Abstract – ITER International School 2023

Fast-ion distribution function affected by sawtooth oscillations

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This work analyzes the impact of sawtooth oscillations on the distribution function of alpha particles in tokamak plasma discharges. Similarly to the case of beam-induced distributions [1], a fast-ion distribution modified by sawtooth oscillations with a period shorter than the slowing down time, i.e. $\tau_{saw}/\tau_s > 1$, may represent a source of free energy for the destabilization of otherwise-stable modes that require an $\partial F/\partial E > 0$, like those characterized by toroidal mode number n=0 [2], as suggested by recent experimental results [3].
It has been shown that fast ions characterized by high energies, like fusion alphas, may not undergo a strong spatial redistribution after sawtooth crashes [4,5]. Thus, here we focus only on the velocity space distribution of the alpha particles and show how two effects, directly induced by the temperature drop associated with a sawtooth crash, may affect the distribution function. Firstly, modulation of the particle source on the sawtooth period timescale is induced, as the fusion yield drops together with the temperature. The second effect is associated with the growth of the slowing down time during the sawtooth ramp. Therefore, particles born in the later stages of the sawtooth cycle will experience less slowing down with respect to those born at the beginning of the cycle, leading to an accumulation-like mechanism at higher energies. We consider the Kadomtsev relaxation model [6] in order to describe analytically the plasma pressure evolution during sawtooth oscillations. The source term and the slowing down time in the Fokker-Plank equation describing the alpha particles will follow the temperature evolution coming from the reconnection model. Within this framework, a periodic time-dependent distribution function is obtained analytically. Due to the combination of the two effects discussed above, the shape of the alpha energy distribution may strongly vary from the standard slowing down distribution function, and a positive derivative in energy can be produced.

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Coupling a kinetic description of relativistic electrons to the fluid equations in the non-linear MHD code JOREK

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Abstract. In spite of all the promise that fusion energy holds, there are several obstacles that one must overcome before commercially viable fusion reactors can be realized. One issue that looks to be ever more prominent in future tokamak reactor designs such as ITER is the type of operational failure known as disruptions, triggered by a sudden loss of plasma confinement. During these off-normal events it is possible for electrons to be accelerated towards relativistic velocities. These highly energetic particles could then accumulate and strike the wall, causing sub-surface melting which is difficult to repair. As such, disruption events could potentially put reactors out of commission for extended periods of time, which cannot be tolerated. In order to fully understand the evolution and consequences of disruptions it is vital that the dynamics of the relativistic electrons are studied in detail, which includes aspects such as how they are generated, to what extent they interact with the bulk plasma, what the transport looks like and where they eventually strike the wall. This work aims to answer these questions by extending the non-linear MHD code JOREK to kinetic particle-in-cell treatment for the phase-space evolution of relativistic electrons. Furthermore, by projecting fluid quantities onto the finite element grid a two-way coupling scheme is obtained in which the particles and the bulk plasma evolve co-dependently.

Keywords: runaway electron, ITER, disruption, MHD, particle-in-cell

Alpha Particle Losses in JET's DTE2 Campaign

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This report presents alpha loss measurements and analysis from JET's 2021-2022 DTE2 campaign. Measurements of fast ion losses were provided from two fast ion loss detectors (FILDs): a scintillator probe which is capable of resolving lost ion pitch and gyroradius at a single geometric location, and a Faraday cup array composed of multiple cups that span a wide poloidal angle at a single toroidal position with a small radial extent. A database of pulses was created from JET baseline scenarios and the "afterglow" and bump-on tail energetic particle experiments. Alpha particle losses were recorded from both coherent (NTMs, kinks, fishbones, etc.) and non-coherent sources (ELMs and sawteeth). In particular, coherent losses with low frequency (<100 kHz) MHD were strongly observed. Since DT interactions are much more likely than additional DD and TT interactions, the bulk neutron rate was used as a proxy for the 3.5 MeV alpha production and an estimate of the alpha loss fraction was determined to be a maximum of 2-3% due to coherent, low frequency, MHD activity. A strong poloidal dependence was also observed and appears to peak around 25 degrees below the midplane. The radial trend is relatively flat and is consistent with the Faraday cup spacing being less than the typical alpha particle gyroradius (10-12 cm). A clear spatial trend is apparent in the poloidal direction. Additionally, scintillator probe loss footprints show preferential losses in pitch-space. First orbit, prompt, losses have also been detected and are consistent with reverse orbit trajectory integration. Analysis for higher frequency Alfven eigenmode induced losses is ongoing along with numerical validation studies.

Acknowledgements

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Poster abstract

Gyrokinetic study of transport in the Scrape-Off Layer with SPARC-relevant parameters

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As fusion devices approach reactor-scale conditions, it is crucial to manage the heat poured into its walls and divertor. Due to the high temperatures of burning plasmas, fluid theory becomes unreliable not only in the core, but also in boundary plasmas. For this reason, first-principles gyrokinetic theory and modeling is important for understanding turbulent transport from the core to the edge and scrape-off layer (SOL) of burning-plasma reactors. This poster will present results obtained using the gyrokinetic code *Gkeyll* to perform simulations in a simple-model helical geometry with SPARC's characteristic magnetic field, temperature and density. In this project, we study the dependance of the temperature, density and divertor heat flux profiles on the magnetic configuration and simulation parameters. As the pitch angle of the magnetic field lines in the SOL is decreased, it is expected that the interchange stability driving transport across the field lines is enhanced and the characteristic time of transport along the field lines increases as well. Analytical work and numerical simulations support the conclusion that this results in broader profiles and a larger pressure gradient scale length, which could help to spread the heat load along the divertor plates. In addition, we study the dependance on the simulation box radial length to observe how our boundary conditions affect the decay lengths of the profiles. Ongoing work includes evaluating the driving terms from gyrokinetic equations with the objective of deriving a scaling law for the pressure decay length of the SOL, and comparing it with previous predictions from fluid theory and modeling.

Ion cyclotron emission dependence on the evanescent layer and fast ion density in the DIII- D tokamak

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Diagnosis of the fast ion population, which is necessary for heating but can drive dangerous instabilities, is crucial in achieving and maintaining a burning plasma regime. Present fast ion diagnostic methods tend to rely on delicate components unlikely to survive in a reactor environment, motivating exploration into alternative diagnostic methods. One such candidate entails measurement of collective ion cyclotron emission (ICE) spectra via robust magnetic pickup loops integrated with the first wall, making it potentially compatible with ITER and other reactor-relevant devices. Recent Ph.D. thesis work [1] undertaken on the DIII-D tokamak aimed to characterize ICE mode structure and phenomenology in L- and H-mode plasmas using the ICE diagnostic, which was upgraded to include additional channels and consequently new measurement capabilities [2]. Since, these upgrades have enabled investigations regarding the relative impacts of fast ion distribution characteristics and shifts in plasma location on ICE frequency, amplitude, and mode structure. Simultaneously, investigating how the size of the vacuum region between the plasma and the pickup loops affects the aforementioned ICE mode properties may inform evaluations of diagnostic sensitivity in future devices. Disentangling these effects may help to reconcile experimental observations with synthetic diagnostic measurements in future modeling efforts. This work aims to characterize at least some of these effects and motivate further investigations in both DIII-D and future devices.

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ABSTRACT

Stabilization of sawtooth instability by short gas pulse injection in ADITYA-U Tokamak

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The sawtooth instability [1] in tokamak plasma results in periodic relaxations of the core plasma density and temperature. Observation of sawtooth oscillations in soft-X ray signals coming from plasma core is very common in Aditya-U tokamak. A typical sawtooth cycle consists of three phases: A ramp phase, precursor phase with growth of internal kink mode [2] and fast collapse phase. Enhancement of sawtooth ramp phase has been observed in Aditya-U tokamak after injection of short gas pulse (~1ms), which contain (0.2-1.2)*10^18 hydrogen or deuterium molecules, It has been observed that enhancement of sawtooth ramp phase is followed by the fall in edge density with each gas pulse. Growth rate of the low frequency oscillation riding on the sawtooth oscillation suppressed by the gas pulse. And a clear correlation between signals coming from mirnov probes and the oscillation present in sawtooth has been found. This study will show how the gas pulse injection effect the dynamics of the internal kink mode and its non-linear coupling with other resistive mhd modes[3].

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Turbulence suppression by fast ions in the KSTAR internal transport barrier (ITB) plasma with a high fast ion fraction

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Fast ions generated from fusion reactions will play a crucial role in sustaining the future burning plasmas. Therefore, understanding the effects of fast ions in fusion plasmas is important. It has been shown that fast ions can also affect turbulence by various mechanisms including the increased pressure gradient [1], changed zonal flow level [2], and dilution effects [3]. In this presentation, we investigated the turbulence suppression mechanisms by fast ions in one KSTAR internal transport barrier (ITB) plasma with a high fast ion fraction through the gyrokinetic simulation. Gyrokinetic simulation results show that the thermal energy fluxes are reduced significantly when fast ion species is included. Comparing the effect of each mechanism, among increased pressure gradient, dilution effects, and changed zonal flow level, on the reduction of thermal energy flux levels predicted by the gyrokinetic simulation, it turned out that the dominant mechanism of turbulence suppression by fast ions in this discharge is the dilution effects. In addition, we also separate two dilution effects, which are the reduced main ion fraction and changes in the main ion density gradient, and each dilution effect on turbulence suppression is evaluated. We found that the effect of change in the main ion density gradient, which was inverted in this discharge, on turbulence suppression were significant and sufficient for ITB formation.

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This study was supported by the R&D Program of the KSTAR Experimental Collaboration and Fusion Plasma Research (EN2101-12), and the Korea institute of Fusion Energy (N05220017). The computing resource supporting this study was provided by the National Supercomputing Center with supercomputing resources including technical support (KSC-2022-CRE-0161).

Keywords: fast ions, turbulence, dilution, internal transport barrier, gyrokinetic

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Study of current spike in tokamak disruptions using simulations (Abstract)

Modeling of disruptions and runaway electrons is crucial for the safe operation of fusion reactors. However, creating conditions representative of disruptions in reactor-scale devices in current experiments is not possible, calling for the development of reliable and validated simulation tools. The validation requires the knowledge of plasma parameters during disruptions, but they are poorly constrained due to the rapid timescales.

In this work, we simulate the total plasma current evolution to better constrain some of the parameters, such as the assimilated fraction of material during massive gas injection, the heat diffusivity and the hyperdiffusivity[1] of current density, that is responsible for the current density flattening and the associated current spike[2]. To find the optimal values of the free parameters, Bayesian optimization was employed, which has proven to be efficient for multi-parameter optimization, based on the numerical framework developed by Järvinen et al.[3]

Our results show that the time scale of the injection and transport of argon cannot be neglected compared to the time scales of current and temperature evolution. We were able to successfully constrain the amount of assimilated argon, the hyperdiffusivity, and the time scale of argon assimilation, but obtained surprisingly small values for the magnetic perturbation amplitude characterizing the temperature evolution, with double minima.

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First Fluctuation Measurements using Imaging Neutral Particle Analyzer on DIII-D

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An upgrade to the Imaging Neutral Particle Analyzer (INPA) on DIII-D to include high temporal resolution (1 MS/s) measurements has been tested with its first measurement of a Neoclassical Tearing Mode (NTM). The passing INPA was able to detect the m/n = 2/1 mode and a 3/2 harmonic while the mode locked over a period of 150 ms. Analysis shows that the signals come from passive charge exchange (CX) events at the plasma edge. Contributions to the signal come from both the slowing down distribution of beam ions as well as prompt CX events from multiple neutral beam sources. Further upgrades to the INPA are underway to improve the pitch and energy resolution of fluctuation measurements.

Numerical simulations of the Radio Frequency Plasma Interaction Experiment at ORNL using the hPIC2 and RustBCA codes

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Abstract

In this work, we performed a numerical characterization of the ion dynamics involved in the Radio Frequency Plasma Interaction Experiment (RF-PIE) at Oak Ridge National Laboratory (ORNL) using the hPIC2 Particle-in-Cell code and the RustBCA ion-surface interaction code. The RF-PIE experiment consists of a cylindrical magnetized plasma chamber with an RF-biased electrode on one side of the chamber, which is used to characterize impurity emission from selected plasma-facing components. We analyzed a helium plasma impacting on a W substrate under typical RF-PIE conditions ($n_e = 6 \times 10^{17} \mathrm{m}^{-3}$ and $T_e = 4.5$ eV) to explore the sheath and material release under controlled conditions. To analyze the ion energy-angle distribution (IEAD) as a function of DC bias and RF voltage in the range of 100V-500V relevant for RF sheath rectification, we performed a parametric scan using hPIC2. The resulting IEADs showed the typical two-peak energy structure of RF sheaths with a linear broadening due to the increase in DC bias. As expected, we observed a high concentration of ions centered at impact angles $\theta \approx 0$ for all analyzed cases. We used the RustBCA code to analyze the sputtering behavior of the tungsten electrode. This code can accept distribution functions from the hPIC2 codes as an input. We characterized the W impurity release as a function of biasing conditions for direct comparison with experimental measurements.

Alfvén eigenmode detection using Machine Learning Methods and CO_2 Interferometer data on DIII-D

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The primary objective of this paper is to compare machine learning models that use CO_2 interferometer data and a labelled database to classify Alfvén eigenmodes on the DIII-D tokamak. Understanding fast-ion physics is important for the success of planned burning plasma devices such as ITER, since fast ions can resonate with Alfvén eigenmodes (AE), transfer energy to the wave and degrade the performance of the plasma or damage the inner walls of a fusion device. Machine Learning can be used to identify AEs and help mitigate these effects in real-time detection and control algorithms during steady-state plasma scenarios. The weights of two Recurrent Neural Network-based models (RCN and LSTM) are trained separately from scratch using simple magnitude and crosspower spectrogram representations of the CO_2 phase data. All CO_2 chords are used to train both models, but only one chord is processed during each training step. The results from the model and data comparison show high performance for the LSTM and RCN model (True Positive Rate $> 91\%$ and False Positive Rate $< 12\%$), and that using simple magnitude spectrograms is sufficient to detect AEs. Identification is slightly better for the vertical chord that passes closest to the magnetic axis. Correlations between LSTM predictions and the metadata for a subset of extremely well labelled "super shots" are also discussed. Supported by the U.S. Department of Energy under DE-FC02-04ER54698, DE-SC0021275, DE-SC0020337, DE-SC0014664, Army Research Office (ARO W911NF-19-1-0045), National Science Foundation under 1633631 and Ghent University Special Research Award No. BOF19/PDO/134.

Bayesian optimization of massive material injection for disruption mitigation in tokamaks

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One of the main issues threatening the success of future reactor-scale tokamaks is disruptions. It is the sudden loss of confinement where the plasma rapidly dissipates its energy onto the surrounding structures, exposing the device to excessive mechanical stress and heat loads. In addition, an electric field is induced that can accelerate a significant fraction of the electrons to relativistic energies, giving rise to runaway electrons (REs). Unmitigated disruptions could potentially cause severe damage to the device and, thus, modeling such events is crucial for being able to assess the effectiveness of various mitigation techniques.

Using the numerical RE modeling framework DREAM [Hoppe CPC 2021], we study the effects massive material injection (MMI) of deuterium and neon has on disrupting plasma representative of ITER, particularly the RE generation and the dissipation of its energy content. We self-consistently evolve the electric field, ion charge state densities, thermal electron temperature and density as well as the RE density in a flux surface-averaged fluid description of the plasma. This model is used together with a Bayesian optimisation tool to find suitable MMI parameters that minimise potential damage to the device.

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Spectroscopic Diagnostic of Periodic Fields in Edge Plasmas

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The study of atom and ion spectra in plasmas revealed the existence of various complex signatures resulting from the effect of periodic fields [1]. These fields may be created by the collective behavior of non-thermal plasmas or by external sources, such as microwave generators. Radio-frequency (rf) waves have long been used to heat plasmas in various devices. In tokamak plasmas rf waves are also used for the current drive, with e.g. electron cyclotron wave heating and current drive developed for a steady state operation of ITER [2]. Spectroscopy can provide a local and in real time diagnostic of the plasma and wave parameters. Hydrogen line shapes have been used for in situ measurements of rf wave field in the region where it is coupled to the plasma [3]. For a tokamak like ITER, this requires a modeling retaining the simultaneous effect of electrons, ions and the periodic wave on the hydrogen emitter. We here present computer simulations combining the electric field resulting from the motion of charged particles in a cubic box with the periodic field, and providing a numerical solution of the hydrogen emitter Schrödinger equation. We will present hydrogen line shapes of the first Lyman and Balmer lines for electric field magnitudes of the periodic field which are of the order of or larger than the mean plasma microfield in edge plasma conditions. We shall discuss how the observed changes in the line shape can be used to diagnose simultaneously the plasma and periodic field parameters.

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Towards Real-Time Control of Alfvén Eigenmodes at DIII-D Using Data-Driven Models and High-Resolution Diagnostics

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Abstract

We have previously developed a data-driven model based on reservoir computing networks (RCNs) to detect, classify, and localize Alfvén eigenmodes in a database of over 1000 DIII-D discharges. The model looks at 40 Electron Cyclotron Emission (ECE) signals, sampled at 500kHz, to distinguish AE activities such as Low-frequency modes (LFMs), Beta-induced Alfvén eigenmodes (BAE), Reversed-Shear Alfvén eigenmodes (RSAE), and Toroidal Alfvén eigenmodes (TAE).

Here, we report on follow-up research to develop multimodal machine learning models to predict and control the AE modes based on the current plasma profiles, diagnostics, and actuators. The model is trained on various input data such as ECE, neutrons rate, electron density, plasma pressure, injected neutral beam power and ECH. Our preliminary results show the potential of the proposed model in predicting the probability of pronounced AE activities 200ms in advance. To control the AE activities in real-time, such a model can be used to tune the actuator values by predicting the evolution of AE modes based on the current plasma conditions and different proposals for actuator values.

The models are being deployed for integration in the DIII-D plasma control system (PCS) to be tested in the upcoming experiments campaign.

Keywords: Alfvén eigenmodes, Machine learning, Electron cyclotron emission, DIII-D, Image Processing

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Development of a scintillator based fast-ion loss detector for the Wendelstein 7-X stellarator

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A primary scientific goal of the Wendelstein 7-X stellarator (W7-X) is to demonstrate improved fast-ion confinement for this type of fusion reactor. W7-X therefore requires diagnostics capable of inferring the fast-ion confinement properties of the device. Fast-ion loss detectors (FILD) are especially well suited for this purpose. In particular, scintillator based FILDs [1, 2] provide the capability of obtaining time-resolved velocity-space measurements of the escaping fast-ions. Furthermore, these detectors offer high signal-to-noise ratios (SNR) allowing for high speed measurements and the ability to infer losses due to magnetohydrodynamic instabilities.

In this contribution we will present the design and development of a scintillator based FILD system for W7-X. The mechanical design of the new so-called sFILD diagnostic will be presented along with a mechanical analyses of the structural and electromagnetic loads expected on the diagnostic. Furthermore, an analysis of the thermal characteristics of the actively cooled sFILD probe head will be presented. Finally, the expected measurement performance of the diagnostic based on the characteristics of the embedded optical relay system and ASCOT5 [3] predicted losses will be presented. Here, the FILDSIM code [4] will be used to determine the instrument response function of the detector and used to calculate synthetic signals via forward modelling. To determine the expected SNR various noise contributions such as photon, camera readout and neutron induced noise will also be modelled.

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A Framework for Synthetic Diagnostics using Energetic-particle Orbits in Tokamaks

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In fusion plasma physics, the large-scale trajectories of energetic particles in magnetic confinement devices are known as drift orbits, or simply orbits. To effectively be able to work with orbits, the Orbit Weight Computational Framework (OWCF) was developed. The framework is comprised of a set of scripts and function libraries capable of computing, visualizing and working with quantities related to orbits in tokamaks, e.g. orbit weight functions. The OWCF is modular in the way that any synthetic diagnostic code can be easily integrated to compute new types of weight functions. The framework can also compute projected velocity spectra for orbits. Furthermore, the OWCF can work with any magnetic equilibrium file used by the TRANSP code, as well as any user-specified Solov'ev magnetic equilibrium. The framework also provides interactive applications that can be used both as tools for investigative research as well as for intuitive teaching. These can be used to analyze and simulate the diagnostic results of current and future fusion experiments such as ITER. The OWCF fascilitates the reconstruction of the fast-ion distribution from measurements via tomographic inversion, by streamlining the computation of orbit weight functions and related quantities.

