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Research statement

Fluctuations in the preparation to burning plasma

Plasmas, and in particular Fusion plasmas represent a complex system where many interacting degrees of freedom coexist determining a variety of non-linear behavior spreading over a broad range of spatio-temporal scales [B2, B9]. It is known since a lot of time that simplified diffusion paradigm can't correctly describe the transport of energy, particles and momentum and a different description is mandatory for this dynamical system. Proper description of plasma dynamics require consequently to disentangle the role played by fluctuations, which are found to emerge at all spatial and temporal scales. My personal research activity has been indeed devoted to the analysis, interpretation and modeling of experimental and numerical results obtained in magnetized plasmas, with emphasis on magnetically confined ones. More in details I've focused my effort on electromagnetic fluctuations induced transport of energy, particle and momentum, with interpretation in the wider framework of turbulence theory. During my research activity I have collected a large experience on electromagnetic transport analysis, working on different magnetic configurations, from Reversed Field Pinches (working on RFX-mod operating in Padova, Extrap-T2R operating in Stockholm and TPE-1RM20 which was in operation in Japan), stellarators (with experimental activity on TJ-II heliac type operating in Spain) and Tokamaks (ASDEX-Upgrade and JET), and low temperature plasmas as the Simple Magnetized Torus experiment TORPEX at EPFL.

I've started working on fluctuation during my M.Sci. thesis, by studying the effect of externally modified $\mathbf{E} \times \mathbf{B}$ flow on turbulence and transport in the RFX-mod Reversed Field Pinch [A1], observing transport quenching caused by phase decoupling between fluctuations not homogeneous in the $k_\perp$ spectra. The necessity of a multi-scale approach lead me to deepen my interest in turbulence and dynamical system. It is know since pioneering work of Kolmogorov [B3] that a proper description of a non-deterministic process is based on a statistical approach. The Kolmogorov hypothesis is strongly based on the assumption of self-similarity, but plasma turbulence, as well as turbulence observations from hydrodynamic to astrophysics till econophysics [B9], has been proved to exhibit an high degree of *intermittency*. I have contributing to proving this in variety of experiments [A2, A4], with a successful comparison with solar wind and atmospheric turbulence data [A3], providing me a wider comprehension of the mechanism and advanced investigation tools used also in other research field. Stimulated from the observation of this strong intermittent character I've been focused my effort in the characterization and comprehension of those fluctuations (localized both in time and $k_\perp$ spectra) responsible for the multifractal nature of plasma turbulence [B4]. I've worked on the experimental characterization of these eddies in a variety of different devices and magnetic configurations [A9, A10, A11, A17], they are localized pressure perturbation with a vortex-like pattern in the plane perpendicular to the guiding field [A6], extended along the direction of the guiding magnetic field (they are also dubbed as *filaments*) and with an associated parallel current [A9, A10]. These eddies form as a result of non-linear evolution of plasma instabilities, and among various, one of the possible mechanism has been identified as a result of the coupling between Drift Waves (DW) and Kinetic Alfvén Waves (KAW) [A10], in analogy with what observed in the magnetosphere [A8, B8]. Extending the analogy to the astrophysical plasmas, a striking similarities between the enhancement of convective transport caused by these filaments (depending on the parallel closure along the field line) and the modification of the density gradient of the equatorial iogenic plasma torus in the Jovian magnetosphere [B6] has been experimentally proved [A15]. This testify that investigation on plasma fluctuations as observed in fusion plasmas have actually a larger impact and deep analogy with other disciplines. Expertise in current filaments studies has been extended to the studies of Edge Localized Modes (ELM) filaments providing for the first time an experimental direct estimation of the current density associated to a type-I filament [A14, A13, A12, A16].

