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ABSTRACTS AND MEETING MATERIAL

16th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems — Theory of Plasma Instabilities

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Preface

Nuclear fusion is recognised as a long-term energy source. The International Atomic Energy Agency (IAEA) fosters the exchange of scientific and technical results in nuclear fusion research and development through its series of Technical Meetings and workshops.

The 16th Technical Meeting on Energetic Particles in Magnetic Confinement Systems — Theory of Plasma Instabilities (EPPI 2019) was the first joint meeting of experts from the two scientific disciplines. The event aimed to provide a forum to discuss the status of experimental and theoretical work on suprathermal electrons and ions in a wide variety of magnetic confinement geometries, and to discuss theoretical and computational physics issues relevant to burning plasmas.

The EPPI 2019 was organized by the IAEA, in cooperation with the Government of Japan through the National Institute for Fusion Science, in Shizuoka City, Japan. Previous Technical Meetings on Energetic Particles in Magnetic Confinement Systems were held in Kiev, Ukraine (1989), Aspenas, Sweden (1991), Trieste, Italy (1993), Princeton, United States of America (1995), Abingdon, United Kingdom (1997), **Naka, Japan (1999)**, **Gothenburg, Sweden (2001)**, **San Diego, United States of America (2003)**, **Takayama, Japan (2005)**, **Seeon-Seebruck, Germany (2007)**, Kiev, Ukraine (2009), Austin, United States of America (2011), Beijing, China (2013),Vienna, Austria (2015), and **Princeton, United States of America (2017)**.

In addition, previous Technical Meetings on Theory of Plasma Instabilities were held in Seeon-Seebruck, Germany (2002), **Trieste, Italy (2005)**, York, United Kingdom (2007), **Kyoto, Japan (2009)**, Austin, United States of America (2011), Vienna, Austria (2013), **Frascati, Italy (2015)**, and **Vienna, Austria (2017)**.

The main topics of the meeting were: alpha particles physics; transport of energetic particles; effects of energetic particles in magnetic confinement fusion devices; collective phenomena (i.e. Alfvén eigenmodes, energetic particle modes and others); runaway electrons and disruptions; diagnostics for energetic particles; control of energetic particles confinement; multiscale physics and instabilities in burning plasmas.

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Modification of Alfvén Eigenmode Drive and Nonlinear Saturation Through Variation of Beam Modulation in DIII-D

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Recent DIII-D experiments show that small variations in neutral beam modulation period, even with constant time averaged power input, can have a dramatic impact on the beam driven Alfven eigenmode spectrum and resultant fast ion transport. Neutral beam modulation is a common technique used in fusion experiments for regulation of injected power and various diagnostic applications, however, the period is often chosen arbitrarily or to accommodate hardware constraints without regard for the physics implications. When one beam is temporarily turned off or replaced by an unlike beam (different geometry or injection voltage), a bump-on-tail like distribution in velocity space is transiently created that can provide free energy for instability drive. The persistence of the bump-on-tail feature depends on, among other things, the modulation period. Continuous modulation which is fast compared to the slowing down time creates a more persistent velocity space inversion while slow modulation transiently creates a bump-on-tail associated with each beam pulse before filling in. For heating scenarios where different modulated beams are interleaved, the time-dependent mix also depends heavily on the modulation period. The dependence of the unstable AE spectrum on these effects is investigated in the current ramp phase of DIII-D discharges by varying beam modulation periods in a sequence of discharges with interleaved tangential and perpendicular beams. Imaging neutral particle analyzer (INPA) measurements confirm a persistent bump-on-tail feature for short modulation period. As the modulation period is incrementally increased from 7 ms to CW, the underlying mode spectrum changes from steady toroidicity induced Alfven eigenmodes (TAEs) at large radius and reversed shear Alfven eigenmodes (RSAEs) at mid-radius to modulated TAEs at large radius and a spectrum of chirping beta induced Alfven eigenmodes (BAEs) at mid-radius. The mode induced neutron deficit is also observed to decrease as modulation period is increased. In addition, for longer modulation periods, individual TAEs are found to be unstable at each tangential beam pulse with instability setting in at increasingly higher values of local fast ion density as the minimum safety factor decreases – an effect explained by reduced coupling to side-band resonances. Further, while the individual TAE frequencies are relatively constant, the saturated mode amplitudes exhibit up to 75% variation on timescales of ∼10-100 mode periods. For scenarios in which maximum beam power is not required, these results indicate that fine-scale tailoring of beam modulation and interleaving may offer additional opportunities for instability control.