Structure-preserving Hybrid Code, STRUPHY: Energy-conserving Hybrid MHD-driftkinetic Models

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STRUPHY (STRUcture-Preserving HYbrid codes [2]) is a Python package for the simulation of energetic particles (EPs) in plasma. The package features a collection of PDE solvers for hybrid fluid-kinetic systems in curved three-dimensional spaces where the bulk plasma is treated as a fluid and the EPs are described kinetically (Particle-In-Cell method). The discretization is based on the GEMPIC [3] framework. We will introduce energy-conserving hybrid MHD-driftkinetic models which were newly implemented in STRUPHY. Existing hybrid MHD-kinetic models often suffer from not conserving the total energy, especially when reduced kinetic models are used to describe EPs such as driftkinetic or gyrokinetic. However, this property was recently recovered by adding additional terms derived from variational principles [4][1]. The investigation of the conservation laws on the discrete level will be considered with some simulation results.

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Weight functions for orbit tomography based on projected velocities in constants-of-motion space

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It is of vital importance to understand the behaviour of energetic particles in fusion plasmas in the pursuit of realising fusion power as a reliable energy source. For this matter, tomographic reconstruction of fast-ion distribution functions in fusion plasma devices has proven to be a useful tool for extracting information about the fast-ions, as well as helping the practical utilisation of diagnostics. In general, a diagnostic signal is related to the fast-ion distribution by a so-called weight function, which quantifies the phase-space sensitivity of the given diagnostic. Weight functions have been developed for several types of diagnostics in velocity-space coordinates.

In this work, we numerically calculate fast-ion orbit weight functions in constants-of-motion coordinates, the energy E, the toroidal canonical angular momentum P_ϕ and the magnetic moment μ. This is done using the projected velocities of fast-ions along the lines of sight, which acts as a proxy for several spectral diagnostics. This allows us to quickly and easily test new inversion methods for tomographic reconstruction. Also, knowledge of the origin of the observed sensitivity patterns in the constants-of-motion space is expected to be useful in the future study of energetic particles. In addition to this, calculating the orbit weight functions in the constants-of-motion coordinates, provides a direct link to the stability analysis often done in constants-of-motion space.

Here a detailed explanation of the sensitivity patterns seen in the weight functions given different viewing angles and measurement volumes is provided, and the methods will be applied to fast-ion systems from MAST- and COMPASS-Upgrade.

Development of synthetic diagnostics for Fast Ion Loss Detection systems in Wendelstein 7-X

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In this work, a method is outlined for simulating signals to fast ion loss detectors (FILDs) in Wendelstein 7-X (W7-X), including those currently operating—the Faraday cup FILD (FC-FILD) and the FILD provided by the National Institute for Fusion Science (NIFS-FILD)—as well as the scintillating FILD (S-FILD), which is currently under development.

The confinement of fast ions is one of the primary targets of the optimization of W7-X. The heating systems of W7-X include 55 keV hydrogen neutral beam injection (NBI), which produces ions with normalized Larmor radii equivalent to those of 3.5 MeV alpha particles in a HELIAS-type reactor. As such, information about the success of this optimization can be gleaned by measuring the confinement of these NBI-produced fast ions with diagnostics such as FILDs, which can often measure not only fast ion loads but also their energy and pitch angle. Accurate simulation of their expected signals is necessary both to design FILDs that are sensitive to the expected fast ion distributions in W7-X as well as to compare measured losses to predicted confinement.

Using the Monte Carlo codes BEAMS3D and ASCOT5, markers representing NBI ions are followed from injection to a plane of constant toroidal angle near the chosen FILD. Simultaneously, simulations in ASCOT5 and FILDSIM are used to determine a probability matrix, binned by normalized energy, pitch angle, and gyrophase, for transmission from the plane, through the aperture of the FILD, and onto the sensor. This probability matrix is then convoluted with the simulated markers reaching the plane, allowing the FILD signal, including the position of ion strikes from which energy and pitch angle can be inferred, to be predicted from a relatively small number of markers. Simulated signals will be presented covering a range of W7-X experimental conditions.

First ERO 2.0 simulations of liquid metal transport and redeposition from divertor of COMPASS Upgrade

Abstract

The COMPASS Upgrade tokamak will be a medium-sized tokamak that, thanks to its large magnetic field (5 T on-axis) and high plasma density ($\sim 10^{20}\ m^{-3}$), will achieve heat fluxes relevant to DEMO reactor. Along with DEMO-like plasma geometry and tungsten plasma-facing components (high heat flux regions made of bulk tungsten tiles and others probably coated with tungsten), COMPASS-U will provide crucial answers (among many others) to sustainable plasma power exhaust of future fusion power plants.

Technologies using liquid metals (lithium, tin, or their combination) will be one of the heat shields tested. Either as individual capillary porous tiles inserted into divertor region using a dedicated material-testing manipulator or as a proposed & submitted larger project of a fully toroidal liquid metal divertor.

For both cases, simulations clarifying the transport of vaporized liquid metal in the plasma scrape-off layer and its redeposition on the surrounding components are necessary. The results will contribute to questioning the real long-term applicability of liquid metals as heat shields. The first set of simulations were performed using the massively parallelizable 3D Monte Carlo code ERO 2.0 and the results and future plans are discussed.

Study of TAE effects on the global confinement in TCV L-mode plasmas

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In present and future tokamaks, the ever-present fast ions can destabilize several kind of instabilities, among which the fast-ion-driven Alfvén Eigenmodes (AEs) are one of the most studied. These instabilities are a major issue for fusion reactors since they can cause losses of the main heating source and therefore to a degradation of the plasma performance. Additionally, Toroidal Alfvén Eigenmodes (TAEs) are expected to be destabilized in ITER [1], and therefore it is crucial to determine their effects not only on the fast-ion confinement, but also directly on the bulk plasma characteristics.

Nevertheless, it has been pointed out that fast-ion-driven TAEs can have a beneficial impact on the ion-scale turbulent transport [2] by triggering a complex mechanism involving nonlinear coupling between TAE waves and zonal component of both electrostatic and magnetic potential [3]. More recent studies validated such a complex mechanism against JET experimental results of improved ion thermal confinement in the three-ion heating scheme scenario [4].

Recent observations of unstable Toroidal Alfvén Eigenmode (TAE) in counter-current Neutral Beam Injection (NBI) scenario developed in TCV [5] offer the possibility for in-depth analyses on the impact of such modes on the global plasma confinement and performance, building thus a parallel with the analysis at JET [4]. The present study shows experimental evidence of improved global confinement in the presence of unstable Toroidal Alfvén Eigenmodes (TAEs) driven by fast ions generated through Neutral Beam Injection heating system. Together with the TAEs, diverse instabilities associated with the injection of the fast neutrals are observed by multiple diagnostics, and a first characterization is given. Nonlinear wave-wave couplings are also detected through multi-mode analysis, revealing a complex picture of the stability dynamics of the TCV scenario at hand. Detailed and advanced studies on the measurements provided by the Short-pulse Reflectometer corroborate the identification and radial localization of the instabilities. Preliminary, but not conclusive, analysis on the impact of TAEs on the amplitude of the electron density fluctuations are carried out. Exploratory numerical gyrokinetic analyses are eventually carried out and reported in this contribution, showing however that the local approximation employed in such analyses is not valid for the specific plasma conditions developed in a specific pulse of this TCV scenario. This is due to the large ratio between the fast-ion Larmor radius and the size of the TCV device, invalidating therefore the inherent assumption of the local gyrokinetic approximation.

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Optical collection lens design for KSTAR divertor Thomson Scattering

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In this study, we report on the Divertor Thomson Collection Lens Systems used in the Korea superconducting advanced research (KSTAR) Thomson scattering (TS) diagnostic system. TS diagnostics is one of the plasma diagnostic methods that analyzes the density and temperature of electrons from light emitted through the interaction between ionized free electrons and a laser beam. KSTAR uses various plasma diagnostic systems, and among them, a tangential TS diagnostic system using a 1064nm laser is currently in operation. Recently, KSTAR is in the process of replacing the tungsten divertor, and we are planning the divertor TS diagnostics to perform plasma diagnosis on the divertor X point area. We investigated an appropriate lens system and conducted optical design to plan a collection lens system that allows TS diagnostics to be performed for the area where the laser and the X point inside the KSTAR tokamak intersect.

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Energetic particle modelling using simplified continuum Vlasov Maxwell model

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Abstract

The energetic electrons accelerated by parallel electric fields well known as runaways in a tokamak disruption event, whistlers interacting with energetic electrons are the key players in the realm of mitigation of fast electrons in tokamak disruption events. Recent experimental observation[1] on fusion plasma experiments shows that there is a cut off in torodial magnetic field below which there should not be any runaways. The faster primary runaways produce a secondary runaway beam having an avalanche like nonthermal velocity distribution. To analyse this kind of beams we have modelled the parallel propagating whistlers using self cosistence Vlasov equation coupled to the Maxwell's equations using three point finite difference technique with nonlinear flux corrected transport algorithm. Presented simulation involves the interaction of whistler with anisotropic beam and the variation of growth of whistler by external magnetic field. The phase space dynamics of coherent structure of the beam plasma system will be presented.

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The interplay between energetic particles and type-I ELMs in different collisionality regimes

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The high confinement mode (H-mode) is one of the foreseen operational scenarios for future fusion devices like ITER due to its higher energy content and larger confinement time than the standard low confinement mode (L-mode) [1]. However, it has been widely reported experimentally that the high gradient edge region can suffer from cyclic instabilities that reduce the overall confinement for H-mode operation. This instability is the so-called Edge Localized Modes (ELMs) which has to be prevented since the large heat loads expelled towards the wall during the ELM crash can damage critically the Plasma Facing Components (PFCs). The ELMs further lead to the undesired expel of supra-thermal ions damaging the PFCs. The interplay between the supra-thermal ions and the ELMs can also lead to a net power transfer which can result in the acceleration of the NBI fast ion population [2]. This interplay has been preliminary reproduced numerically in the non-linear hybrid kinetic code MEGA for the AUG tokamak, which also predicts a reduction of the supra-thermal ion energy [3]. These simulations further predict a change in the magnetic fluctuations measured with the magnetic coils as well as in the radial penetration of the ELMs. All these features have been reported experimentally on the TCV tokamak showing a key dependence on the plasma collisionality. In low-density H-mode plasmas, both the ECE and SXR diagnostics report further radial penetration of the ELMs crash into the plasma. Likewise, it has been observed a change in the magnetic coil spectrogram frequency range for different plasma collisionality regimes. The supra-thermal ion losses have been measured with the TCV-FILD. During the ELM crash, an increment of the losses is clearly observed independently of the plasma collisionality. However, only in the low-collisionality plasmas, a supra-thermal ion population with lower energies than the NBI primary injection one is observed. These losses exhibit a wide range in pitch $(v_{\parallel}/v)$ which can indicate different initial radial locations of the lost ion population. Furthermore, the FILD spectrogram shows a clear footprint during the ELM crash which, contrary to the one of the magnetic coils, is localized in specific frequency ranges (<50, 120 and 170 kHz). The frequency-resolved components in the supra-thermal ion losses are only present in the low and medium collisionality plasmas whereas, in the high collisionality cases, there is not any resolved footprint in the FILD spectrogram. Preliminary simulations with the ASCOT5 code provide information on the NBI prompt and scattering losses contribution before and after the ELM crash which helps to isolate the ELM crash contribution in the different plasma scenarios.

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The investigation of Alfven eigenmodes excited by energetic particles using the Doppler backscattering method on the spherical Globus-M2 tokamak

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Keywords: Doppler backscattering, plasma diagnostics, tokamak, energetic particles, Alfven eigenmodes

On the upgraded spherical Globus-M2 tokamak the values of the magnetic field up to 1 T, plasma current up to 0.5 kA, higher electron density and new auxiliary heating conditions of neutral beam injection (NBI) led to the development of many types of Alfven eigenmodes (AEs) excited by energetic particles. They degrade energetic ion confinement and lead to fast ion losses.

For example, Alfven cascades (ACs) would develop at an early stage of the discharge when the NBI is injected during the growth of the plasma current and a reversed shear of the magnetic field appears. They are characterized by their frequency increase along with the growth of the plasma current. Analysis showed that the twofold growth of the magnetic field could have played the key role in providing the conditions necessary for the development of the ACs that had not been seen on the previous Globus-M tokamak [1].

Also, toroidal Alfven eigenmodes (TAEs) similar to those observed in previous experiments on Globus-M developed under the new conditions on Globus-M2 [2]. They can be seen in the form of chirping instabilities lasting from 0.1 up to 1 ms. TAE–related transport and losses were observed by multiple diagnostics. It was also found that the dependence of the fast ion losses on the amplitude of TAE is predominantly linear, as shown by experimental data and numerical modelling.

Apart from that, AEs with higher frequencies over 300 kHz spanning from 10 to 20 ms could sometimes be found at a late stage of plasma heating. These were understood to be Doppler shifted TAEs due to the fact that their frequency showed a dependency on the frequency of the plasma rotation. Their development indicated that there was significant toroidal plasma rotation on Globus-M2 that could also be estimated using the characteristics of the Doppler shifted TAE. A decrease of fast ion transport and losses compared to TAEs was observed during these modes.

The Doppler backscattering (DBS) method was used alongside magnetic probes for the detection of AEs on Globus-M2. The measurements allowed to calculate various properties of the AEs, such as their magnetic field amplitude and localization. Several multifrequency DBS systems were used to study the area of AE development [3-4]. The available probing frequencies ranging from 20 to 65 GHz covered different plasma regions of Globus-M2 and allowed to obtain the spatial distribution of AE amplitude.

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Experimental Comparisons and Analysis of MAST-U Solid State Neutral Particle Analyzer Data with Synthetic Diagnostic Signals

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A solid state neutral particle analyzer (SSNPA) [1] diagnostic oriented to measure trapped ions and a tangentially viewing fast-ion deuterium alpha (FIDA) [2] diagnostic that measures mainly passing fast ions operates in Mega Amp Spherical Tokamak Upgrade (MAST-U). A dedicated experiment designed to validate the SSNPA system in MHD-quiescent discharges was performed in the second MAST-U science campaign. This experiment yielded excellent baseline results with repeated shots using multiple NBI duty cycles. Similar experiments were also used to validate SSNPA performance across a wider range of plasma conditions, including different plasma currents, densities and NBI energies. A careful analysis of the instrumental results has been performed. Additionally, synthetic diagnostic signals have been computed using the FIDASIM[3] and SRIM[4] codes and deviations between synthetic and instrumental results are explored in this work. Active diagnostics show evidence of fast ion transport during Alfven wave and MHD activity. The phase space sensitivity of the SSNPA and thus the capacity it provides to diagnose the fast-ion population is discussed.

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12th ITER International School Poster abstract

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Ion cyclotron emission (ICE) is regularly observed in magnetic confinement fusion (MCF) experiments, both tokamaks [1] and stellarators [2]. The electromagnetic radiation is suprathermal and is often spectrally structured, consisting of narrow peaks at sequential cyclotron harmonics of a fast ion population. In particular, ICE was reported from JET [3] and TFTR [4] DT plasmas, driven by 3.5 MeV alpha particles. Energetic populations arising from neutral-beam injection (NBI) and ion cyclotron resonance heating (ICRH) also generate ICE. The distribution function of these fast ions is typically characterised by an anisotropy in velocity space at the emission location. In this poster, we present hybrid particle-in-cell (PIC) simulations [5] of the magnetoacoustic cyclotron instability [6] which results from the resonance between a fast-Alfvén wave supported by the thermal plasma and cyclotron waves generated by the minority fast ions [7]. We apply the velocity-space tomography method [8] which has been successfully applied to several diagnostics in MCF, such as collective Thomson scattering (CTS), fast ion D_α (FIDA), fast-ion lost detector (FILD), neutron emission spectrometry (NES) as well as gamma-ray spectroscopy (GRS). To that purpose, an inverse problem is posed which allows to reconstruct the velocity space distribution function of the fast ions based on measurements/calculations. We first compute synthetic power spectra from a large set of simulations to obtain the weight functions that in turn allow to determine the fast-ion distribution function [9]. Obtaining a reliable forward model of ion cyclotron emission [10] is important to enable predictive capabilities as this would allow to exploit ICE as a fast ion diagnostic in ITER [11].

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Equilibrium and Plasma Reconstruction using Physics-Informed Neural Networks

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Abstract

In nuclear fusion reactors, reconstructing the local plasma properties, such as the density, temperature, and magnetic fields, is crucial for both the understanding of the physical phenomena and the control of the machine. Unfortunately, diagnostics can provide only a limited amount of information. In fact, most of them return only external measurements, such as magnetic probes or integrated ones, as the one provided by the interferometer, polarimeter, and bolometric measurements. In order to reconstruct the local information, inverse problems must be solved. Two typical examples are equilibrium reconstruction by the Grad-Shafranov equation and the emissivity reconstruction through tomographic inversion. However, such inverse problems usually need to make recourse to some assumptions, such as toroidal symmetry and steadiness. In this work, the possibility of using Physics-Informed Neural Networks (PINN) to reconstruct plasma properties is investigated. PINNs are a new artificial intelligence methodology allowing to train the neural network constraining it with physical equations and boundary conditions, without the need to know the target during the training phase. In this work, the method is applied to the equilibrium reconstruction problem. The physical prior information used is the one-fluid Magnetohydrodynamic (MHD) equations, and the algorithm is tested in 2D and 3D cases. The tests on numerical cases show that PINNs can provide very accurate results, opening up the possibility of reconstructing the plasma without the need of simplifying assumptions. Moreover, specific neural network architectures and training logics may be established to achieve accurate equilibrium reconstructions in real-time, which is indispensable for accurate control of the plasma.

Keywords: Equilibrium Reconstruction, Inverse Problems, Machine Learning, Nuclear Fusion, Physics-Informed Neural Network

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Poster Title

Observation of fast-ion driven Alfvén-eigenmodes in JET and their effect on turbulence and thermal transport

Abstract

Recent experiments using the 3-ion ICRH heating scheme [Kazakov NF 2015] have been successful at generating substantial populations of MeV range fast ions in the deep core of JET, mimicking the effect of fusion-born alpha particles in future burning plasmas. These fast ions are capable of destabilizing a wide range of Alfvén modes as observed using magnetics, reflectometer and Doppler backscattering measurements. Previous nonlinear gyrokinetic simulations have shown that turbulence existing at the ion-gyroradius scale can be stabilized [Mazzi Nat. Phys. 2022, PPCF 2022], producing close to neoclassical levels of ion heat flux. This results in a thermal transport regime dominated by the electron heat flux. We report on the transport and gyrokinetic modelling using GS2 and CGYRO in conditions when Alfvén eigenmodes are both stable and unstable, as observed from magnetics and Doppler backscattering fluctuation measurements. We probe the origins of the anomalous electron thermal transport in the presence of MeV range fast ions and unstable Alfvén eigenmodes. The implications of these scenarios to burning plasmas will be discussed.

Understanding argon impurity transport using visible and VUV spectroscopy in ADITYA-U Ohmic discharges

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Active impurity seeding is an efficient way to minimize the plasma-material interactions in terms of controlling the heatloads and heating of the peripheral materials through radiative power dissipation at the plasma boundary [1]. Also, the externally injected impurities directly influence various plasma parameters and overall plasma behavior. Argon is one of the effective radiation impurities on many tokamaks and is also an important candidate for ITER.