Multi-scale dynamics is involved also in the process of turbulent generated flow. It is indeed well known that Turbulence, and in particular Drift Wave Turbulence (DWT) can spontaneously generate patterns [zonal flows and currents/fields, generally zonal structures (ZS)] on scales that are typically larger than the perpendicular (w.r.t. the equilibrium magnetic field B_0) wavelength of the underlying fluctuations, $\lambda_\perp$, but still shorter than the equilibrium nonuniformity scale length [B1]. The emergence of this sheared ZF arises due spatial anisotropy of fluctuation coupling, through a mechanism known in the fluid turbulence literature as the turbulent Reynolds stress [B13]. I've deeply investigated this process [A5, A7], which can be interpreted also as a non-linear energy transfer process: it is worth noting that it is one of the invoked mechanism to explain the bifurcation to enanched confinement regimes (H-modes) in tokamaks [B17].

Apart from the aforementioned multi-scale process regarding turbulence and flow, which has been the primary subject of my research so far, other complex dynamical processes connected with the presence of non-thermal energetic particles (EP) are presently under consideration by the scientific community. This is motivated by the fact that EPs are expected to dominate the power balance in future burning fusion plasmas [B22] and by the necessity to correctly predict current profile redistribution due to the injection of Neutral Beams in future devices like ITER.

The interaction between fast ion and background turbulence have to be considered from a dual perspective. From one side the role of background fluctuations on the redistribution of fast ion has to be addressed. From the theoretical point of view as a first approximation fast ions should not be affected by small scale fluctuations due to their large gyroradius through a process know as *orbit averaging*. Recent numerical and theoretical observation [B14] actually reveal that the influence of electrostatic turbulence on fast ion depends on the ratio E/T_e: in some case it has been indicated as one of the causes of the observed experimental observation of fast broadening of current profile after off-axis injection of Neutral Beam [B12, B11]. Concerns exist for foreseen scenario of off-axis N-NBI injection on ITER at lower power has arisen [B14].

On the other hand Energetic particles can provide the free energy source for Shear Alfvén Waves (SAW) and drift-Alfvén waves (DAW) excitation on the micro and meso-scales [B22] with the inclusion of even shorter wavelength through a process of mode conversion of SAW/DAW to kinetic Alfvén waves. All of these instabilities could generate

Zonal-like structures at intermediate scales which interact with the original fluctuations in a complex cross-scale self-regulated process. Energetic Particle induced Zonal Structure, as those for example of the Energetic Particle Geodesic Acoustic Modes (EGAMS) [B19, B10, B15] have a complicated interaction with turbulent eddies induced by thermal ion instabilities: this interaction could provide enhance plasma transport and it is thus obvious that in view of burning plasmas with a substantial fraction of energetic particles these mechanism should be addressed. This topic is an hot issue in the fusion community but there are a variety of open issues which need to be addressed, particularly from the experimental point of view:

(i) How fast particle density is modified in presence of different type of fluctuations? Thus by modifying from electron to ion dominated turbulence is anomalous fast particle transport different?

(ii) Which is the role of magnetic fluctuations in determining the fast-particle current redistribution?

(iii) How shaping and *exotic* configuration as negative triangularity affect the fast-particle distribution?

(iv) Is that possible to experimentally investigate the cross-scale coupling between EP-driven ZF and DWT ZF?

(v) How different population of fast particle, generated for example during reconnecting processes interact with each other and with the background plasma?

The TCV tokamak in operation at the Swiss Plasma Center at EPFL has recently received a significant upgraded with the installation of a new Neutral Beam Injector with energy up to 30 kEV and delivered power up to 1 MW. This new system, coupled with the forthcoming upgrade of the Electron Cyclotron Resonant Heating system will allow to reach unexplored scenario for this machine, with high values of normalized pressure β and a wide range of T_e/T_i including $T_e \sim T_i$ and with a significant population of fast ion. It appears clearly that the TCV machine could be the ideal test-bed for the proposed investigation of multi-scale and energetic particle physics, but this require an aggressive program on experimental side. This represents the main subject of the present proposal. So far indeed the tokamak is equipped with a Compact Neutral Particle Analyzer which can be used for the investigation of fast particles. Actually to experimentally address this topic new diagnostics should be installed. Among them we list the following, together with possible international collaboration to be activated or reinforced:

FIDA: *Fast Ion D_α diagnostic* is based on the same principle of Charge eXchange Recombination Spectroscopy, considering the emission from $n = 3$ to $n = 2$ Balmer series, combined with a proper geometrical arrangement in order to disentangle this emission from other source of radiation. Presently this diagnostic is under consideration for a fast-track implementation of TCV. Possible collaboration to be activated University of California, Irvine, Princeton Plasma Physics Laboratory, Max Planck Institüt für Plasmaphysik

FILD: *Fast Ion Loss Diagnostic* can be described as a mass-spectrometer for Fast Ion providing discrimination of Energy (through gyro-orbit evaluation) and pitch angle of the collected fast ions. It can also be combined with photodiods or photomultiplier which can give information on fast-ion fluxes at higher temporal resolution. Collaboration to be activated, Max Planck Institüt für Plasmaphysik

Ion Energy Analyzer probe: This type of probe is presently under development in the framework of a European collaboration and it will combined with fast magnetic measurements giving the possibility for local investigation of the relation between magnetic fluctuations and fast ion fluxes

DLP: *directional langmuir probe* can be considered as an extension of the Mach probe for flow measurement and can be used in presence of population of fast ion induced by tangential beam. This diagnostic is relatively easy and can be rapidly implemented

Neutron Camera: Collimated Neutron Flux Camera for the measurement of the 2.45 MeV neutron emission from the D-D fusion reaction can be installed. They can provide spatial and time resolved volume integrated neutron emissivity in the presence of NBI heated plasmas [B20]. Possible collaboration to be activated University of Uppsala

To complement fast ion investigation a diagnostic for the determination of the current profile is mandatory, and in this framework the implementation of a Motional Stark Effect is suggested. The development, installation and exploitation of each of this diagnostic can be performed in the cycle of a PhD thesis, giving the student the possibility to gain deep insight on the experiment, and the possibility to contribute with the data obtain in a fascinating and cutting edge research. All the information gained by these diagnostic can be coupled with the already existing fluctuations diagnostic, as correlation ECE, Doppler Reflectometry and Tangential PCI which would give the fundamental information on the typical spatio-temporal scale of underlying turbulence. Such an ambitious experimental program must be tightly linked to the theory department of plasma physics of SPC. Indeed an effort is already in progress (see for example [B14, B21]) for the investigation of the fast ion dynamics but the proposed experimental program could provide the indispensable results to test and validate theoretical models. On this, development of synthetic diagnostics for proper interpretation of experimental data is foreseen and envisage as well as application of transport paradigm different from usual diffusion/convective one (non-diffusive, Levy Statistics etc. see for example [B18, B7]). This could strengthen the collaboration between experiment and theory department.

As a final remark, to highlight the Interdisciplinarity of the proposed research line it must be noted that fast ion studies on basic plasma devices is already ongoing in the basic plasma department. Apart from that a program for the establishment of an astrophysical plasma experiment is foreseen in the following year for the SPC. In within this program the study of energetic ion could represent a possible branch considering that ion acceleration is almost ubiquitous in astrophysical phenomena, from reconnection in the planet magnetosphere [B16] to shock waves driven outward by Coronal Mass Ejections (CMEs), and are observed because of termination shock at the outer edge of heliospheric cavity [B5]. Thus technology and expertise developed for the Tokamak experiment could be transferred in the view of a cross-fertilization between different branches of the plasma physics.

Concluding addressing the role of fast ion and its relation with turbulence media represents a research field of frontier in the plasma physics studies. It requires a deep knowledge of both plasma physics and non-linear dynamics, as multi-scale processes are involved and paradigm beyond simple diffusive processes must be considered. I'm convinced that my previous research on non-linear dynamics and fluctuations give me the proper background to tackle this subject even in within the novelty of the research. I'm convinced that the proposed plan will put the Swiss Plasma Center at the forefront in the plasma physics research, and I'm excited to the idea of possibly contributing to this.

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