times B}$ and $\Gamma_{\text{phase}}$). There is a significant similarity in the statistical properties of both turbulent...
fluxes. The average turbulent fluxes, $\Gamma_{E \times B}$ and $\Gamma_{\text{phase}}$, are in agreement within a factor of four. Further experiments are clearly needed with over-sampled signals (2–5 MHz) to increase the time resolution in the computation of velocity fluctuations. These results suggest that, in some conditions, the measurement of $E \times B$ turbulent transport in the plasma core region might be achieved from measurements of density at different radial locations [11]. Microwave reflectometry or beam emission spectroscopy (BES) [11] diagnostics can provide those measurements.

Recent numerical simulations support the idea that measurements of radial velocity fluctuations deduced from density fluctuations can provide, under some circumstances, an estimation of fluctuating electric fields [44]. However, it remains as an open question to clarify the validity of the computation of turbulent transport from phase velocity fluctuations in plasmas with different instabilities.

6. Conclusions

Significant improvement in our understanding of the statistical properties of fluctuations, the physics of $E \times B$ sheared flows, the interplay between magnetic topology, electric fields and transport, as well as in the development of new diagnostics and analysis tools, have recently been achieved in fusion plasmas. The main conclusions can be summarized as follows:

(1) An empirical similarity in the PDF of turbulent transport has been observed in the plasma edge region in fusion plasmas. Experimental results emphasize the importance of the statistical description of transport processes, based on probability density functions, as an alternative approach to the study of transport based on the computation of effective transport coefficients.

(2) Comparative studies in different magnetic confinement devices show that fluctuations and $E \times B$ sheared flows organize themselves to be close to marginal stability. This property should be considered as a critical test for improved confinement transition models. Whereas this property is consistent with turbulent driven fluctuating radial electric field, it is difficult to understand in what way ion orbit loss mechanisms can allow sheared flows and fluctuations to reach marginal stability.

(3) Magnetic configuration scan experiments have shown the complex interplay between transport and radial electric fields in the proximity of rational surfaces. The important role played by magnetic topology (e.g. rational surfaces) in transport may be understood in terms of the competition between fluctuation induced transport mechanisms (which would deteriorate confinement) and $E \times B$ sheared flow mechanisms linked to magnetic surfaces.

(4) The development of new fluctuating analysis tools, based on the measurements of velocity fluctuations, has opened the possibility of investigating turbulent transport in the plasma core region from measurements of density fluctuations.

Acknowledgments

This research was sponsored in part by Ministerio de Ciencia y Tecnología of Spain under project no FTN2000-0924-C03-02. One of the authors (BG) acknowledges support by the Fundação para a Ciencia e Tecnologia (Lisbon) under grant no PRAXIS XXI/BD/15814/98.

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