In that context, experiments on trace argon impurity transport in Ohmic discharges have been carried out on ADITYA-U tokamak [2]. Argon line emissions in visible and VUV range have been measured simultaneously using high resolution visible and VUV spectroscopic systems respectively [3]. During the experiments, space resolved brightness profile of Ar^{1+} line emissions in visible range at 472.68 nm ($3p^4 4s\ ^2P_{1.5}$ - $3p^4 4p\ ^2D_{1.5}$), 473.59 nm ($3p^4 4s\ ^4P_{2.5}$ - $3p^4 4p\ ^4P_{1.5}$), 476.48 nm ($3p^4 4s\ ^2P_{0.5}$ - $3p^4 4p\ ^2P_{1.5}$), 480.60 nm ($3p^4 4s\ ^4P_{2.5}$ - $3p^4 4p\ ^4P_{2.5}$) are recorded together with simultaneous measurements of VUV line emissions of Ar^{13+} at 18.79 nm ($2s^2 2p\ ^2P_{1.5}$ - $2s2p^2\ ^2P_{1.5}$) and Ar^{14+} at 22.11 nm ($2s^2\ ^1S_0$ - $2s2p\ ^1P_1$). The diffusivity and convective velocity of argon were calculated from the integrated use of these two spectroscopic diagnostics and the 1D impurity transport code STRAHL. Results confirm enhanced diffiusivity ~ 12 m^2/s in the edge and ~ 0.3 m^2/s in the core together with a strong inward convection of ~ 10 m/s thus resulting in the peaked profile of total argon density. Moreover, experimental diffusivity and convective velocity exceed their respective neoclassical estimations thus suggesting that argon impurity transport is mainly anomalous in nature in ADITYA-U plasma.

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MITIGATION AND SUPPRESSION OF ENERGETIC PARTICLES DRIVEN INSTABILITIES BY RADIO-FREQUENCY WAVES ON THE HL-2A TOKAMAK

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Energetic ions driven instabilities are usually weakly damped and have become a major concern in plasma physics since they can not only cause great ions losses but also degrade confinement of thermal plasma [1]. Series of measurements have been taken to monitor energetic ions driven instabilities on magnetic confined fusion devices. Feasibility of three-dimensional magnetic perturbation fields, outboard beam injection and electron cyclotron resonance heating/electron cyclotron current drive (ECRH/ECCD) on instability control has been verified. However, the underlying physical mechanisms are not well known due to its diversity. To get a better understanding, radio-frequency waves, namely electron cyclotron wave and lower hybrid wave are recently utilized to mitigate and suppress the energetic ions driven instabilities on HL-2A tokamak.

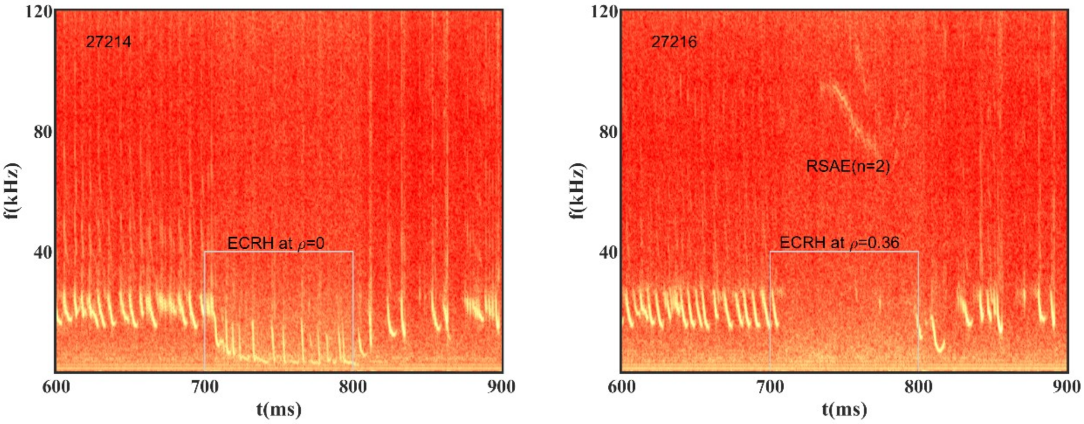

FIG.1. Fishbone activities during suppression experiments by electron cyclotron resonance heating with a same input power (0.95MW) and different deposition location of $\rho=0$ *(Left) and* $\rho=0.36$ *(right). The gray dotted curves are the injected power (×40) of ECRH.*

Stabilization of ion fishbone by electron cyclotron resonance heating (ECRH), was observed for the first time in a toroidal plasma. The interested achievements depend not only on the injected power but also on the radial deposition location of ECRH. On one hand, it is found that the higher input ECRH power, the better stabilization effect [2]. Analysis by the fishbone dispersion relation, including the resistive effect, suggests that the magnetic Reynolds number plays a key role in the mode stabilization. It weakens the mode growth rate and enhances the critical energetic ion beta without changing the energetic ion population. The theoretical result has been confirmed by NIMROD simulation and provides a plausible explanation for the experimental observation. On the one hand, the fishbone activity will be completely suppressed only in the phase of off-axis ECRH [3], as shown in FIG.1. Comparison experiments reveal that off-axis heating is more effective route for sustainable increasing of electron temperature, which regulates the evolution of total pressure and its gradient during ECRH. By altering the pressure gradient ($\nabla P = J \times B$, $J \wedge B$ are current and magnetic field), the perpendicularly injected electron cyclotron wave can also modify plasma current and then change safety factor or magnetic shear. Two down sweeping reversed shear Alfven eigenmodes with toroidal mode numbers of n=2, 3 can be observed when the fishbone mode is suppressed. The appearance of RSAE suggests that the minimum safety factor jumps above the unity [4] and it finally leads to the suppression of fishbone modes.

Mitigation of long-lived mode (LLM) by lower hybrid wave (LHW) is also achieved on the HL-2A tokamak [5]. The LLM changes from a typical steady-state to a fishbone-like frequency-chirping characteristic, and its higher poloidal harmonics disappear when LHW is injected into toroidal plasma. It is found that density fluctuation declines during this process while the total neutron count increases gradually. Those evidences indicate there is a mitigation effect of LHW on LLM, and the underlying mechanism can be explained as follows. On one hand, high power LHW firstly causes a drop in toroidal rotation and then results in decline of $E \times B$ shear, which is unfavorable for the maintenance of the internal transport barrier. The resulting relaxation of ion temperature gradient enhances thermal transport and leads to a drop of ion temperature at the core region. Thus, the plasma pressure becomes flattened and finally contributes to the mitigation of highly saturated internal mode. On the other hand, hybrid simulation by M3D-K suggests that the off-axis LHW can also reduce the grower rate of LLM via changing safety factor and magnetic shear.

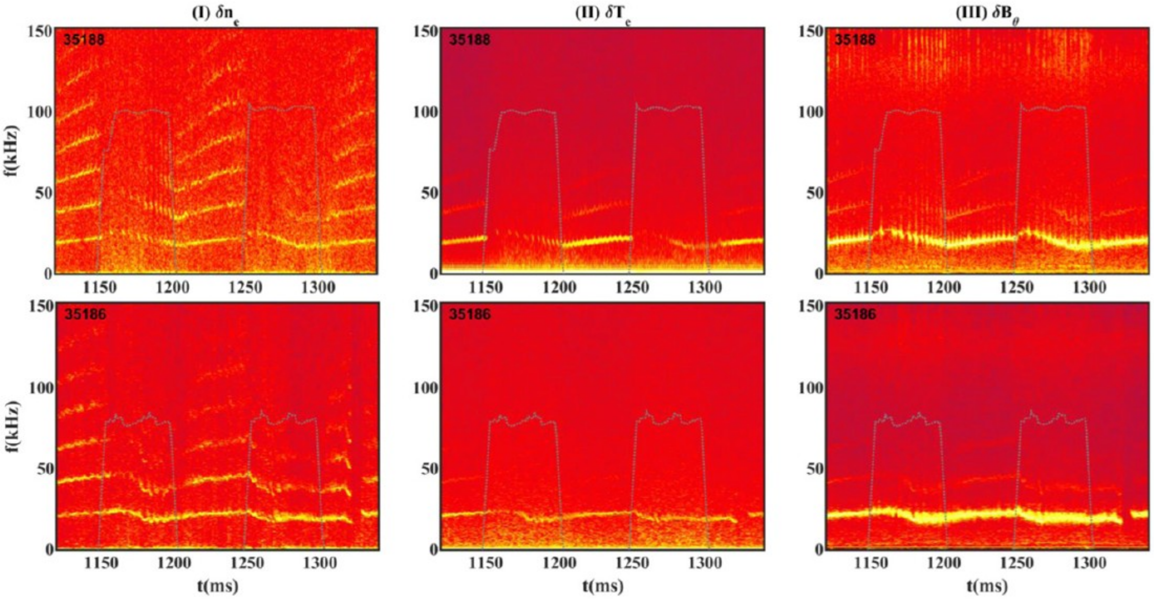

FIG.2. Evolution of (I) density fluctuation δne, (II) temperature fluctuation δTe and (III) magnetic fluctuation δB_θ *during long-lived mode mitigation experiments by lower hybrid wave. The gray dotted curves are the injected power (×100) of LHW.*

Mitigation and suppression of LLM and fishbone modes have been achieved on HL-2A tokamak, but we also note that both ECRH and LHW play a negative role in maintenance of ITB and degrade the plasms confinement. So an overall consideration for usage of radio-frequency waves to control energetic particle modes should be needed. Only in this way, we can optimize the contribution of those waves at instability mitigation and suppression and minimize its negative effects on plasma confinement. In other words, much more efforts are needed before the radio-frequency waves are used to active control of energetic ions driven instabilities on the future devices.

ACKNOWLEDGEMENTS

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ABSTRACT

Low frequency Zonal Flow in ADITYA-U tokamak

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Plasma turbulence is known to be one of the strong driving mechanisms of energy and particle transport degrading the plasma confinement in tokamaks. Hence, it is important to understand different physical processes which drive and control the turbulence. It has been observed that the self-generated axis-symmetric structures such as zonal flows play a key role in controlling the turbulence and associated transport [1, 2]. Low-frequency zonal flows (LFZF) and high-frequency geodesic acoustic mode (GAM) have been observed and studied in several toroidal devices [2], however, several features related to nature of these modes are still not fully understood.

Low-Frequency component of zonal flows (LFZF) have been studied in ADITYA-U tokamak using poloidally and toroidally distributed Langmuir probe arrays. Detailed analysis of density and floating potential fluctuations revealed presence of the LFZFs in typical ADITYA-U discharges. It has been observed that LFZF component can be effectively controlled with controlled gas-puffs and with modifying the radial electric fields using a bias-electrode. The complete analysis of LFZFs in ADITYA-U plasma will be presented in this paper.

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Nonlinear saturation characteristics of ITG and TEM turbulence in a tokamak using nonlinear gyrokinetic simulations and a POD method

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Magnetically confined plasma shows anomalous transport by micro-scale turbulence modes such as ion temperature gradient mode (ITG) and trapped electron gradient mode (TEM). The gyrokinetic code CGYRO [1] simulates the particle/energy transport induced by the microinstabilites in a local flux tube. Unlike ITG, which is saturated by zonal flows, TEM has different dominant saturation mechanisms depending on the electron profile [2]. In this study, we examine how the characteristics of turbulence differ depending on the saturation mechanism in ITG and TEM simulations by examining their proper orthogonal decomposition (POD) modes [3] and triad energy transfers [4]. The POD is a useful method to find a localized dominant basis contributing the saturation. Triad energy transfer between the modes shows whether the generated microinstabilities energy is transferred to larger or smaller scales.

The dependency of the electron density gradient and ion temperature gradient are investigated by both linear and nonlinear simulations in the cyclone base geometry. The results of the analysis revealed that different energy cascade patterns were observed among the low and high electron density gradient TEM and ITG. In the TEM with a low electron density gradient, no zonal mode POD pattern was observed. These results could potentially contribute to the development of reduced models for predicting plasma turbulence.

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Permeation, effective diffusivity, and solubility of gaseous tritium in thermal isolator materials considered for application in ITER

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Permeation, effective diffusivity, and solubility experiments of gaseous tritium in materials proposed for ITER is crucial for estimating occupational safety conditions for maintenance operations of the Test Blanket Systems equipment. With these results simulation models can be prepared to predict tritium inventory and therefore help estimate tritium retention within the material.

Three different grades of thermal isolator material have been tested. To assess effective diffusion coefficients tritium (in the form of HT) permeation experiments have been performed using a dynamic flow through system equipped with monitor for continuous tritium measurements in temperatures ranging from ambient to 650K. HT solubility calculations have also been derived from permeation experiments. Prior to permeation measurements materials were characterized using SEM/EDX.

Effective diffusion coefficient which involves gas transport through structure defects has been evaluated based on Fick's law. Effective diffusivity results are obtained in the range of 1 to 5 x 10^{-1} cm^2/s and the results show no significant difference between the three grades analysed. Effective diffusivity was found to be orders of magnitude larger than in other silica-based materials which can be explained by structural defects observed using SEM. Calculations show that material's solubility is mostly dominated by its porosity

Entropy and conservation laws to predict the saturation amplitude for a kinetic instability in a collisionless plasma.

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By enforcing the conservation of momentum, Dewar [1], was able to determine the approximate saturated amplitude for a single Langmuir wave, growing due to the bump-on-tail instability. Assuming the wave grows adiabatically, the saturated distribution function can be approximated and a wave amplitude is found to satisfy $\omega_b = 2.88\gamma$, where ω_b is the bounce frequency and γ is the linear growth rate. Alternatively, the wave can be assumed to have formed suddenly which leads to the to the relation $\omega_b = 3.93\gamma$. These two results can be compared to numerical results by Fried et al [2] which found $\omega_b = 3.2\gamma$.

In order to improve on these analytical prediction we require a method of more accurately approximating the final distribution function in the saturated state. We propose employing the principle of maximum entropy to determine the final state that both satisfies the conservation laws of energy and momentum, and maximises entropy. First we compare the entropy of previous final state approximations, such as the adiabatic and sudden cases. Then we consider more general distributions where we extremize entropy to more accurately determine the saturation amplitude.

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Poster Abstract

Study of Fast Ion 3D Weight Functions for 2-step Gamma-Ray reactions: analytical and numerical validation

29th of March, 2023

The presence of energetic particles, up to the MeV range, is a familiar concept in nowadays fusion devices and, given their importance in terms of plasma heating mechanisms and MHD instability interactions, proper techniques to diagnose these non-Maxwellian sub-populations of ions have to be developed. This study answers to this need by focusing on the calculation of 3D weight functions of gamma-ray spectrometers for 2-step reactions, where an excited nucleus is created from a fusion reaction; subsequently, it transitions into a lower state, emitting a prompt photon with nominal energy in the order of the MeV. For toroidally symmetric tokamaks, the 6D phase-space can be reduced to a 3D one called 'orbit-space', in which a triplet of *energy* E, max value of *pitch* p_m and max value of *major radius* R_m uniquely identifies a Fast Ion orbit of a certain class within the plasma. The role of the weight function is to quantify the sensitivity of the spectrometer to this reactions throughout this 3D orbit-space.

From a numerical perspective, these weight functions can be found by calculating expected spectra from all possible orbits, once a single ion is artificially placed onto each one and evolved through time and space. This calculation is performed by the hereby employed Orbit Weight Computational Framework (OWCF) for 1-step reactions by default: we present the implementation of 2-step reactions generating gamma-rays in this framework, where prohibited regions in the domain of the scattering angle - that in the laboratory rest frame arise from kinematics implications - are accounted for. This is the case, for instance, of the 9Be(4He,ng)12C reaction that makes us able to detect and study the alpha particle signature expected in gamma-ray spectrometer signals obtained, for example, in the D-T discharges operated at JET during the 2021 experimental campaign. This work can be further extended depending on the available impurities, and so reactions, in a given experimental facility.

Runaway Electron Dynamics in ITER Disruptions with Shattered Pellet Injection

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The sudden loss of confinement of the energy content of fusion plasmas in off-normal events, called disruptions, are among the most severe threats to the future of fusion energy based on the tokamak design. An efficient disruption mitigation system will therefore be of utmost importance for future large, high-current devices such as ITER. The potentially greatest threat to be mitigated is posed by currents carried by highly energetic electrons, called runaway electrons, which may cause severe damage upon wall impact. The disruption mitigation system must also ensure a sufficiently homogeneous deposition of the thermal energy on the plasma-facing components, and avoid excessive forces on the machine due to currents flowing in the surrounding structures. The currently envisaged mitigation method is to make a massive material injection when an emerging disruption is detected, attempting to better control the plasma cooling and energy dissipation.

In this work, we have systematically explored the parameter space of disruption mitigation through shattered pellet injection in ITER with a focus of runaway electron dynamics, using the thoroughly benchmarked disruption modelling tool DREAM [1]. We aim to provide a fairly comprehensive coverage of experimentally feasible scenarios, including plasmas representative of both non- activated and high-performance DT operation, different disruption onset criteria and transport levels, a wide range of hydrogen and neon quantities injected in one or two stages, and pellets with various characteristic shard sizes.

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Velocity-space analysis of the first fast-ion losses measured in MAST-U using a high-speed camera in the FILD detector

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A Fast-Ion Loss Detector (FILD) was installed for the first time at MAST during its upgrade in 2021 [1]. FILD consists of a probe near the plasma edge on the low field side that acts as a magnetic spectrometer, collimating the ions and dispersing them onto a scintillator plate. The acquisition system comprises two cameras, one CMOS camera providing enough spatial resolution (up to 1.1 MPx), and one APD camera providing temporal resolution (up to 4 MHz) to infer both the velocity space and the frequency of the fast-ion losses, respectively. For the second MAST-U experimental campaign (2022), the CMOS camera has been upgraded (from 23 Hz to up to 3.5 kHz acquisition frequency), in order to properly capture the temporal variation in velocity-space. In addition, the reciprocating probe of the diagnostic has been commissioned.

The velocity-space of the losses observed in MAST-U has been inferred with the FILDSIM code [2]. The first results show that the low NBI injection energy, plasma current and toroidal magnetic field used in the first campaign have led to larger gyro-radii than expected during the design phase (15 cm versus the maximum design value of 12.5 cm) [1]. In addition, the orbit-following Monte-Carlo code ASCOT [3] has been used to simulate fast-ion losses in a wide range of scenarios, with $B_t = [0.4, 0.7]$ T and $I_p = 750$ kA to analyse the dependence of the fast-ion loss distribution with the plasma safety factor (q). This has shown that lower q values help bring the losses closer to the probe's head. The NBI has been modelled in ASCOT5 to generate realistic particle inputs. The modelling of first orbit losses with ASCOT5 has enabled the benchmark of the experimental data measured by FILD, and the numerical simulations of the velocity-space are in good agreement with the experimental results. Furthermore, a scan of the probe's radial position with respect to the separatrix (17 to 8 cm) has shown an inverse correlation between the number of particles hitting the detector and its proximity to the separatrix. This correlation agrees with the experimental measurements obtained in the second campaign.

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Radially resolved thermal and fast-ion dynamics with collective Thomson scattering at ASDEX Upgrade

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For magnetically confined plasmas, fast ions and their behavior will play a key role in the performance of reactor-grade machines. To monitor their dynamics, Collective Thomson Scattering (CTS) has been chosen as a primary fast-ion diagnostic in ITER for diagnosing fusion-born alpha particles across their full energy range [1]. In current machines such as ASDEX Upgrade (AUG), various plasma properties can be inferred with CTS [2], providing a reliable tool to study thermal- and fast-ion transport in preparation for ITER operation. However, despite this diagnostic's versatility, CTS at AUG is usually confined to a single measurement volume, thus limiting its use in obtaining spatially resolved measurements.