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Characteristics of fast ions profile with MHD activities and improvement of fast ion confinement with AE suppression by counter-ECCD in LHD

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Characteristics of fast ion profile with MHD activities have been investigated in LHD deuterium experiments. The beam deposition profiles are changed by means of the selection of the operational ion source in tangential NBIs. Two ion sources are mounted on tangential NBIs with different tangential radius, therefore, the combination of ion sources operation and plasma position control enables us to change the beam deposition profiles in LHD plasmas. The demonstration of fast ion profile control without any Alfven eigenmode (AE) activity ($V_{\rm fast ion} < V_{\rm Alfven}/3$) was carried out. Qualitative agreement of neutron emission profile was obtained between the numerical calculation (GNET code [1]) and the experimental observation with the vertical neutron camera (VNC) [2].

In the case of existing MHD activity ($V_{\rm fast ion} > V_{\rm Alfven}/3$), two types of characteristic of fast ion profiles were identified depending on the bulk plasma density. In low density regime, experimentally observed fast ion profiles are independent of the beam deposition profile, which is very similar to the profile stiffness observed in DIII-D plasmas [3] and in a hybrid simulation [4]. On the other hand, in the high density regime, the fast ion profile changes depending on the beam deposition profile.

The effects of ECH and ECCD application on the fast ion confinement characteristics have also been investigated in low density regime where the experimentally observed fast ion profile exhibits profile stiffness properties. In the case of ECH application, no clear changes of neutron emission were observed, although some changes in AE activity were observed. On the other hand, in the case of ECCD application, clear stabilization of AEs with counter-ECCD and destabilization of AEs with co-ECCD were observed. The neutron emission was significantly enhanced when AEs were stabilized with counter-ECCD application. The smaller neutron emission with co-ECCD was observed in comparison to those in ECCD-free cases, although the electron temperature is almost double in the plasma with the co-ECCD application.

The experimental results demonstrated that the fast ion profiles in low density regime with AE activity exhibits profile stiffness properties, and the ECCD application has the capability to overcome the profile stiffness properties and to improve fast ion confinement of fast ions through suppression of AE activity.

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Efficient generation of energetic D ions with the 3-ion ICRH+NBI synergetic scheme in H-D plasmas on JET-ILW

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An extended version of the 3-ion scheme relies on using fast NBI ions as resonant species for heating mixed plasmas[1,2]. NBI ions can efficiently absorb RF power at the mode conversion (MC) layer, where the wave polarization is particularly favourable for ion cyclotron heating, through their Doppler-shifted resonance. This advanced ICRH+NBI scheme was earlier observed in D-3He plasmas on JET[3] and was recently demonstrated in JET-ILW H-D plasmas[1]. The neutron rate was increased by a factor of 10-15, when 2.5MW of RF power was coupled in addition to 3.5MW of D-NBI. In this contribution, we summarize fast-ion observations, confirming the high-efficiency of the 3-ion D-(DNBI)-H scheme to accelerate D-NBI ions to higher energies with ICRH. Good agreement between a range of fast-ion diagnostics (including the neutron rate, neutron spatial profile and energy spectrum, neutral particle analyzer, gamma-ray spectroscopy and MHD analysis) and time-dependent ICRH modeling (TRANSP/TORIC and PION) has been achieved[4,5].