Here we present the first highly radially-resolved CTS measurements at AUG, obtained by repeatedly sweeping a single measurement volume from the plasma core to mid-radius ($\rho \in [0.1; 0.7]$) for a sweep duration of 0.65 s. This results in 70 measurement locations, in which the fast-ion velocity distribution, ion temperature and rotation velocity were measured with CTS, in a moderate-density ($n_e \approx 6 \times 10^{19}$ m^{-3}), MHD-quiescent, H-mode discharge, with both on- and off-axis neutral beam (NBI) deposition. The plasma conditions (notably magnetic equilibrium, plasma pressure and stored energy) being remarkably stable across many confinement times allow the inference of thermal- and fast-ion radial profiles, and detailed comparison to other diagnostics. Thus, neoclassical predictions can be confronted with the inferred ion transport in real- and velocity-space.

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Effect of ideal internal MHD instabilities on NBI fast ion redistribution in ITER 15 MA scenario

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For the future operation of ITER, the fast ions generated from NBI play an important role in the plasma heating [1,2]. The interaction between MHD instabilities and NBI fast ions, however, can leads to degraded confinement of fast ions and reduces the heating power [3,4]. In future ITER 15 MA scenario, the high current may result in burst of the internal kink mode in the plasma core. Meanwhile, the fishbone instability can be excited by the interaction of fast ions with the internal kink mode [5]. Hence the NBI fast ion redistribution triggered by internal kink mode and fishbone instability is a key issue in ITER.

This work utilizes the codes MARS-F [6] and ORBIT [7] to study the redistribution of half a million of NBI fast ions with ideal internal kink modes and fishbone instabilities in ITER 15 MA scenario. Effects of three parameters on the transport and loss of fast ions are investigated, respectively: the perturbation amplitude A of the internal kink, the perturbation frequency f of the fishbone, and the toroidal mode number n of the internal kink.

In this study, redistribution of NBI fast ions is found to be sensitive to the perturbation amplitude and frequency. As shown in figure 1, with the $n = 1$ internal kink perturbation, the NBI fast ions transport from the region of $0 < s \leq 0.32$ to $0.32 < s \leq 0.53$, where s labels the normalized plasma radial coordinate. The transport becomes greater as the perturbation amplitude increases. As the perturbation amplitude rises to 500 G, which is 1% of the background magnetic field in ITER, the maximum relative change of fast ion number in radial position approaches 5%. With respect to effect of fishbone perturbation frequency, figure 2 presents a strong fast ion transport occurs between the regions of $0 < s \leq 0.05$ and

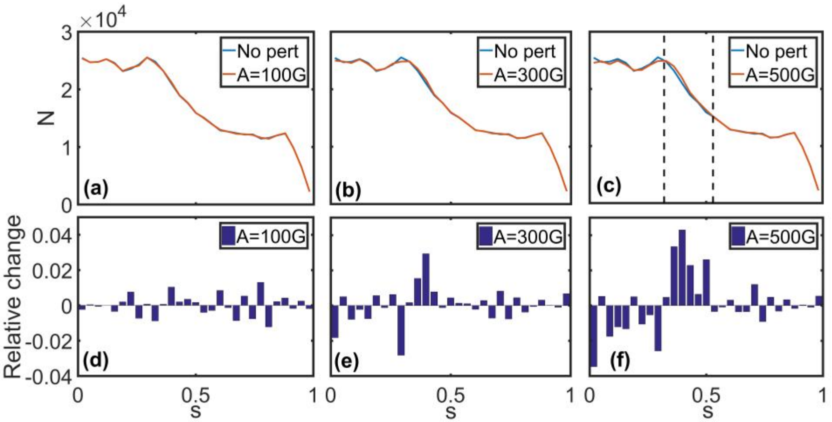

Figure 1. NBI fast ion number profiles in real space. The first row (a)-(c) and the second row (d)-(f) present the variation of fast ion number profiles and the relative change of fast ion number in real space in the presence of the perturbation amplitude A = 100 G, 300 G, 500 G internal kink perturbations (f = 0 and n = 1). The two black vertical dotted lines in plot (c) represent the radial positions of s = 0.32 and s = 0.53.

$0.05 < s \leq 0.12$, and higher frequency leads to stronger transport. When the perturbation frequency reaches 100 kHz, the number of fast ions in the region of $0 < s \leq 0.05$ is reduced by 30%.

The perturbation structure with different toroidal mode numbers n does not affect the relative change of the NBI fast ion number in real space. But as the value of n increases, the fast ion transport regions shift outward along the radial direction, which is consistent with the outward excursion of internal kink perturbations with different n in the radial direction.

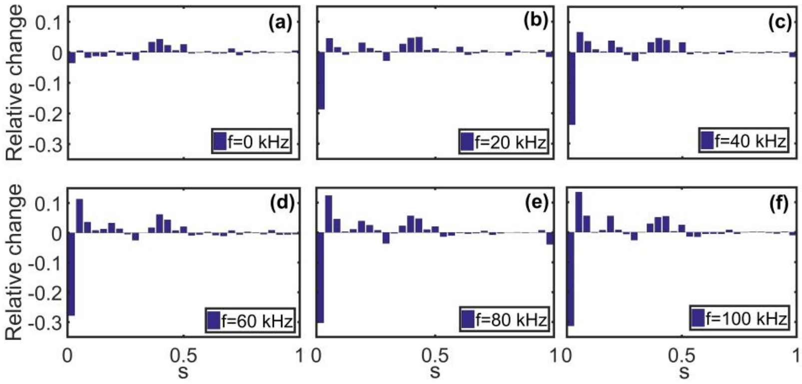

Figure 2. Relative change of NBI fast ion number in real space in the presence of perturbations with the perturbation frequency f = (a) 0 kHz, (b) 20 kHz, (c) 40 kHz, (d) 60 kHz, (e) 80 kHz, (f) 100 kHz (A = 500 G and n = 1).

As for the loss of NBI fast ions, we find that the loss number is independent of the perturbation amplitude A, the perturbation frequency f and the toroidal mode number n. This is because the internal kink mode/fishbone perturbation occurs in the core region in ITER, which is a device sufficiently large in size to allow particles to escape. Transport induced by MHD perturbations considered in this work is not sufficient to cause the NBI fast ions to move to the plasma edge and escape from the plasma. Hence the ideal internal MHD perturbation does not affect loss of NBI fast ions in ITER.

In conclusion, although the NBI fast ion transport induced by 100 kHz fishbone perturbation can result in a maximum decrease of 30% in the relative value of fast ion number, the transport regions of $0 < s \leq 0.05$ and $0.05 < s \leq 0.12$ are still located in the core region of the plasma where the fusion reaction mainly occurs. Thus the strong transport of NBI fast ions triggered by high-frequency fishbone perturbations does not affect the NBI heating power and fusion condition in ITER. On the other hand, the particle transport from $0 < s \leq 0.32$ to $0.32 < s \leq 0.53$ can cause a 5% decrease of the fast ion number when the perturbation amplitude reaches 500 G. The influence of this kind of transport on the fusion condition of ITER needs a further study in the future.

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The impact of tokamak geometry on runaway electron formation in a disrupting plasma.

Tokamak disruption mitigation continues to be a broadly pursued effort, specifically in the context of runaway electron (RE) damage to plasma facing components (PFCs). The formation of a RE beam occurs through an avalanching process, where the current carried by near bulk electrons is converted to current carried by REs. The present work evaluates the efficiency of the avalanche mechanism in a disrupting plasma, with particular emphasis on the impact of tokamak geometry. It is found that the collisionality at the critical energy for an electron to run away ν^*_{crit} determines the impact of tokamak geometry on the efficiency of the avalanche mechanism, where for $\nu^*_{crit} \ll 1$ tokamak geometry significantly reduces the efficiency of RE formation due to particle trapping, whereas for $\nu^*_{crit} \gtrsim 1$ the impact of tokamak geometry is largely negligible. To evaluate which of these two regimes applies to a tokamak disruption, an idealized but self-consistent model of a disruption is employed. Here, a power balance between Ohmic heating and radiative losses is used to evaluate the electron temperature, where Ohm's law is employed to evaluate the resulting electric field. It is found that for plasmas with a substantial quantity of high-Z impurities such as Neon or Argon, ν^*_{crit} is robustly greater than one, implying trapping effects are negligible leading to a more efficient RE avalanche. In the opposite limit of a deuterium dominated plasma, ν^*_{crit} is found to be asymptotically small, indicating that trapping effects will significantly reduce the efficiency of the avalanche mechanism. These findings are subsequently verified by carrying out direct simulations of the avalanche growth rate using the relativistic drift kinetic RE code RAMc, where the value of ν^*_{crit} is shown to modify the avalanche growth rate by up to a factor of two in the outer half of the plasma, as well as the overall efficiency of RE avalanching.

Atomic beam diagnostics and energetic particles

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The plasma equilibrium of a tokamak is a complex and interconnected system, where a significant energetic particle population can have profound effects on the performance of the machine. In the case of deuterium-tritium devices, such a population is comprised of the alpha particles produced by fusion, but more commonly, energetic particles are also introduced by auxiliary heating systems on most machines, like neutral beam injection (NBI) or ion cyclotron resonance heating (ICRH). These ions can drive a variety of magnetohydrodynamic (MHD) waves, which in turn can contribute to the radial redistribution of the energetic particles, leading to non-optimal heating profiles, energetic ion losses, and therefore also wall damage [1,2].

Atomic beam diagnostics can both contribute to the measurement of the distribution of energetic particles and the measurement of the associated plasma waves. In terms of the distribution of fast deuterons, the applicable method is fast ion charge exchange, also called FIDA (Fast Ion D-Alpha) [3,4]. When the beam atoms are introduced to the plasma, they can lose their electrons to excited states of the plasma ions, including the energetic populations. The following spontaneous emissions can be observed, providing information about the distribution of the energetic particles. The measurement of plasma waves usually happens with magnetic diagnostics, but fluctuation beam emission spectroscopy has also been demonstrated as a viable tool for this purpose [5,6]. This method utilizes the emission of an atomic beam separated by a narrow-band optical filter. The intensity of the beam emission is correlated with the local plasma density, therefore the method provides a spatially resolved measurement of the plasma density fluctuations up to the MHz range.

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First measurements of a scintillator-based fast-ion loss detector in reversed I_p/B_t at the ASDEX Upgrade tokamak

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Fast-α losses in future fusion power plants are expected to follow the co- and counter-current directions due to the isotropy of the fusion reaction. At the ASDEX Upgrade tokamak, the co-current direction (achieved with positive plasma current and negative toroidal magnetic field) has been extensively studied thanks to an array of five fast-ion loss detectors (FILD). A new fast-ion loss detector compatible with reversed I_p/B_t (negative plasma current and positive magnetic toroidal field, defining positive as counter-clockwise when the machine is viewed from the top), namely RFILD, has been designed and commissioned to study the behaviour of counter-current fast-ion losses and to expand our knowledge on QH-mode, I-mode, and the L-H transition. The detector is a modified version of the midplane manipulator fast-ion loss detector [1] that features a new probe head orientation and collimator geometry, optimised using the FILDSIM code [2,3]. A fast CMOS camera is used as a high spatial resolution acquisition system, while an array of photomultipliers (up to 1 MHz) serves as a fast channel.

First measurements have been taken in I-mode, QH-mode, L-mode and H-mode with core densities ranging between $4\cdot10^{19}$ and $9\cdot10^{19}$ m^{-3}, I_P between -0.8 and -0.6 MA and B_t of 2.5 T approximately. NBI fast-ion losses were observed for the first time in reversed I_p/B_t, producing high pitch (60 – 80º) losses. ICRH losses in H-minority heating configuration have also been observed in I-mode experiments. These losses correspond to the outer leg of banana particle trajectories. An upgraded double collimator detector design is also presented, that will increase the measurable particle range in future experimental campaigns (co- and counter-current particles simultaneously). Thus, we expand our understanding on the mechanisms behind fast-ion losses at the ASDEX Upgrade tokamak in the reversed I_p/B_t configuration.

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Self-organization and confinement in tokamak plasmas with very low edge safety factor

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There has long been interest in understanding tokamak behavior for $q(a) < 2$, in part due to the strong scaling of energy confinement with plasma current. We report internal measurements and nonlinear MHD modeling for very low safety factor, steady, Ohmic tokamak plasmas spanning $0.8 < q(a) < 3$. The experiments are conducted in the Madison Symmetric Torus device ($a = 0.5$ m, $R = 1.5$ m, $B_T = 0.13$ T), where the disruptive kink instability typically encountered at $q(a) = 2$ is mitigated passively by the close-fitting, thick, conducting shell. A family of self-organized $q(r)$ profiles is discovered in which $q(0) \sim 1$ as $q(a)$ decreases toward 1, such that the flat core region expands outward toward the wall. Internal electron density and temperature measurements also exhibit increasingly broad, flat profiles. The experimental results are compared to nonlinear MHD simulations with $q(a) \geq 1.5$ using the NIMROD code with a similar Lundquist number $S \sim 10^5$, which also show $q(0)$ relaxing toward unity. Experimental data show that periodic sawtooth behavior gives way to irregular fluctuations, and electron energy confinement drops as $q(a)$ decreases below 2. Interesting nonlinear mode coupling behavior near and below $q(a) = 1$ is also discussed. Work supported by US DOE.

Overview of activities in Kazakhstan related to study of beryllium and beryllium compounds

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Kazakhstan is one of the world leaders in the production of beryllium and beryllium products. Since recently, the Ulba Metallurgical Plant has set up production of beryllium-based intermetallic compounds; in particular, beryllides of titanium, chromium, molybdenum, etc. are produced. Beryllides are candidate materials for fusion plants as a neutron multiplier. In addition, beryllides are considered as a material for hydrogen storage. On the basis of research reactors in Kazakhstan, studies are being conducted on the effects of neutron irradiation on the properties of beryllium and beryllides. This report provides an overview of research programs in Kazakhstan to study the radiation resistance of metallic beryllium of different grades and beryllides.

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Fast electron dynamics in tokamak plasmas with high-Z impurities

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Abstract

In order to avoid the tritium retention issue experienced with carbon walls, the International Thermonuclear Experimental Reactor (ITER) will be using tungsten (W) components. However, this means that tungsten impurities will be present in the ITER plasma. They are able to significantly affect the operation of the tokamak, sometimes even leading to the termination of the plasma discharge [1]. In particular, a critical issue that needs to be investigated is the effect of high-Z impurities on the dynamics of fast (suprathermal) electrons. This issue arises when considering either the mitigation of a runaway electron beam in a post-disruptive plasma or a suprathermal electron population generated with a current drive method, using, e.g. Lower Hybrid (LH) waves [2]. So far, the main focus in this research field has been put on relatively low-Z impurities such as carbon, nitrogen or argon. However, it is now necessary to extend the methods of studying the dynamics of fast electrons to heavier impurities such as krypton, molybdenum or tungsten. Consequently, it is necessary to consider the so-called partial screening effect during the interaction between impurity ions and fast electrons in a plasma. This goal has been achieved by consistently incorporating the partial screening theory into kinetic and non-thermal bremsstrahlung calculations [3]. A particular emphasis is placed on the consequences of high-Z non-fully ionized impurities on LH current drive and the fast electron bremsstrahlung intensity on WEST.

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Analysis of the AE activity in the TJII periphery using Landau closure model

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The aim of this study is to analyze the Alfven Eigenmodes (AE) activity at the plasma periphery in the frequency range of 200 kHz observed in TJII discharges heated by neutral beam injectors (NBI)[1]. The analysis is performed using the linear version of the gyro-fluid code FAR3d [2], that solves the reduced MHD equations for the thermal plasma coupled with moments of the kinetic equation for the energetic particles (EP), and the STELLGAP code [3] including the effect of the sound wave and the helical couplings. The simulations indicate the presence of 8-12 and 3-7 helical gaps at $r/a = 0.65$ and 200 kHz as well as unstable $n/m = 8/5$-$12/8$, $7/4$-$15/9$ and $5/3$-$13/8$ Helical AEs (HAE) triggered around $r/a = 0.65$ showing a frequency of 230 and 210 kHz, respectively. A parametric study is performed with respect to the thermal ion density and iota profile at the plasma periphery to verify the simulation results by mimicking the uncertainty of the experimental profile. The analysis confirms the destabilization of the same dominant HAEs for all the configurations tested, although the helical gaps radial location and frequency range change from $r/a = 0.6$ to 0.65 and from 170 to 230 kHz, respectively, as well as the dominant HAEs growth rate, frequency and eigenfunction radial location. To reproduce NBI operational regime [4], an AE stability analysis is performed for the $n = 3, 7, 11, 15$, $n = 5, 9, 13, 17$, $n = 6, 10, 14$ and $n = 8, 12, 16$ helical families for a energy range of 10 - 30 keV for energetic particles (EP) and 0.005 to 0.03 for EP β, identifying the EP populations leading to the strongest drive. The simulations indicate the EP populations with energies above 25 keV leads to the destabilization of $n = 5, 9, 13, 17$ HAE at the plasma periphery and 200 kHz.

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Visible camera tomographic inversion for RE studies under Ar and D gas injection on the COMPASS tokamak

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Keywords: runaway electrons, tomographic inversion, tokamaks, gas injection

Runaway electron (RE) mitigation by gas injection of argon (Ar) and deuterium (D) has been investigated in the COMPASS tokamak in past campaigns [1, 2]. Ionisation or excitation of Ar and D due to the presence of the RE beam leads to subsequent recombination or deexcitation. Part of the emitted radiation is captured by rapid (5 kfps) visible color imaging systems. The presence of ArII and D bulk plasma during a singular discharge is characterized by the dominance of the blue ($\sim 450\,\mathrm{nm}$) or red spectral bands ($\sim 650\,\mathrm{nm}$), respectively. The light emission in the poloidal plane is reconstructed by tomographic inversion assuming toroidal symmetry of the RE beam.

Different algorithms were used [3, 4]. Each method presents advantages and disadvantages that will be discussed in the present work. The effect of toroidal asymmetry, due to inhomogeneous gas injection and reflections, also plays a role in the accuracy of the reconstructions and will be discussed. From these tomographic inversions and the help of modeling, temporal evolution of both bulk plasma (T_e and n_e) and RE beam (position, spatial profile evolution, energy) parameters is estimated.

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Reduced fast-ion transport in NT plasmas in the presence of TAEs at TCV with 3D nonlinear hybrid kinetic-MHD MEGA code

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Recent experiments at TCV have shown a strong mitigation of Toroidal Alfvén Eigenmodes (TAEs) in negative triangularity (NT) plasma compared to its counterpart experiment in positive triangularity (PT). In order to better understand the underlyuing physics mechanisms, non-linear simulations with positive (δ=+0.4) and negative (δ=-0.4) triangularities have been carried out with the hybrid kinetic-magnetohydrodynamic code MEGA [1]. Realistic and anisotropic initial fast-ion distributions have been used, showing a significant mitigation of the AE amplitude and growth rate. Synthetic fast-ion losses show a significant reduction in fast-ion heat loads in NT compared to the PT, using a 2D wall [2] for the TCV case. Significant differences are observed when comparing the power exchange between the confined fast-ion population and the modes, showing transit harmonics being strongly mitigated in the negative triangularity case. Single-*n* toroidal mode and multi-*n* simulations show that the leading mechanism for the fast-ion losses is the TAE activity, being a 3-fold smaller for the negative triangularity case. Different pitch-angle and energy distributions are studied to assess whether the effects are dependent on the initial fast-ion distribution in phase-space.

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Theoretical Study of Alfvénic Stability Optimization for TJ-II Stellerator

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The objective of this study is to analyze the Alfven Eigenmode (AE) activity in a hypothetical configuration concerning the NBI and magnetic field configuration of TJ-II device. The analysis is performed using the linear version of the gyro-fluid code FAR3d [1], which solves the reduced MHD equations for the thermal plasma coupled with moments of the kinetic equation for the energetic particles (EP), including the effect of the sound wave and the helical couplings. The Alfvén Continuum is computed with the STELLGAP code [2]. AE stability analysis is performed for the $n = 3,7,11,15$, $n = 5,9,13,17$, $n = 6,10,14$ and $n = 8,12,16$ helical families including EP populations with energies in the range of 10 - 90 keV and EP beta from 0.005 to 0.1, identifying the EP populations leading to the strongest drive. Simulations show the presence of 8-12 and 3-7 helical gaps at $r/a = 0.65$ and 200 kHz. EP populations with an energy less than 40 keV, a transition from Helical (HAE) to Toroidal (TAE) Alfvén Eigenmodes along EP β appears, show the destabilization of dominant HAEs if the EP beta is below or equal to 0.02, although TAEs are triggered for larger EP beta values. EP population with energies in the range of 40 to 70 keV, HAE are the dominant modes, $n/m = 7/4 - 15/9$, $13/8 - 9/5$, $10/6 - 14/8$ and $8/5 - 12/8$ at the periphery. EP populations with energies of 80 and 90 keV, simulations present global AE (GAE) with dominant modes $n/m = 7/4$ and $5/3$ with 60 and 65 kHz, respectively at $r/a = 0.9$ and all EP $beta$ values, while HAE instabilities for the dominant modes $n/m =$ 10/6-14/8 and 8/5-12/8 with frequencies of 200 and 360 kHz triggered at the plasma periphery, respectively for all EP $beta$.

The authors acknowledge J.M. Reynolds and V. Tribaldos for their support on this project managing the UC3M cluster Uranus.

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First Measurements with an Imaging Neutral Particle Analyzer in the ASDEX Upgrade tokamak

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A new Imaging Neutral Particle Analyser (INPA) [1-2] diagnostic has been installed and commissioned at the ASDEX Upgrade (AUG) tokamak. The AUG INPA diagnostic measures fast neutrals escaping the plasma after CX reactions. The neutrals are ionised by a 20 nm carbon foil and deflected towards a scintillator by the local magnetic field. The use of a neutral beam injector (NBI) as active source of neutrals provides radially resolved measurements while the use of a scintillator as active component allows us to cover the whole plasma along the NBI line with good phase-space resolution (~ 10 keV and 8 cm); making it suitable to study localized fast-ion redistribution in phase-space. The diagnostic explores pitch angles ($\lambda = v_{||}/v$) close to 0.5 at the magnetic axis and close to 0.7 at the plasma edge in the low field side.

First measurements taken in MHD-quiescent plasmas are compared with neoclassical simulations to validate the synthetic diagnostic, showing a good agreement within errorbars. Energy and position localised redistributions of FI were found during phases with strong FI driven modes such as BAE and TAE, showing the capability of INPA to measure localized fast-ion transport.

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On the role of deeply sub-Alfvénic energetic ions in generating ion cyclotron emission from fusion and laboratory plasmas

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Ion cyclotron emission (ICE) is widely observed from toroidal magnetically confined fusion (MCF) plasmas in both tokamaks and stellarators, and from cylindrical plasmas in the LAPD facility. ICE is generated by the collective relaxation of non-Maxwellian energetic ion populations, notably by fusion-born protons in deuterium plasmas and alpha-particles in deuterium-tritium plasmas, and by neutral beam injected (NBI) ions. ICE is excited under conditions where the deviation of the energetic ions from a Maxwellian velocity-space distribution is both substantial and spatially localised. This results in the characteristically well-defined spectral structure of ICE, with narrow-band peaks at local cyclotron harmonics. The ICE spectrum depends both on local plasma conditions and on the velocity-space distribution, where a key parameter is the ratio of the perpendicular and parallel components of energetic ion velocity to the Alfvén speed. The magnetoacoustic cyclotron instability (MCI) drives ICE, and diagnostic exploitation of ICE is assisted by simulations of the fully nonlinear MCI from first principles. We have carried out such simulations for conditions relevant to deeply sub-Alfvénic NBI ions in the W-7X stellarator and in LAPD. In this regime, these simulations, which use the particle-in-cell (PIC) kinetic code EPOCH to self-consistently solve the Lorentz force equation and Maxwell's equations for tens of millions of gyro-motion-resolved ions and electrons, are computationally expensive. For this reason, previous simulations of other plasmas in this regime have instead treated electron physics using a fluid description, nevertheless recently enabling the identification of ICE from fusion-born proton populations in pure deuterium plasmas in the LHD heliotron-stellarator (B Reman *et al.* 2022 *Plasma Phys. Control. Fusion* **64** 085008). The sub-Alfvénic MCI also gave rise to ICE from NBI ions in DT plasmas in the TFTR tokamak, investigated analytically (R O Dendy *et al*. 1994, Phys. Plasmas **1** 3407). Our new simulations address the electrostatic versus electromagnetic character of ICE in this regime; the relation between the MCI and, at higher frequencies, the lower hybrid drift instability; the role of parallel versus perpendicular components of energetic ion velocity; and the likely observational signatures of these effects in ICE driven by NBI ions in W-7X and LAPD.

This work was carried out within the framework of the HPC Midlands+ partnership.

Uniformity optimisation of the negative ion beam source for the ITER neutral beam injector

Beatrice Segalini, and NBTF team

Negative ion sources are fundamental components of neutral beam injectors (NBI) for future fusion reactors. SPIDER is the prototype negative ion source for ITER NBIs. It is hosted in Padua as part of the Neutral Beam Test Facility (NBTF), and it aims to accelerate 50A of negative hydrogen ions up to 100keV, and beam uniformity must be within 10% over the entire beam cross section of approximately $2m^2$. It is composed of 8 cylindrical drivers, capable of igniting the plasma through the inductive coupling with 4 radio frequency generators, each delivering up to 200kW. It started its operations in 2018, and ever since has been under constant performance monitoring. In 2021 it firstly operated with caesium seeding, in order to increase the accelerated current density. Recently it entered a major shutdown aimed at improving most of the plants, with the goal of fulfilling ITER requirements.

These first years of operations highlighted some important NBI issues that have to be addressed in order to reach the nominal performance. One of them is the plasma uniformity and caesium distribution, whose quality is directly related to the beam uniformity. To assess this issue, the present contribution will display simulations and some diagnostics that are currently in development to study this challenging issue.

One of the diagnostics described is a Retarding Field Energy Analyser (RFEA) probe, which will be installed on the front of SPIDER's Bias Plate so that it can collect information about the positive ion energy distribution close to the extraction area. Positive ions are, in fact, precursors of the negative ones produced by surface processes. Experimental data collected with a RFEA can also be compared with energy distributions obtained by a 3D Monte Carlo particle tracking code. In addition, a movable Langmuir probe along the vertical direction is designed so that it can provide a scan of the main plasma parameters close to the plasma grid, possibly interacting with other sensors to produce complementary measures.

Numerical investigation of runaway electrons generation in tungsten-rich tokamak plasma

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The presence of tungsten impurity in tokamak plasmas can have an important impact during both normal operation and disruptions. During normal plasma operation, the tungsten concentration can be kept sufficiently low to avoid strong radiation loses [1]. However, there are records of sudden influx of tungsten impurities, related to dust particles or melted droplets entering the plasma [2, 3]. In such situations, the tungsten concentration can rise abruptly, leading to a disruption.

As a heavy element, tungsten (Z=74) is expected to have a significant effect on the disruption dynamics even in relatively low concentrations; it contributes to radiative heat losses, can scatter energetic electrons and provide target electrons for close collisions in a Runaway Electrons (RE) avalanche. Disruptions caused by the sudden influx of tungsten may occur on so short time scales that mitigation measures cannot be invoked, posing a risk of generating intolerably intense RE beams. This scenario is a major concern for ITER, where RE may cause serious sub-surface damage in the plasma facing components [4].

In this work, a series of numerical simulations were conducted using the DREAM code [5] to assess the risk related to tungsten-induced disruptions. This, first required extending the atomic data used in DREAM, which was done using the ADAS database [6] and modifying existing atomic models to estimate mean excitation energy for heavy elements. The goal was to study the dependence of RE generation on various disruption parameters. A dependence of RE current on tungsten concentration, magnetic perturbation strength and thermal quench duration is presented, among other issues like tungsten concentration profile or modelling approach. The results provide a better insight into tungsten-induced disruptions, as well as recommendations for future simulations of such events.

Acknowledgment

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COMPLEX SPATIAL STRUCTURES OF FISHBONE INSTABILITIES INFERRED WITH MULTIPLE DIAGNOSTICS IN MAST/-U

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This paper reports measurements of the complex, temporally evolving spatial structure of fast-ion driven fishbone (FB) instabilities and associated fast-ion transport in the MegaAmp Spherical Tokamak (MAST) and MAST Upgrade (MAST-U). The temporal evolution of FB spatial structures has been inferred using multiple diagnostics in MAST/-U. These results could provide insight for improving models of fast-ion transport and hence the predictive capabilities for potentially dangerous FB-induced fast-ion losses in future fusion devices. FBs pose a significant threat to the operation and maintenance of future magnetic confinement fusion devices.. They can redistribute fast ions, reducing the fusion reaction rate, or even eject fast-ions, potentially damaging the plasma-facing components. There have been efforts to model the characteristics of FBs as well as their associated fast-ion transport [1-2]. However, these models sometimes neglect important features of FBs such as the temporal evolution of the mode structure and fast-ion orbits. This paper highlights the importance of some of these neglected features in many fast-ion transport models.

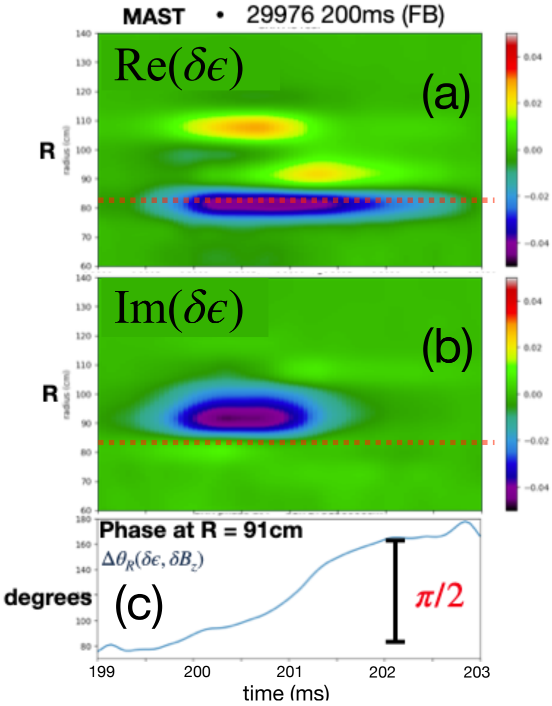

Figure 1. Real (a) and imaginary (b) parts of $\delta\epsilon$ of shots 29976. (c) Phase variations $\Delta\theta(\delta\epsilon, \delta B_z)$ over time of 29976 at R = 91cm.

Multiple diagnostics that measure various physical quantities were used to study different aspects of FBs. An outboard array of Mirnov coils was used to measure poloidal, radial, and toroidal components of magnetic fluctuations (δB_z, δB_R, δB_T) and for toroidal mode number (n) identification. Line integrated soft x-ray (SXR) emissions from an array of tangential views were also used. A set of correlated chirps (rapid changes of mode frequency) observed in the SXR and magnetic fluctuations measurements, identified as FBs, were selected for this study. The set of chirps selected for the study were determined to have toroidal mode number n = 1. Both SXR and δB_z signals were band-pass filtered to isolate the chirping component, and inverted into time-domain analytic signals that preserve phase information. The SXR signals were then further filtered by means of linear regression with the δB_z signal from one of the Mirnov coils as a reference to eliminate non-global contributions. The line-integrated SXR signals were then inverted to extract spatial profiles of local SXR emissivity fluctuations ($\delta\epsilon$), providing information on electron density, electron temperature, and effective ion charge fluctuations (δn_e, δT_e, and δZ_{eff}).

Temporal phase variations observed between spatially separated measurements of fluctuations associated with the FBs reveals the distortion of modes during the chirping period (fig. 1a). For example, the real part of $\delta\epsilon$ for an FB in MAST discharge 29976 (fig. 1a) shows a positive peak at R ~ 110cm at t = 200.5ms, which disappears after t = 201.5ms, only for another peak to emerge at R ~ 90cm (near the magnetic axis). This particular case has been documented in Ref. 3, where it was suggested the FB had the characteristics of a type of instability known as an energetic particle mode (EPM) at the beginning of the chirp, but that resonant fast ions were relocated by the mode, changing the nature of the mode. The imaginary parts of $\delta\epsilon$, not reported [3], is obtained using the previously mentioned analysis and filtering methods (fig. 1b). The real and imaginary parts of the time-dependent SXR emissivity structures differ from each other. Taken together, the real and imaginary parts of $\delta\epsilon$ exhibit a temporal phase variation at some radial locations. This is illustrated by, for example, phase of $\delta\epsilon$ near the magnetic axis, which shifts by $\pi/2$ over the period of chirping in about 2 ms (fig. 1c). The phase from this analysis is actually a difference in the temporal phase of the $\delta\epsilon$ and δB_z oscillations. Hence the phase variations of the signal can be understood as phase variations between spatially separated SXR and δB_z measurements, meaning the FB spatial structure was distorted during the chirping period.

The FB mode distortions appear to be associated with strong fast-ion redistribution during the chirping period. The passive FIDA signals from various locations in pulse #29976 during the FB chirp peaked between 201.0 and 201.5ms (fig 2d). The growth and peak of passive FIDA were delayed in comparison with those of δB_z. The δB_z started growing before 200.0ms, peaked at 201.0ms and then decayed (fig. 2a). The passive FIDA did not grow significantly until after 200.5ms. The δB_z peaked at 201.0ms and passive FIDA signals peaked after that. The phase of SXR verses δB_z at 91cm changed most significantly between 201.0ms and 201.5ms. On the other hands, the outboard Mirnov system in MAST has a set of three coils that measured B_z, B_R, B_T at the same toroidal location. Neither the angle between δB_z and δB_R (fig. 2b), nor their relative amplitude, changed significantly, suggesting no change in the direction of the poloidal magnetic field at the coil location (and perhaps no vertical shift in the plasma). However, the amplitudes of δB_z increased significantly relative to δB_T between 200.2 and 201.2 ms (fig 2c), indicating a change in the magnetic field pitch at the coils location. The changing structure of $\overrightarrow{\delta B}$ and the fast-ion redistribution both potentially contribute to the measured temporal phase variations since an FB can be viewed as a wave propagating in the combined medium of the fast ions and thermal plasma.

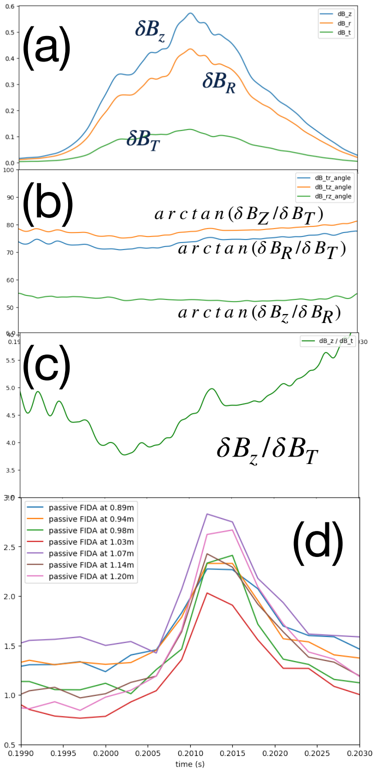

Figure 2. (a) real parts of the FB associated δB_z, δB_R, δB_T; (b) angle between real parts of $\overrightarrow{\delta B}$ components; (c) ratio of δB_z and δB_T amplitude; (d) the passive FIDA signals from various locations.

Explanations for the measured FB spatial structure distortions are needed. One of many possibilities would be that significant changes in resonant fast-ion orbits during the chirping period caused the phase slips. On the other hand, although only n = 1 was selected for this study, the plasma exhibited chirps with n = 2 at twice the frequency, so non-linear mode-mode interaction with modes of higher toroidal mode number n could influence the structure of the targeted n = 1 mode. Further studies on data from more diagnostics, fast-ion orbit simulations, as well as new experiments in MAST-U with a new suite of fast-ion diagnostics will be needed to identify the mechanisms and causes of the temporal phase variations.

ACKNOWLEDGEMENTS

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On the Study of Grad-Shafranov Equation Solver using Physics-Informed Neural Networks on Non-homogenous Collocation Points

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Keywords: MHD equilibrium, Grad-Shafranov equation, PINN.

ABSTRACT

This paper provides a comprehensive overview of the computation of MHD equilibrium in a tokamak plasma. The problem is primarily addressed by solving the Grad-Shafranov equation, which describes the equilibrium of plasma in an axisymmetric magnetic field. A variety of methods exist to solve this equation, but this paper proposes the use of physics-informed neural networks (PINN) to solve it without using numerical schemes. The architecture and activation function of the neural network generate a transformation that approximate the solution of Grad-Shafranov equation. For the standard technique of PINN, randomly sampled collocation points are used to enforce the Grad-Shafranov equation within the solution domain. The choice of collocation points is crucial to ensure that the differential equations are satisfied at all points in the domain. The paper also explores three different options for the right-hand side of the Grad-Shafranov equation: Solov'ev solutions when the magnetic flux is not a function, linear function of magnetic flux, and nonlinear function of magnetic flux.

Iterative Method for Including Parallel Dispersion for RF Waves in Two-Dimensional Axisymmetric Finite Element Models

Björn Zaar

March 2023

Abstract

Modelling the propagation and dissipation of RF waves in the ion cyclotron range of frequencies is challenging due to the presence of spatial dispersion. In this work, we are presenting an iterative scheme that includes dispersive effects in all tensor elements in 2D axisymmetry. The proposed method is implemented in the existing full wave solver FEMIC and applied to two fast wave heating scenarios, one with an ITER-like plasma and the other with an AUG-like plasma, in order to evaluate the importance of parallel dispersion in the two different cases. It was found that parallel dispersion is of marginal importance in ITER when using dipole phasing, but has larger impact on the power deposition profiles in AUG, due to up-down asymmetric heating. Furthermore, it is shown that the described iterative method can account for mode conversion to the ion cyclotron wave.

The impact of tokamak geometry on runaway electron formation in a disrupting plasma.

Tokamak disruption mitigation continues to be a broadly pursued effort, specifically in the context of runaway electron (RE) damage to plasma facing components (PFCs). The formation of a RE beam occurs through an avalanching process, where the current carried by near bulk electrons is converted to current carried by REs. The present work evaluates the efficiency of the avalanche mechanism in a disrupting plasma, with particular emphasis on the impact of tokamak geometry. It is found that the collisionality at the critical energy for an electron to run away ν^*_{crit} determines the impact of tokamak geometry on the efficiency of the avalanche mechanism, where for $\nu^*_{crit} \ll 1$ tokamak geometry significantly reduces the efficiency of RE formation due to particle trapping, whereas for $\nu^*_{crit} \gtrsim 1$ the impact of tokamak geometry is largely negligible. To evaluate which of these two regimes applies to a tokamak disruption, an idealized but self-consistent model of a disruption is employed. Here, a power balance between Ohmic heating and radiative losses is used to evaluate the electron temperature, where Ohm's law is employed to evaluate the resulting electric field. It is found that for plasmas with a substantial quantity of high-Z impurities such as Neon or Argon, ν^*_{crit} is robustly greater than one, implying trapping effects are negligible leading to a more efficient RE avalanche. In the opposite limit of a deuterium dominated plasma, ν^*_{crit} is found to be asymptotically small, indicating that trapping effects will significantly reduce the efficiency of the avalanche mechanism. These findings are subsequently verified by carrying out direct simulations of the avalanche growth rate using the relativistic drift kinetic RE code RAMc, where the value of ν^*_{crit} is shown to modify the avalanche growth rate by up to a factor of two in the outer half of the plasma, as well as the overall efficiency of RE avalanching.