The developed scheme is also relevant for fast-ion studies in stellarators. Since stellarators generally poorly confine energetic trapped ions, recently an idea of passing particle acceleration with ICRH was proposed for W7-X [6]. This idea relies on channeling RF power to resonant ions with a large Doppler shift, leading to more efficient increase in their parallel kinetic energies due to ICRH. In addition, as follows from the analysis of here reported JET experiments, plasma parameters for the 3-ion D-(DNBI)-H scheme can be tuned to provide strong core localization of RF power deposition, corresponding to the location of the MC layer in the plasma. This, in turn, brings forward effects associated with the non-standard particle orbits in the plasma core and sets up an additional spatial filter for resonant wave-particle interactions. For the conditions of the 3-ion JET experiments, theoretical analysis of the quasilinear evolution of ICRH-heated ions shows that originally passing NBI ions do not cross the trapped-passing boundary during their acceleration due to ICRH. These results are also backed up by TRANSP/TORIC modeling of JET pulse #91256[4]. Figure 1 illustrates ASCOT-computed orbits of passing NBI ions (ED=100keV, v||/v=0.62) and passing ICRH+NBI ions (ED=500keV, v||/v=0.45), together with the spatial distribution of the left-hand polarized RF electric field |E+|^2 (TORIC code).

We conclude the contribution with the discussion of the implications of the 3-ion schemes in D-3He and D-T plasmas on JET. In particular, these experiments could provide a deeper insight on the impact of highly energetic ions, mainly those in the alpha particle energy range, on the ITG turbulence. This can significantly clarify the role of alpha particles on ITER plasmas, for which recent theoretical studies have shown that they could significantly reduce heat transport [7].

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![Fig1][8]

[8]: https://i.ibb.co/Gkrg1gv/Figure01.jpg

Electromagnetic turbulence suppression by energetic particle driven modes

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Transport due to plasma turbulence determines the energy content and thus the performance of a tokamak reactor. A recent striking observation in experiments [1,2] and numerical gyrokinetic simulations [3] is the particularly interesting link between the presence of fast particles and a substantial improvement of energy confinement. These findings are intriguing in view of reactor-grade plasmas, which will naturally contain a high fraction of fast ions. The underlying physics has been shown to be rather complex. Besides the possibility of a linear resonant stabilization of the ion temperature gradient (ITG) modes due to fast ions in particular circumstances [4], micro-turbulence, axisymmetric zonal flows and energetic particles driven modes, such as Toroidal-Alfvén-eigenmodes (TAE) strongly interact via nonlinear mode coupling. A detailed analysis based on gyrokinetic GENE simulations has shown for the first time a clear and coherent picture of the role of energetic particles in nonlinear electromagnetic plasma scenarios [5]. A new approach based on a frequency-spectral decomposition of the free-energy balance reveals that fast ions lead to a reduction of the heat fluxes through the excitation of marginally stable Alfvén modes in the frequency range of TAEs, which (i) deplete the energy content of the turbulent (ITG) modes and (ii) can act as an additional mediator for an increased zonal-flow activity. In particular, an increased zonal-flow activity mediated by high-frequency modes with relatively low wavelength has been observed in different simulation setups corresponding to both ASDEX Upgrade and JET discharges with improved ion energy confinement. The details of the coupling processes are clarified.

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Study of shaping effect on ITG/TEM instabilities through full-f gyro-kinetic simulation

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In Tokamak plasmas, the modification of magnetic shaping can cause significant influence on both magnetohydrodynamic (MHD) and drift-wave instabilities, and thus affects the confinement performance to a large extent. For instance, the effect of elongation has been proved to increase the global energy confinement time as seen in the ITER IPB98(y, 2) H-mode confinement scaling: _E ^0.78. In the past decades, people found that the D-shaped plasma can give a much better core confinement, which has a high edge pressure limit and is consistent with the reduced edge transport by the H-mode operation. Due to this advantage, such a magnetic shaping is utilized in most present and being constructed Tokamaks including ITER.

On the other hand, a negative triangularity shape which exhibits better confinement even under the L-mode has been frequently discussed recently. Characteristics of plasma instabilities in such a geometry have been widely studied numerically and experimentally [1∼3]. Since this shaping can have larger power handling area at the low-field side, it is considered to be a possible scenario of Tokamak reactor. However, lacking of theoretical analysis and global full-f simulation, its effect on turbulent transport in the toroidal system due to multi-scale ion temperature gradient (ITG) and trapped electron mode (TEM) instabilities is still not fully understood.