Investigation of multiple modes and their interaction generated by localized current drive onto the rational-q surface of the tokamak plasma

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Electron cyclotron current drive (ECCD) is considered one of the notable techniques to control sawtooth instabilities. With the electron cyclotron emission imaging (ECEI) system installed on the KSTAR tokamak, it is possible to analyze large-scale instabilities and small-scale turbulence with a high spatial resolution (~ 2 cm). Dynamics of electron temperature fluctuations measured by ECEI suggest that multiple current-carrying flux tubes can be generated during an ECCD blip [1,2]. These flux tubes can be generated as the electrons gain kinetic energy from RF waves within a few passages of resonance position and sustain longer than the current dissipation time when the q profile is flat inside sawtooth inversion radius [3]. Furthermore, we performed multichannel correlation analysis to analyze small-scale fluctuations associated with filaments of flux tubes [4]. During the ECCD pulse, the coherence spectrum shows broadband fluctuations localized to the ECCD deposition radius, contrary to the narrow-band features (MHD modes) observed during ECCD inter-pulse. Furthermore, we present evidence on the energy inverse cascade by comparing it with the relation of wavenumber and energy, suggesting the mechanism for the generation of flux tubes induced by localized current drive. This work is supported by NRF of Korea under grant no. NRF-2019M1A7A1A03088456.

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Self-organization and confinement in tokamak plasmas with very low edge safety factor

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There has long been interest in understanding tokamak behavior for $q(a) < 2$, in part due to the strong scaling of energy confinement with plasma current. We report internal measurements and nonlinear MHD modeling for very low safety factor, steady, Ohmic tokamak plasmas spanning $0.8 < q(a) < 3$. The experiments are conducted in the Madison Symmetric Torus device ($a = 0.5$ m, $R = 1.5$ m, $B_T = 0.13$ T), where the disruptive kink instability typically encountered at $q(a) = 2$ is mitigated passively by the close-fitting, thick, conducting shell. A family of self-organized $q(r)$ profiles is discovered in which $q(0) \sim 1$ as $q(a)$ decreases toward 1, such that the flat core region expands outward toward the wall. Internal electron density and temperature measurements also exhibit increasingly broad, flat profiles. The experimental results are compared to nonlinear MHD simulations with $q(a) \geq 1.5$ using the NIMROD code with a similar Lundquist number $S \sim 10^5$, which also show $q(0)$ relaxing toward unity. Experimental data show that periodic sawtooth behavior gives way to irregular fluctuations, and electron energy confinement drops as $q(a)$ decreases below 2. Interesting nonlinear mode coupling behavior near and below $q(a) = 1$ is also discussed. Work supported by US DOE.

Numerical study on the Wave instability by the Energetic Electron Beam

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Mitigating the average kinetic energy or defocusing the energetic electron beam, called the runaway electron (RE) beam is one of the significant objectives for the safe operation of fusion devices. It is essential to understand the dynamic features of the RE beam in the tokamak plasma to establish strategies to mitigate the growth of RE beams. It is known that the RE beam can generate electrostatic waves [1] or whistler waves [1, 2, 3]. To understand the detailed interplay between the RE beam and the plasma waves, we have conducted a numerical study using a 2-dimensional electromagnetic particle-in-cell (PIC) simulation. More specifically, the connection among the dispersion properties of the plasma wave generated by the RE beam, temporal evolutions of the energy in the system, and the momentum distribution of the plasma and RE beam are studied with linear analysis. As a result, we observed that the Cherenkov resonance accompanies the electrostatic wave and the diffusion of the RE beam distribution function in the parallel direction, and anomalous Doppler resonance evokes the whistler wave and the diffusion of the RE beam in the perpendicular direction. The condition of whether the Cherenkov resonance or the anomalous Doppler resonance occurs depends on the beam energy. Further study for the features of the distribution will be done in the future.

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Key words: Tokamak, runaway electron (RE) beam, Doppler resonances, particle-in-cell (PIC) simulation

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Spectroscopic investigation of plasma-material interactions on the ZaP-HD sheared-flow-stabilized Z-pinch device.

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High energy density plasma-material interactions occur on the ZaP-HD sheared-flow-stabilized Z-pinch device. In particular, erosion of the graphite cathode contributes to impurity production and limits the lifetime of the component. Understanding the plasma-electrode interaction is critical for ongoing work in scaling the concept to a reactor device and the associated increase in energy density. Spectroscopic methods provide in-situ, non-perturbing measurements of various parameters in this extreme environment. A fast-framing camera coupled to a Czerny-Turner spectrometer provides time-resolved relative intensity measurements of impurity ions over a range of spatial locations. These can also be used to calculate plasma temperature and velocity near the cathode. In addition, a CCD camera and PMT provide a time-integrated spectrum and time-resolved intensity respectively for a single impurity line. Together, these instruments characterize the spatiotemporal distribution of impurity ionization stages. These results will support implementation of the ionizations per photon (S/XB) method to infer sputtered impurity flux.

Development of machine-learning-based interatomic potentials for sputtering simulation of silicon

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The goal of this study is to establish techniques to develop interatomic potential functions to model plasma-surface interaction by molecular dynamics (MD) simulation, especially for sputtering with the use of machine learning (ML) techniques. As the first example, we developed neural-network (NN)-based interatomic potential functions among silicon (Si) atoms, so that we can simulate the self-sputtering of crystalline Si. Data to develop such a NN model is provided by the density functional theory (DFT) calculations. Here, we used Quantum Eespresso[1, 2] to perform DFT calculations.

Recently, ML methods have been used to develop interatomic potential functions for various materials. Several studies have shown that ML-based interatomic potentials can achieve the accuracy of DFT calculations as well as the computational speed of classical potentials and MD simulations based on MD-based interatomic potential functions can predict material properties with high accuracy in thermal equilibrium. However, there remain some challenges in describing short-distance repulsive interactions, which typically do not exist in DFT calculation data for solid materials. In order to solve this problem, we incorporated Ziegler-Biersack-Littmark (ZBL) potential functions,[3] which are known to be a good description for the short-distance interaction. The newly developed potential functions are compared with other existing (non-ML-based) potential functions for the Si system and their accuracy are tested against experimentally measured materials and sputtering properties.

Figure 1 shows a comparison among two-body interatomic potential functions of the ZBL function and the ML-based function as well as those obtained from DFT calculations by Quantum Expresso and Gaussian. It is seen that, for short separation lengths, the ZBL and DFT calculation differ, which may lead to a large discrepancy in sputtering yield simulation. Comparison among self-sputtering yield simulations data obtained from MD simulations based on these potential functions and with the corresponding experimental data will be also discussed in the presentation.

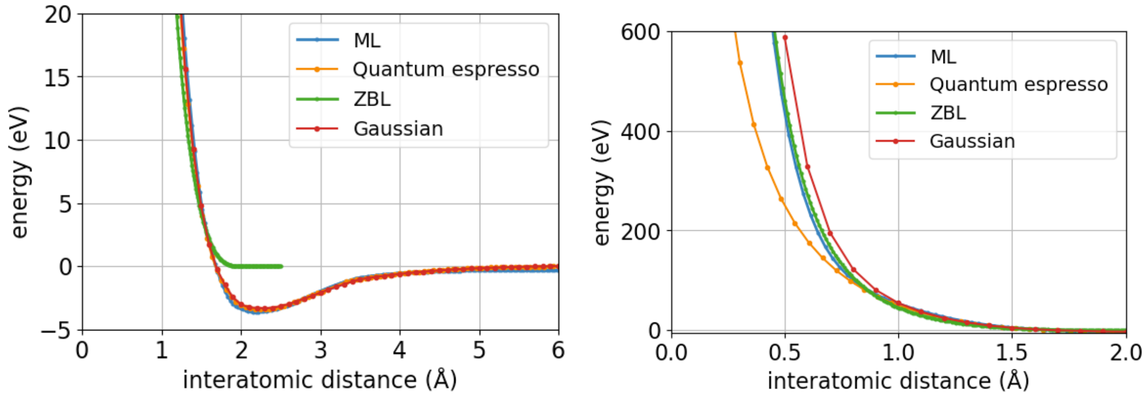

Fig. 1: Comparison among Si two-body interactions of the ZBL function, the ML-based potential function, and those obtained from Quantum Espresso and Gaussian[4] calculations.

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Data-Driven Modeling of Impurity Transport in the Edge Plasma of Tokamaks

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Confinement quality in fusion plasma is substantially affected by heavy impurities, which can lead to radiative heat loss and reduced confinement. This study explores impurity transport modeled by inertial particles in edge plasma, a previously unexamined aspect in plasma physics, using high-resolution numerical simulations, the Hasegawa-Wakatani equations, modeling electrostatic drift-waves in edge plasma. Our simulations employ one-way coupling of a million inertial point impurity particles.

We observe that with Stokes number (St) which characterizes the inertia of particles being much less than one, impurities closely follow the fluid flow without pronounced clustering. For intermediate St values, distinct clustering appears, with larger Stokes values even generating more substantial clusters. When St is significantly large, impurities tend to detach from the flow and maintain their trajectory, resulting in fewer observable clusters and corresponding to random motion.

By applying Voronoi tessellation, each impurity particle is assigned a specific volume to determine volume changes, thereby calculating impurity velocity divergence. Positive divergence signifies void formation; negative indicates clustering. We find that the modified (flux-driven) Hasegawa-Wakatani model, compared to its classical (gradient-driven) counterpart, exhibits a narrower probability density function (pdf) of divergence in impurity velocity, particularly evident with larger values of adiabatic parameter c.

A core component of this work involves advanced machine learning techniques, specifically, generative adversarial networks (GANs). Through this, we synthesize preferential concentration fields of impurities, input vorticity, and predict impurity number density fields. This approach holds the potential to reduce computational costs by eliminating the need to track millions of impurities.

Acknowledgements

We thankfully acknowledge the financial support from I2M, ANR CM2E and FR-FCM.

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Identification of core ion cyclotron instabilities on HL-2A

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Instabilities with ion gyrofrequencies have become popular and been attached with great importance both in nature and lab plasmas. In the magnetic confinement devices, fast ions and fusion α particles are the key ingredient to heat plasmas, reach and sustain nuclear fusion. These particles would excite the coherent instabilities with frequency peaks at ion cyclotron instabilities termed ion cyclotron emission (ICE). A strong correlation between ICE spectra and neutron emission rate has been observed in JET[1] and TFTR[2]. The experimental results raised the implications of ICE to diagnostic fast ions and α particles, which has been preliminary verified through simulation[3]. In addition, the probes for detecting ICE could be noninvasively, installing outside the vacuum or behind the plasma facing surface. The role of ICE for diagnostic energetic particles is suitable for the fusion reactor environment. Besides, ICE is considered to be a novel “alpha-particle channeling” scenario from experimental[4] and simulation results[5].

Instabilities in the range of ion cyclotron frequency are identified and termed as core ICE in recent HL-2A NBI heated experiments. Characteristics of the core ICE are presented, including frequency dependence, harmonics feature and amplitude dependence. It is found that the detected frequencies agree well with the ion cyclotron frequencies, mainly depending on the toroidal magnetic field. The radial location of the core ICE is around the magnetic axis under different experimental conditions. In addition, the polarization of core ICEs shows a rather compressional property. Distinctive spectrum and excitation of the different harmonics are found, which imply that the driven mechanism of the harmonics is different. A strong correlation between the ICE intensity and electron density is observed, rather than NBI heating power. This strong correlation suggests a candidate for the exciting mechanism of core ICE.

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First ERO 2.0 simulations of liquid metal transport and redeposition from divertor of COMPASS Upgrade

Abstract

The COMPASS Upgrade tokamak will be a medium-sized tokamak that, thanks to its large magnetic field (5 T on-axis) and high plasma density ($\sim 10^{20}\ m^{-3}$), will achieve heat fluxes relevant to DEMO reactor. Along with DEMO-like plasma geometry and tungsten plasma-facing components (high heat flux regions made of bulk tungsten tiles and others probably coated with tungsten), COMPASS-U will provide crucial answers (among many others) to sustainable plasma power exhaust of future fusion power plants.

Technologies using liquid metals (lithium, tin, or their combination) will be one of the heat shields tested. Either as individual capillary porous tiles inserted into divertor region using a dedicated material-testing manipulator or as a proposed & submitted larger project of a fully toroidal liquid metal divertor.

For both cases, simulations clarifying the transport of vaporized liquid metal in the plasma scrape-off layer and its redeposition on the surrounding components are necessary. The results will contribute to questioning the real long-term applicability of liquid metals as heat shields. The first set of simulations were performed using the massively parallelizable 3D Monte Carlo code ERO 2.0 and the results and future plans are discussed.

A High Resolution Neutron Spectrometer for Burning Plasma Studies on SPARC

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February 2023

1 Abstract

This poster presents the design for the high-resolution neutron spectrometer to be installed on the SPARC tokamak, a compact high field tokamak under construction in Devens, MA. Neutron spectroscopy provides unique insight into the kinetic physics of fusion plasmas and is particularly well suited to studying alpha heating and the transition to the burning plasma regime. The neutron spectrum can be directly related to the alpha particle birth spectrum since there is a one to one kinematic relationship between two body collision products. In addition, the precise form of the spectrum gives information about the fuel ion distribution functions, and can therefor be used to learn about the mechanism of alpha heating. The spectrometer is of the Magnetic Proton Recoil design, inspired by the system used at JET[1]. Collimated neutrons elastically scatter protons out of a polyethylene wafer and into an ion optical system where they are focused by a pair of multipoles and a large dipole magnet disperses the protons according to their momentum. The spectrum of incident neutrons can then be determined from the distribution of proton counts along an array of detectors. The spectrometer has been optimized using COSY[2], an ion optics code, and is designed to have a variable energy acceptance ranging from 1-20MeV in order to measure fusion neutron spectra in both Deuterium and Deuterium-Tritium plasmas. This enables investigations of fuel ratio and tritium burn-up during low-tritium concentration commissioning campaigns, and detailed kinetic studies of burning plasmas during high performance discharges. The spectrometer is designed to have an energy resolution better than 200keV when centered on the 14MeV peak and a time resolution less than 200ms during high power shots, enabling observation of the evolution of the fusion power and production spectra over the course of a discharge.

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Correlation between fast-ion D_α emissions and ion cyclotron harmonic emissions in KSTAR H-mode plasmas

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Fast ion D_α (FIDA) spectroscopy has been proposed as an efficient tool for diagnosing fast ion distribution [1]. FIDA spectroscopy is a visible spectroscopy that measures the Doppler-shifted D_α emissions from the charge-exchange process with either beam neutrals (active) or gas neutrals (passive). The KSTAR FIDA diagnostic system [2] can cover the spectral band from 647–663 nm, which is sufficient for the energy range of KSTAR neutral beam sources. An advanced aberration-free spectrometer (Schmidt-Czerny-Turner spectrometer) is applied to avoid the curvature of the image plane. Using the advanced spectrometer, we have routinely observed intense FIDA emissions in $E_{\parallel} = 50-80$ keV range near the edge region (R~2.12–2.16 m, r/a > 0.8–0.9). During inter-ELM periods, the FIDA intensities have dynamic features independent of the ELM crash, which are correlated to the intensity of deuterium ion cyclotron harmonic emissions (ICEs) (150–250 MHz) measured by the fast radio-frequency (RF) diagnostic systems [3–4]. For example, edge FIDA and deuterium ICEs intensities become stronger with the appearance of modes at the edge region. The correlation between edge FIDA intensities and deuterium ICEs shows that the active charge-exchange component may contribute to the edge FIDA emissions in KSTAR H-mode plasmas. The deuterium ICEs can be excited by energetic ions from neutral beam sources with a narrow range of initial pitch angles, supported by particle-in-cell simulations [5]. This work was supported by the R&D programs of “KSTAR Experimental Collaboration and Fusion Plasma Research” (KFE Grant Code: EN2301-14) and “ITER Burning Plasma Research and Development of ITER Plasma Exploitation Plan” (KFE Grant Code: IN2304-9) through the Korea Institute of Fusion Energy (KFE) funded by the Government funds.

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Tomographic Reconstruction of alpha-particles source in D-^{3}He plasmas at JET and prospects for SPARC

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Combining spectroscopic capabilities with a set of collimated lines of sight that cover almost the entire poloidal plane of a tokamak, neutron and gamma cameras are excellent diagnostics for studying fast particles starting from the detection of the products generated in nuclear reactions. The JET tokamak is equipped with a neutron[1] and a gamma camera[2], which share two sets of 10 horizontal and 9 vertical lines of sight. During 'three-ion' Ion Cyclotron Resonance Heating experiments in D-(D_{NBI})-^{3}He plasmas, the JET gamma camera measured 16.4 MeV gamma-rays emitted in a minor branch of the aneutronic D+3He fusion reaction, thus allowing study of the spatial distribution of (D-^{3}He)-born alpha particles. In this work, first we introduce the tomographic method used for the analysis. Second we apply it to the reconstruction of the alpha particles source in JET and compare the results with TRANSP simulations showing good agreement. Third, we consider the SPARC tokamak, which is planning to install a neutron camera with 10 or more horizontal lines of sight. We present a workflow for assessing SPARC total fusion power via the tomographic inversion algorithm developed for JET[4]. A minimum number of lines of sight and their optimal field of view are suggested. Finally, the accuracy of the reconstruction of the neutron yield is estimated by propagating uncertainties in the camera geometry, magnetic flux surfaces reconstruction, and neutron attenuation along each LOS.

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Title:

Analytical Evolution of Coupled Weakly-Driven Waves in a Dissipative Plasma

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Abstract:

The nonlinear collisional dynamics of coupled driven plasma waves in the presence of background dissipation is studied analytically within kinetic theory. Sufficiently near marginal stability, phase space correlations are poorly preserved and time delays become unimportant. The system is then shown to be governed by two first-order coupled autonomous differential equations of cubic order for the wave amplitudes and two complementary first-order equations for the evolution of their phases. That system of equations can be decoupled and further simplified to a single second-order differential equation of Liénard's type for each amplitude. Numerical solutions for this equation are obtained in the general case while analytic solutions are obtained for special cases in terms of parameters related to the spacing of the resonances of the two waves in frequency space, e.g., wavelengths and oscillation frequencies. These parameters are further analyzed to find classes of quasi-steady saturation and pulsating scenarios. To classify equilibrium points, local stability analysis is applied, and bifurcation conditions are determined. When the two waves saturate at similar amplitude levels, their combined signal is shown to invariably exhibit amplitude beating and phase jumps of nearly π. The obtained analytical results can be used to benchmark simulations and to interpret eigenmode amplitude measurements in fusion experiments.

Characterization of NBI energetic particle confinement in Divertor Tokamak Test plasmas

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The Divertor Tokamak Test (DTT) [1], [2] is a super-conductive device under construction in Frascati, Italy. DTT was proposed to optimize ITER operations and DEMO design. The power required for DTT operations is provided by three auxiliary systems, including a Neutral Beam Injection (NBI) system which is capable of one of the highest injection energy before ITER (E_{NBI} = 250-510 keV, $P_{NBI} \leq 10$ MW). The NBI generates a population of energetic particles (EPs), known also as fast ions. EP confinement is crucial both for plasma performances and to avoid potentially harmful particle losses.

In this work, we characterize the beam energetic particle confinement in the Divertor Tokamak Test device. Initially, we introduce the energetic particle physics, especially discussing the possible orbits that energetic particles can follow in a tokamak [3]. After that, we analyze the confinement of energetic particles generated by the DTT NBI, exploring how the confinement depends on some plasma parameters, e.g. plasma density or temperature, and on NBI energy. To accomplish this analysis, the orbit following Monte Carlo ASCOT suite of codes [4] is used. The classification of EP orbits and the evaluation of the fraction of prompt losses, i.e. particle born in unconfined orbits which are lost almost immediately after the ionization, is done also through the Constant of Motion (CoM) phase space [5], defined by EP constants of motion and an adiabatic invariant. Results of this work show that in DTT passing and trapped particles are predicted while non-standard orbits, e.g. potato or stagnation, are not expected. Moreover, even if DTT NBI is directed co-current, a small fraction of prompt losses remains.

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Abstract

Orbit-Space Integrated Data Analysis of Fast Ions in the C-2W Field Reversed Configuration

G. Player, S. Dettrick, E. Granstedt, S. Kamio, R. M. Magee, B. S. Nicks, T. Tajima, and the TAE Team

The C-2W advanced beam-driven field reversed configuration (FRC) device utilizes 15-40 keV neutral beams to create a large population of fast ions, which are critically important for FRC heating, current drive, and stabilization. [1, 2] The suite of fast ion diagnostics on the C-2W device include neutral particle analyzers (NPAs), scintillating neutron detectors, silicon proton detectors, and particle bolometers. Fast and accurate diagnostic modeling techniques are vital to developing an understanding of these fast ion diagnostic signals, and how they relate to fast ion dynamics. We present an integrated data analysis (IDA) paradigm which utilizes weight functions to model these signals. Fast ion orbits in high-beta FRCs are well described by three conserved variables, which allows for the development of three-dimensional “orbit-space” weight functions which fully represent the diagnostic sensitivity, instead of the full four or six dimensions required by many traditional methods. Combined with Monte Carlo particle simulations, they provide a powerful tool for rapid modeling of fast ion diagnostics in an integrated framework with other diagnostic information. We also utilize this newly-developed IDA model to infer properties of the fast ion distribution and explore fast ion dynamics, utilizing both forward simulations and experimental data.

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3D Plasma-Wall Interaction in the RFX-mod device

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see the author list of L. Marrelli et al, Nuclear Fusion* ***59**, 076027 (2019)*

This poster is about the characterization of MHD tearing modes causing a Plasma-Wall Interaction (PWI) during a magnetic reconnection event in a high current plasma discharge in the RFX-mod Reversed Field Pinch (RFP) device (major radius R = 2 m and minor radius a = 0.5 m). PWI is measured via a fast camera [1] observing the inner first wall of the device, showing two separated stripes of neutral carbon radiation. The analysis aims at simulating and understanding the origin of such a pattern, by following the methods used in pioneering experiments in the TEXTOR device [2].

A preliminary study considering a simplified model of 3D topology shows that the number of MHD modes involved in the magnetic reconnection event is larger ($N_{PWI} \approx 35$) than the experimentally measured ones via magnetic sensors [3] ($N_{meas.} \approx 23$). This result is important in view of the upgraded RFX-mod2 device [4], which will start operating by the end of 2024.

A more refined description with the guiding center code ORBIT [5] involves the calculation of the 3D map of connection lengths to the wall $L_{c,w}(r, \theta, \varphi)$. This map reproduces quite well the experimental PWI pattern measured by the fast camera, showing that the two stripes are due to modes with different poloidal numbers: m = 0 and m = 1. This result confirms the importance of the m = 0 tearing modes in the edge of the RFP [6], especially during magnetic reconnections.

The relationship between the observed PWI and the physics of magnetic reconnection phenomena in RFP, especially regarding the behavior of fast ions accelerated during these events [7, 8], will also be discussed.

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Design and Development of Neutral Particle Analyzer (NPA) on HL-2A/2M

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A new neutral particle analyzer (NPA) diagnostic based on sCVD (single crystal chemical vapor deposition) and the electromagnetic field of a new E//B NPA capable of mass resolution and energy resolution have been designed, the relative position between NPAs and NBI on HL-2A is depicted in figure 1. The sightline of DNPA intersects almost perpendicularly with 4 sources of NBI #2 (tangential injection) near plasma core (R_{tan}=1.54 m and R_0=1.65 m), which manifests this DNPA has an active view. With the fast ion distribution calculated from TRANSP/NUBEAM module, the velocity-space measurement range of this active DNPA overlaps with the fast ion distribution over the most energies with the pitch angle defined by the sightline of the detector. Figure 1(c) and 1(d) demonstrate the simulated neutral flux using FIDASIM peaks at approximately 7×10^9 (neutrals [s^{-1} keV^{-1}]) at low energy. At relatively low energies ($E < 10$ keV), active components prevail the spectrum. At relatively high energies ($E > 15$ keV), passive component from reactions with cold neutrals is dominant.

The stripping unit of E//B NPA is composed of a stripping room, a vacuum chamber and a vacuum pumping system as shown in figure 1(e). The stripping efficiency of the stripping room is calculated in the form of global efficiency $R \times f_{+1}$, where R is the non-scattered-away rate and f_{+1} is the fraction of charge state +1. The magnetic field of the E//B analyzer is produced with a permanent magnet. The magnetic poles are specially designed to focus the ion trajectories and to increase the use rate of the magnet. The shape of the magnet and the electric plates are carefully designed so that the ions are dispersed into two lines of H^+ and D^+ on the detector plane. On the detector plane, the striking points of the 10 to 200 keV ions are clearly divided into two lines and the separation between the two lines is about 1.8 cm, enough for putting the detectors.

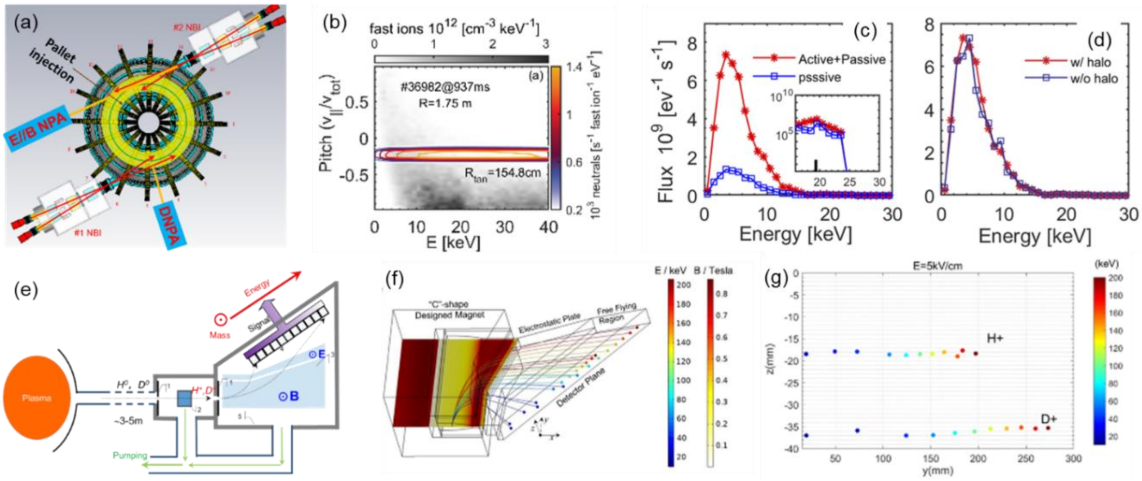

Figure 1. (a) Top-down view of relative position between NPA and NBI. (b) Weight functions of DNPA sightline in velocity space (pitch, energy), a simulated velocity space of fast ion distribution function predicted by TRANSP (gray contour). (c) Active and passive signals and (d) the contribution of halo neutrals to DNPA flux. (e) The schematic diagram of E//B NPA. (f) Flying trajectories of particles with different energy and mass in bird view and (g) detector plane view.

Poster Title
Observation of fast-ion driven Alfvén-eigenmodes in JET and their effect on turbulence and thermal transport

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Abstract

Recent experiments using the 3-ion ICRH heating scheme [Kazakov NF 2015] have been successful at generating substantial populations of MeV range fast ions in the deep core of JET, mimicking the effect of fusion-born alpha particles in future burning plasmas. These fast ions are capable of destabilizing a wide range of Alfvén modes as observed using magnetics, reflectometer and Doppler backscattering measurements. Previous nonlinear gyrokinetic simulations have shown that turbulence existing at the ion-gyroradius scale can be stabilized [Mazzi Nat. Phys. 2022, PPCF 2022], producing close to neoclassical levels of ion heat flux. This results in a thermal transport regime dominated by the electron heat flux. We report on the transport and gyrokinetic modelling using GS2 and CGYRO in conditions when Alfvén eigenmodes are both stable and unstable, as observed from magnetics and Doppler backscattering fluctuation measurements. We probe the origins of the anomalous electron thermal transport in the presence of MeV range fast ions and unstable Alfvén eigenmodes. The implications of these scenarios to burning plasmas will be discussed.

ITER poster abstract:

Energetic ions, which have greater energies than the average thermal ion in a plasma, are sourced from high power neutral heating beams or born as products of nuclear reactions. Results are presented from an investigation of linear and non-linear aspects of these instabilities in DIII-D using the Ion Cyclotron Emission (ICE) diagnostic, a non-intrusive diagnostic to observe energetic ions in fusion plasmas via radio frequency emission at low harmonics of the ion cyclotron frequencies (ie. $f < 500$ MHz), known as ion cyclotron emission, that results from these instabilities. Results are also presented for an investigation of ion cyclotron emission from negative triangularity plasmas in DIII-D. Energetic ion instabilities can eject energetic ions from the plasma, potentially making it difficult to heat the plasma and causing damage to plasma facing equipment. The DIII-D National Fusion Facility at the General Atomics San Diego, California site is currently testing the ICE diagnostic as a tool for observing energetic ions because it is potentially much better suited to a burning plasma environment than existing diagnostics for energetic ions. Current available diagnostics for energetic ions rely on collimating these ions through hardware that are sensitive to extreme environments and cannot be used in a burning plasma environment. The ICE diagnostic is a set of conductive coils that are placed on the walls of the DIII-D tokamak. Ion cyclotron emission that is excited by energetic ions can be observed with the ICE diagnostic when the emission induces a signal in the coils. This signal is passed through a set of filters and captured by a digitizer. ICE is a potentially valuable diagnostic for energetic ions and can prove to be useful for future projects in DIII-D.

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Charge particle transport across the magnetic field in plasmas containing negative ions

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Over the last several decades, in low-pressure electronegative plasmas, there has been a lot of interest in understanding the phenomenon of charge particle transport across magnetic field lines due to its overwhelming applications in plasma processing, space plasma, and ion sources. These sources' fundamental distinction from the fusion plasma is that ions are not fully magnetised. Since negative ions have a higher recombination efficiency than positive ions, they are proficient at generating a MeV range of neutral beams for auxiliary heating of the tokamak plasma up to fusion requirements. Negative ions have a mass comparable to positive ions and have the same electric charge as electrons. Thus, their presence in the discharge significantly impacts global plasma parameters, charge particle transport, and particle loss towards the walls [1].

The present experimental work investigates the effect of changes in the axial magnetic field and the axial boundaries on the equilibrium plasma parameter profile across the magnetic field in a 13.56 MHz CCRF argon and oxygen discharge. It is observed that the equilibrium plasma profiles change drastically with the external plasma-facing boundary and magnetic field [2]. A plausible explanation for the observed behaviour and its application to determining plasma electronegativity are briefly discussed.

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Neutronics Effects Study for Tritium Breeding Blanket of Fusion Reactor

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Abstract

Nuclear fusion is one of the most promising options that can provide sustainable clean energy to meet growing demand while having a relatively low impact on the environment [1]. After several decades of research and development (R&D) on magnetic confinement fusion, many of the scientific and technological obstacles to fusion have now been overcome. At present, the International Thermonuclear Experimental Reactor (ITER) is under construction in France [2]. The ITER is an international collaboration of China, India, Japan, Korea, Russia, United States of America, and Europe which will be the first burning plasma machine to demonstrate the feasibility of fusion energy [3]. To overcome the primary missions of internal fusion heating, fusion energy production with long pulses and tritium breeding testing; a tritium breeding blanket (TBB) is an essential component for the tritium breeding fusion reactors. The TBB has functions of tritium breeding, energy generation and neutron shielding. Moreover, tritium breeding ratio (TBR) is a key parameter for a fusion reactor to evaluate whether the TBB could produce enough tritium to achieve tritium self-sufficiency (TBR > 1). However, the TBR of the fusion reactor can be impacted by a number of factors, including the geometries (the opening ports to install the corresponding heating and diagnostic equipment [4], and a heterogeneous model of the blanket [5]), materials (type, density, enrichment), nuclear libraries (uncertainty) and neutron transport codes (uncertainty). Meanwhile, the tritium losses occur during the fuel cycle because of tritium decay, leakage, extraction, and retention, which is a considerable challenge to tritium sustaining. Therefore, a higher TBR is needed. According to the mentioned constraints, the study of neutronics effects for first wall region as shown in Fig.1 tritium breeding blankets would be scientific significance for fusion reactor efficiency improvement in the future.

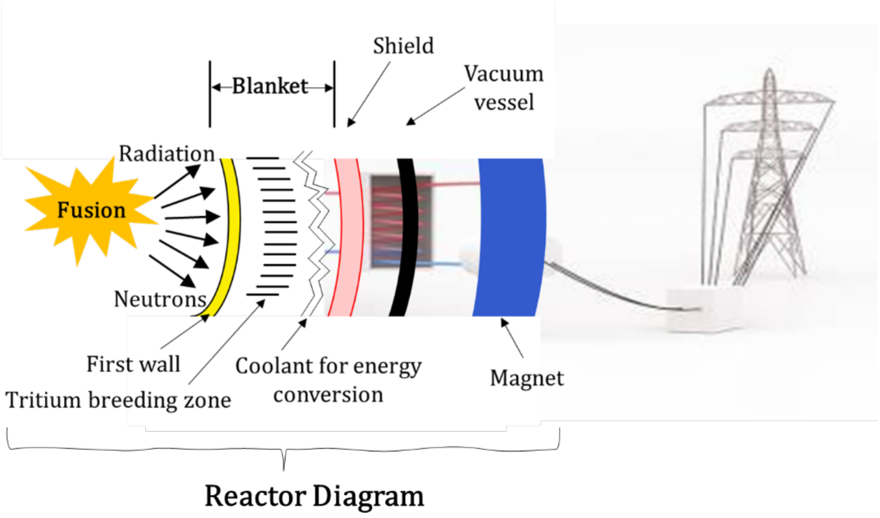

Fig. 1 Internal components and energy generation from nuclear fusion reactor walls diagram [6,7]

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First observation of energetic-electron-driven instabilities at the ion cyclotron on HL-2A tokamak

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Abstract:

Runaway electrons (REs) can form in tokamaks when large toroidal electric fields are present, typically during startup, strong radio-frequency current drive, discharge ramp down, or disruptions[1, 2]. The energy can reach several tens of MeV in present tokamaks, and in a next-step device like ITER, it can reach a maximum energy of up to 100 MeV. It can form a significant hazard to plasma-facing components, and the avoidance or dissipation of runaway electron (RE) beams in ITER and future high current tokamaks is of urgent and critical. Recent experimental results show that the runaway electrons can drive kinetic instabilities, the kinetic instabilities with a very high frequency (in whistler waves[3] and Lower-Hybrid Frequency Range[4]) have been observed on several tokamaks[5]. The instabilities driven by REs have recently received attention as it may be a mean to control and diagnose REs in a tokamak.

Coherent instabilities in the ion cyclotron range of frequencies, termed ion cyclotron emission (ICE), have been attached great importance in magnetic controlled fusion (MCF) plasmas[6-8]. From all the previous results in MCF plasmas, ICE was driven by fusion-born ions[9] and fast ions introduced by auxiliary heating method[7, 10]. In addition, ion acceleration by ion cyclotron instabilities was discovered in C-2U device, in which the instability was driven by energetic ions[11]. The wave-particle interaction between energetic particles and ICE may have great effects on fast particle confinement in ITER.

In this work, ICE driven by energetic electron is detected with the newly developed ICE diagnostic[12] on HL-2A. Characteristics including frequency, spectrum feature and amplitude dependence are investigated. The energetic electron is introduced through low hybrid wave (LHW) with the power of 350 kW. The electron energy is calculated by CQL3D code, which is about 570keV. The wave-particle resonance condition implies that the anomalous doppler resonance may be the mechanism of ICE excitation. The electron energy is also measured by hard x-ray energy spectrum. The results show that the energy of loosed electron is up to 1MeV, which is much higher than the simulation result. This work suggests that ICE may lead to pitch angle scattering, acceleration and radial loss of runaway electrons.

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Interaction of Energetic Ions and Fast Waves in the Large Plasma Device (LAPD)

In fusion devices, energetic ions are produced by ionization and charge exchange of injected neutral beams, ion cyclotron heating and current-drive, and byproducts of fusion reactions. The study of energetic ions-wave interaction on magnetic-fusion devices (e.g. dominant fast ion power absorption in some NSTX-U scenarios)[1] can be challenging due to harsh plasma environments. Doppler-shifted cyclotron resonance through a proton beam was observed to destabilize Alfvén waves on LAPD[2], an 18 m long and 1 m diameter cylindrical device, that produces a magnetized plasma ($n = 10^{11}$-10^{13} cm^{-3}, T_e= 0.1-15 eV)[3]. The high-repetition rate (0.2-1.0 Hz), good reproducibility, and various 3D diagnostic tools facilitate detailed exploration of energetic ions and fast wave interactions in LAPD. Interaction between a spiraling proton beam (2-15 keV, 15 A) and fast waves launched by a single strap RF antenna was studied. Measurements of 3D wave magnetic-field and beam profiles under varieties of conditions are presented, and energetic-ion diffusion in real and velocity space due to resonant interactions is discussed.

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Energetic Particle Marginal Stability Profile for HL-2M Integrated Simulation based on Neural Network Module

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Abstract

The critical gradient model (CGM) is employed to develop a module of energetic particle (EP) marginal stability profile in OMFIT integrated simulation for studying EP transport. Currently, each iteration of transport evolution is approximately 10 minutes in the integrated simulation, whereas, the EP marginal stability profile, which serves as an input in the integrated simulation could take much longer; the reason being a combination of the TGLFEP and EPtran codes is employed in our previous investigation. To reduce the simulation time, the critical gradient is predicted by a neural network instead of the TGLFEP code, and the EPtran code is revised with parallel computing, so that the running time of this module can be controlled to within 5 minutes. The prediction is in good agreement with previous approach. The integrated simulation of HL-2M with Alfven Eigenmode (AE) transported neutral beam EP profile indicates that EP transport reduces the total pressure and current as expected, but also surprisingly raises the safety factor in the core, which is favorable for reversed magnetic shear and high-performance plasmas.

keyword： neural network, integrated simulation, energetic particle

Multiple mode-number instabilities induced energetic-ion transport in magnetic confinement plasmas

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Under the realistic experimental condition, the simultaneous destabilization of different instabilities, such as TAE avalanche event, fishbone/sawtooth and tearing mode, can lead to the significantly enhanced transport of energetic particles due to the synergy between different kinds of instabilities, compared with the case with only one kind of instability. This experimental phenomenon has been clearly observed in some tokamak devices, such as HL-2A, NSTX, DIII-D. In addition, one of the main loss mechanisms for energetic particle in the future reactor-graded device ITER is expected to be the enhanced transport caused by multiple mode-number TAE excitation. The direct effect of mode coupling among them is the flattening of the spatial profiles due to enhanced fast ion transport, which will hinder the achievement of steady-state long pulse operation of future fusion reactor. Thus, understanding such events with multiple-mode or synergy nature is significantly vital.

In this report, two typical events with multiple-mode nature will be numerically discussed in combination with experiments in detail, one is TAE avalanche event on NSTX and the other one is the synergy between fishbone/sawtooth and tearing mode on HL-2A.

For the first example of TAE avalanche event on NSTX, the wave–wave nonlinear coupling among different modes and the resonant interaction between different modes and energetic-ions during TAE avalanches are identified in the nonlinear multiple wave-number simulations. The resonance overlap during the TAE avalanche is clearly observed and two important ingredients for the onset of TAE avalanches is identified as effective wave–wave coupling and sufficiently strong drive. TAE avalanche is considered to be a strongly nonlinear process and it is always accompanied by the simultaneous rapid frequency-chirping and large amplitude bursting of multiple modes and significant energetic-ion losses. The experimental phenomenon is observed on NSTX and is qualitatively reproduced by the simulation results in this report. These findings indicate that the onset of avalanche is triggered by nonlinearity of the system, and are also conducive to understanding the underlying mechanism of avalanche transport of energetic particles in the future burning plasmas, such as ITER.

The second example is the resonant interaction between m/n=2/1 tearing mode and energetic ions redistributed by m/n=1/1 fishbone/sawtooth collapse which is observed recently in HL-2A neutral beam injection-heated high-density plasmas. This event essentially results from a synergistic effect with a multiple-mode nature. Understanding such experimental phenomena, especially when using high-power auxiliary heating, is crucial for achieving high-performance plasmas with high confinement and high β_N in the prospective thermonuclear fusion reactors. In this report, based on the typical experimental phenomenon of synergy between fishbone/sawtooth and tearing mode on HL-2A, a self-consistent nonlinear hybrid-kinetic simulation is conducted utilizing the experimental parameters and profiles before the occurrence of this synergy as the code M3D-K input. In particular, we focus chiefly on the phase-space transport, loss and redistribution of energetic ions induced by two cases, one with only m/n=2/1 TM and one with synergy between m/n=1/1 fishbone/sawtooth and m/n=2/1 TM. It is found that the synergy of the fishbone/sawtooth and m/n=2/1 TM on energetic-ion transport, loss and redistribution is important and can dramatically enhance the loss rate of energetic ions compared with the case with only m/n=2/1 TM. It is due to the fact that such synergy can open up an efficient energetic-ion loss channel which connects the plasma center and edge. The phase space transport and redistribution of energetic ions induced by the two different cases are also respectively analyzed and compared in detail. These findings indicate that the synergy triggering the sawtooth collapse may lead to an enhancement of the energetic-ion transport and can help us understand the underlying mechanisms of synergy-induced energetic-ion transport.

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Studying fast-ion populations in MAST-U plasmas using a Solid-State Neutral-Particle Analyser (ssNPA)

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Plasmas produced in the Mega Amp Spherical Tokamak Upgrade (MAST-U) often contain supra-thermal (“fast”) ion populations, which are produced by the ionisation of injected neutral beams. The study of these fast ions is a key element of gauging the performance of these plasmas, since they play an essential role in auxiliary heating and, in some devices, current drive. One of the tools that can be used to study fast ions is neutral-particle analysis, which relies on charge exchange with beam or thermal neutrals to measure the fast-ion populations via neutrals fluxes, giving distributions as functions of radial position, energy, pitch and time. Results obtained using a Solid-State Neutral-Particle Analyser (ssNPA) will be presented from the first three MAST-U experimental campaigns. Fast ions are often redistributed or lost from tokamak plasmas due to instabilities, many of which are excited by the fast ions themselves. Measurements obtained using the ssNPA will be presented for both stable and unstable plasmas, with strong evidence of fast-ion redistribution being shown in the latter case. Modelling of ssNPA signals carried out for classically-confined fast ions will be compared with measurements in the case of stable plasmas.

Zooming into Vlasov-Poisson using a characteristic mapping method

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In this poster we present an efficient semi-Lagrangian method for solving the one+one-dimensional Vlasov–Poisson equations with high precision on a coarse grid. We show 3rd order in space and time and benchmark our framework against a classical pseudo-spectral method. As a specialty of the method we showcase an outstanding feature zooming into the fine-scale structures illustrated for a two-stream instability.

Model reduction for kinetic equations using the method of moments

Philipp Krah[1] **and Julian Koellermeier**[2]

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Applications of atmospheric re-entry and geophysical flows are characterized by a large variety of separate models for specific tasks. This model variety poses significant difficulties both for the analysis and for the numerical solution. We thus need to rethink mathematical modelling and model order reduction for future numerical simulations.

In this poster, we present hierarchical moment models as a flexible way to derive hierarchies of models in fluid dynamics and other applications. The general derivation procedure of the reduced models results in structural similarities of the models, which facilitate physical insight, model adaptivity, and the development of suitable numerical methods. Based on kinetic equations we exemplify the hierarchical moment approach and highlight runtime and accuracy improvements.

Runaway Electron Mitigation Coil Design and Predictions for the HBT-EP Tokamak

Anson Braun, Chris Hansen, Alex Battey, Carlos Paz-Soldan, Columbia University

Using the ThinCurr code [Battey *APS-DPP* 2022], we design and study the first experimental implementation of a runaway electron mitigation coil (REMC) in the university-scale HBT-EP tokamak. Assessing a variety of REMC coil designs, we select a feasible candidate coil predicted to couple well to disrupting plasmas. For typical disruption parameters, the predicted induced coil current is about 25% of the pre-disruption plasma current. The induced coil current is also shown to vary significantly by changing the plasma major radius and electrical connectivity of the outer vessel segments. These variations are readily accessible in the HBT-EP tokamak allowing for model validation across varying plasma and vessel configurations. Disruptions forces due to the REMC are predicted to be about 500 N, and plans for experimental force measurements on HBT-EP are underway. Considering upcoming plans for REMC installation in the DIII-D [Weisberg *NF* 2021] and SPARC [Tinguely *NF* 2021] tokamaks, we show HBT-EP offers a flexible testbed for the experimental validation of REMC-plasma coupling and disruption force predictions.

This work is supported by Columbia University internal funds.

Modeling of Alfvén cascades in the TJ-II stellarator with *STELLGAP* and *AE3D* codes

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Alfvénic instabilities driven by energetic particles pose a challenge to the efficient operation of magnetic confinement fusion devices. These modes can dispel fast ions leading to the introduction of significant heat loads onto plasma-facing components and degradation of overall plasma confinement. One class of Alfvénic instabilities, known as reversed shear Alfvén eigenmodes (RSAEs) or Alfvén cascades, are of particular risk in devices with reversed shear safety factor or rotational transform profiles. Reversed shear configurations have recently been of interest because of their enhancement to confinement quality; with this in mind, further study of RSAEs is necessary.

Alfvénic activity has been observed in the TJ-II stellarator [1] which resembles the frequency-sweeping behavior characteristic of Alfvén cascade modes previously seen in tokamaks. In this work, we simulate the cascade events using the STELLGAP [2] and AE3D [3] codes and study the relationship between the frequency of the modes that form the cascade and the minimum value of the rotational transform profile. The simulations predict the appearance of a cascade mode sweeping downward in frequency as the minimum value of the rotational transform profile is increased, and whose toroidal and poloidal mode numbers match those predicted in experiments. The results presented support the utility of MHD spectroscopy, a diagnostic tool whereby the temporal gradient of the frequency of an Alfvén cascade can be used to determine the variation in time of the plasma's rotational transform profile.

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Fractional Laplacian Spectral Model of Anomalous Electron Diffusion in Magnetized Plasmas with Magnetic Islands and Stochastic Fields

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Energetic electrons (EEs) in magnetized plasmas are sub-populations of particles whose energy is orders of magnitude higher than that of the bulk electrons. These particles are known to exhibit anomalous diffusion in the cross-field direction, which results in non-Maxwellian energy distribution functions. While EEs are ubiquitous in laboratory conditions (tokamaks and stellarators) and in space plasma (the solar wind and the Earth's magnetotail), their origin and dynamics are poorly understood. Here we investigate how the anomalous diffusion of such particles is affected by the magnetic field topology in magnetized plasmas using data from the DIII-D tokamak and a Fraction Laplacian Spectral (FLS) model [1]. In the FLS model, the probability for anomalous electron transport as a function of magnetic field topology is determined from the spectrum of the corresponding Hamiltonian. Here we examine the Hamiltonian structure of magnetic fields characterized by magnetic islands and stochastic regions. Nonlocal interactions due to magnetic islands are modeled by a fractional Laplacian operator, while random fluctuations of the field due to coil perturbations are represented by a stochastic potential term in the Hamiltonian.

The initial conditions for the FLS model are obtained from DIII-D experiments where Electron Cyclotron Heating and Current Drive (ECH/ECCD) pulses are used to excite electron populations around magnetic islands and stochastic regions. For each examined DIII-D experiment, TRIP3D reconstructions of the magnetic topology are used to quantify characteristic scales of magnetic islands and regions of stochasticity. Data from DIII-D energetic electron diagnostics (Thomson scattering and electron cyclotron emission) is analyzed to determine the observed electron diffusion regime (classical diffusion, sub-diffusion, or super-diffusion). The probabilities for transport calculated with the FLS model are then compared against detections of EEs from these experiments. We discuss universal relationships between magnetic island topology, the Hamiltonian operator that describes it, and the electron energy profiles expected to occur in that magnetic field.

[1] doi:10.1088/1751-8121/ab7499

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Gradient-based optimization of axisymmetric high-field mirror machines

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Troy Carter (UCLA Department of Physics and Astronomy)
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Mirror machines are a promising fusion reactor concept for generating neutrons, heat, and electricity. Recent advancements in HTS magnets and high-energy neutral beams enable access to breakeven-class mirrors with simple axisymmetric coils. We optimize potential mirror configurations, simple and tandem, using heuristics of plasma temperature, stability, and other operational boundaries. An optimization cost function is defined in SymPy. This function is then converted to JAX code which computes gradients of the cost function with respect to the machine design parameters. These gradients are then utilized for gradient-descent optimization of the reactor. Optimizations of a power plant-optimal tandem mirror and a simple mirror with maximal neutron flux are performed, as well as scans over input parameters and a comparisons of two different temperature heuristics. Preliminary results are unexpected but intuitive, such as lower tritium fuel ratios leading to higher fusion power at 100’s-of-keV ion energies. Comprehensive results of these optimizations and scans will be presented.

Impact of edge biasing on the cross-field transport and power spectra

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Electrode biasing (EB) can modify the plasma turbulence [1] in the edge and SOL regions in a tokamak. This can influence a number of transport processes such as particle and heat exhausts, material recycling etc., that can impact the particle and energy confinement time as well as the heat load on the limiter/divertor plates. We report on numerical simulation studies done in the presence of positive as well as negative EB in the edge region [2]. The simulation results show a reduction of the radial particle and energy fluxes at all the radial positions. It is found that a positive bias shifts the peak of the k_y-spectra towards a lower k_y value in the edge region, but no such shift takes place in the SOL region. A negative bias produces a negligible shift. The heat and particle fluxes in the edge region are seen to increase with the radial electric field shear in the region where a flow reversal takes place. Elsewhere, the fluxes decrease with an increase in the shear. The heat and particle loads per unit time on the limiter/divertor material plates decrease with the biasing voltages in comparison to those w/o biasing, but the load intensities increase. It is found that the blob fraction [3] decreases with the radial electric field shear but at lower radial positions around the biasing region it increases from -16 volts to +64 volts.

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Investigation of heating and particle sources locality on plasma profiles based on a three-field bifurcation approach

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Abstract:

The reduced model of thermal, particle, and turbulence intensity transport equations are used to study the effect of heating and particle sources locality on plasma profiles to mimic the impact from external heating such as ion or electron cyclotron heating and pellet injection. In this model, the turbulence equations are based on a bistable model and driven by the critical pressure gradient. The three equations are solved simultaneously using the BOUT++ physics framework, resulting in plasma pressure, density, and turbulence intensity profiles as a function of time and plasma radius. We show that the locality of the heating source has a more pronounced effect on turbulence intensity and plasma pressure profiles than the locality of the particle source because the profiles are sensitive to the heating source by the pressure gradient term in the turbulence equation. This research is supported by TSRI fundamental fund project. T. Aungcharoen would like to thank the Thai-ITER HRD program for giving me the opportunity to join the IIS2023 - 12th ITER International School.

The effects of electron-cyclotron heating on relativistic-electron plasmas in DIIID

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During the quiescent-runaway electron (QRE) phase on DIIID, a beam of runaway electrons (RE) is created and controlled within a background deuterium plasma for several seconds, allowing the complex wave-particle interactions between the REs and waves in the background plasma to be studied. Electron-cyclotron (EC) waves were applied to such a plasma, in pulses of varying power. While these launched EC waves should have been incapable of interacting directly with the RE population due to their low phase velocity their application had significant and unexpected consequences. Changes to the RE distribution function were observed, causing changes in the number and strength of RE-driven whistler waves. The visible light emission from the RE beam and background plasma was also observed to vary significantly before and after the application of EC heating further hinting at a modification to the relativistic electron population. These observations are highlighted in the poster presented along with plans for future work.

Towards non-linear hybrid simulations of the interaction between energetic particles and the plasma in realistic tokamak geometry

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Future burning plasma experiments will feature a high supra-thermal particle pressure which strongly interacts with magneto-hydrodynamic instabilities. To describe these dynamics accurately in simulations, realistic tokamak geometry, the self-consistent evolution of the plasma equilibrium, and a full-f treatment of the energetic particle population are needed. This contribution describes developments towards this goal based on the non-linear MHD code JOREK, in which a hybrid mode for energetic particles had recently been introduced based on a pressure coupling and tested linearly. The non-linear evolution of fishbone instabilities is foreseen as one of the first applications.

Title: Noncollisional Runaway Electron Mitigation Techniques on DIII-D

Coautors: A.F. Battey, C. Paz-Soldan, C. Hansen, P. Aleynikov, H. Chouhury, A. Lvovskiy, E. Hollmann, D. Weisberg, D. Spong, W. Heidbrink

Progress has been made to advance multiple non-collisional techniques for runaway electron (RE) mitigation on the DIII-D tokamak. The first technique involves the implementation of a non-axisymmetric coil designed to passively drive large non-axisymmetric fields during the plasma disruption thereby destroying flux surfaces and deconfining RE seed populations. A new three-dimensional electromagnetic modeling tool (ThinCurr) has been developed using the existing PSI-Tet finite element code in support of conducting structure design work for both the SPARC and DIII-D tokamaks. This model includes accurate details of the vacuum vessel and other conducting structural elements with realistic material resistivities. This model was leveraged to support the design of a passive runaway electron mitigation coil (REMC), studying the effect of various design parameters, including coil resistivity, current quench duration, and plasma vertical position, on the effectiveness of the coil. A second technique for RE mitigation involves a novel combination of secondary gas injection and a vertical displacement event (VDE) which enables access to a large benign MHD kinking event which allows the RE wetted area to be greatly increased which lowers the chance of damage to plasma facing components. This ‘benign termination scheme’ was explored in recent DIII-D experiments to access the effect of secondary gas quantity and compression speed on access to the final loss event. An experiment was also completed to explore the potential wave-particle interaction between launched electron cyclotron waves and the RE population. These waves do not interact directly with relativistic electrons due to their low phase velocity nor can they be injected into plasma above the cutoff density. However, a unique opportunity exists to convert the “free space” O-mode into an internal plasma slow-X mode (a.k.a Z-mode). The phase velocity of the slow-X mode can exceed the speed of light, providing the possibility for direct RE-wave interaction. Access to this conversion window was observed in recent experiments completed on the DIII-D device.

Development of surrogate models for predicting 2D plasma profiles

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Plasma processing is vital to the semiconductor manufacturing industry and is used for a wide variety of processing. It enables precise control over surface modification of semiconductor device materials, allowing the creation of intricate microscopic structures such as high-density integrated circuits. Generally, the quality of semiconductor products depends on plasma parameters during processing, such as electron and ion densities, energy distributions, and particle species. Therefore, it would significantly improve the process control if we had real-time information on the plasma's state and how it is influenced by input control parameters such as applied voltage and gas pressure. While the use of physics-based computer simulations can model the behavior of a plasma in a given system, these are generally slow and computationally expensive. In contrast, employing a surrogate model that is trained on simulation data could strike a good balance between accuracy and speed, making it suitable for applications requiring real-time process control. In this work, various neural network (NN) surrogate models, including an autoencoder NN model, have been developed to reproduce two-dimensional (2D) profiles of plasma parameters inside a device, taking results from 2D fluid simulation of radio-frequency argon discharges as training input. Among other fixed input parameters such as gas mixture and driving frequency, the fluid simulation takes the voltage between electrodes V_{pp} and gas pressure P as input, and solves the 2D profiles of plasma parameters in steady state on unstructured grids. Similarly, using the same control parameters V_{pp} and P as input, an autoencoder-type neural network, combined with a dedicated mapper, is trained to predict 2D profiles of the electric potential, electron density, Ar ion density, Ar metastable density, and electron temperature, in the same simulation domain. Predictions by the physics-based fluid simulation, in its current state, can take several days to reach steady state at several thousands of cycles. On the other hand, even a simple surrogate model can predict similar profiles of all five parameters with reasonable accuracy while only taking several hundreds of milliseconds. Although not as accurate as the original simulation results, this class of model can quickly make predictions of the steady state performance of the plasma in the same device with reasonable accuracy. However, it must be noted that intermediate values predicted by such models cannot be easily verified unlike in numerical simulations, which normally have some criteria for stability, and must be addressed before it can be practically incorporated in process control schemes.

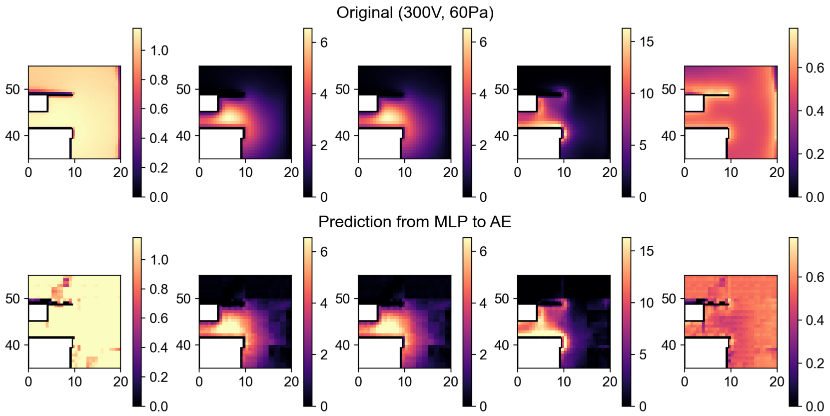

Figure 1. Prediction of 2D profiles (from left to right) of potential, electron density, ion density, metastable density, and electron temperature using a simple network.

Diagnosis of high-energy fast ions using negative-ion neutral beam injection on the Large Helical Device*

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Charge-exchange cross sections for fast-ion D-alpha (FIDA) emission peak at low relative energies around 30-40 keV, sightline geometries that reduce the relative angle to the active beamline can measure high-energy fast ions. The Large Helical Device (LHD) recently had new FIDA sightlines installed that use negative-ion neutral beam injection (NNBI) as the active source. The original sightlines used positive-ion neutral beam injection (PNBI) as the active source which has a lower injection energy than NNBI. Data from MHD-quiescent plasmas collected during the 23rd LHD experimental campaign show a Doppler-shifted peak in the FIDA feature that corresponds to fast ions that have higher energies than those seen by the PNBI view. Validation of the data against predictions confirms that carefully selected geometries allow for measurements of high-energy fast ions.

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Usefulness of CGCNN in physical property evaluation of A15-structures

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Machine learning has emerged as a new tool for efficiently predicting material properties, and structural models that learn crystal structures are superior because they provide accuracy predictions and scientific insight. In this study, using CGCNN, which is a structural model, I predicted five physical properties of A15 structural material, which is considered promising as a high-performance memory material. The prediction using only the A15 structure as training data showed low performance, but the model trained by adding data of a lot of structures to the training data showed an improvement in accuracy. The prediction accuracy of 4 out of 5 physical property values was improved, and a significant improvement was seen especially in the prediction of formation energy. However, there is a tendency for the prediction accuracy to drop when predicting some substances, so it is necessary to improve the model to deal with this.

Machine learning based analysis of etch pits on CR-39 detector for laser ion acceleration experiments

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Laser ion acceleration has been investigated for various potential applications, such as cancer therapy, ignitor for nuclear fusion, and ion radiography. Irradiating a thin foil with an intense laser, a sheath field at the rear side of the foil accelerates energetic ions[1]. Developments of advanced laser technologies[2] and target fabrication techniques[3, 4, 5] allow us to explore the energy frontier of laser-driven ion acceleration. In the laser ion acceleration experiments, the interaction between the laser and the target generates not only energetic ions but also many electrons and high-energy photons, causing strong background signals in ion diagnostics. CR-39 is widely used for ion detection in laser-driven acceleration experiments because it is insensitive to electrons and photons[6]. However, to analyze the CR-39, it is required to find etch pits created by accelerated ions in large amounts of microscope images. We have implemented machine learning on ion etch pit analysis to handle large amounts of microscope images and etch pit data. We show the energetic ions from a laser ion acceleration experiment with the help of machine learning.

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