In this work, the effect of plasma shaping on linear ITG/TEM instabilities is studied based on the full-f GKNET (Gyro-Kinetic Numerical Experimental Tokamak) code. Utilizing the fixed boundary equilibrium code, elongations and triangularity (positive and negative) are scanned to study their influence on ITG/TEM instabilities and corresponding heat transport. At first, linear growth rate and corresponding mode structures are discussed based on the parameter scan. Then, dynamics of linear TEM instability is studied in the negative triangularity shaped plasma. It is found that the tilting of eigenmode structure may be responsible for the reduction of turbulent transport. This work can greatly help us to understand underlying physics of confinement performance change in the shaped plasmas. Hopefully it will be interested in the fusion community.

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Excitation of Alfven Eigenmodes and Formation of ITB during off-axis Sawteeth in EAST

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The internal transport barrier (ITB), Alfven Eigenmodes (AEs) and double tearing modes (DTM) have been observed during the off-axis sawteeth oscillation in EAST.

The ITB of electron temperature T_e is modulated by the sawteeth oscillation, and the formation of ITB can be divided into three stages: (1) the transport produced by sawteeth final crash is suppressed at the first stage with steep gradient of T_e; (2) the micro-instability is developed at the second stage for the further increasing of the gradient of T_e; (3) the ITB is formed eventually after the transition from BAEs to RSAEs, where the BAEs-RSAEs pair enables the tracking of q_min 1 from the experiment directly.

Furthermore, a new BAAE-like instability is also observed that is coexisted with BAEs pair, while the frequency of the former is far below than the latter. The BAAE-like locates outward than the BAEs pair as Ref [1]. Interestingly, the triangle shape of the two modes are similar that travel in ion diamagnetic drift direction, and the phases of outer regions is lag behind than the center as Ref [1-4]. The radial position of BAAE-like shifts inward after the excitation of RSAEs, and the frequencies of BAAE-like and RSAEs are sweeping upward.

The off-axis sawteeth final crash is triggered by DTM: (1) the DTM can be excited by the redistributed of the profile of thermal particles, where the downward transport of energetic ions is detected indirectly by the SXR arrays for the first time; (2) the DTM can be excited by the transformed from kink instability.

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Magnetic Reconnection during Fast Ion Driven Alfvénic Activity

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Recent simulations of so-called Abrupt Large-amplitude Events (ALE) driven by beam ions in JT-60U show evidence of transient changes in the magnetic topology on the sub-millisecond time scale, giving rise to moderately sized magnetic islands [1]. Since the configuration at hand is magneto-hydrodynamically (MHD) stable with respect to reconnecting instabilities in the range of toroidal mode numbers considered ($n = 1,2,3$), a significant amount of mode conversion must have taken place via parity mixing. Although this is physically possible within the framework of nonlinear resistive MHD [2], the result is nevertheless surprising since the effectiveness of parity mixing at the relatively high frequencies (40-$60\,{\rm kHz}$) of the shear Alfvén waves seen during ALEs is not immediately evident. If the numerical prediction can be verified and validated, driven magnetic reconnection may explain the enhanced electron transport seen during ALEs in JT-60U [3]. Moreover, this finding may have significant impact beyond fusion plasmas, for instance in the context of so-called flux transfer events (FTE) in the Earth's magnetopause [4, 5].

Here we report results of a sensitivity study, which is one step towards our goal to clarify the reconnection process that occurs in our ALE simulations. Using the hybrid code MEGA [6, 7], which simulates the self-consistent interaction between beam ions (modeled kinetically) and MHD fluctuations, we test how the numerical parameters affect the evolution of MHD fluctuations with $n = 1,2,3$ during one of the events reported in [1]. It is confirmed that the overall ALE dynamics and magnetic island sizes are similar when the spatial resolution and the number of quasi-particles is increased. Randomizing the initial quasi-particle positions along the toroidal angle φ (i.e., changing the discretization noise) is found to have a noticeable influence on the timing of the ALE, akin to the proverbial "flap of a butterfly's wing causing a tornado". Variations between ALEs in different simulations provide new insight concerning multi-mode interactions [1].

The next step is to study the role of dissipation. The default values of the resistivity, viscosity and thermal diffusivity are $\eta/\mu_0 = \nu = \chi = 10^{-6} v_{\rm A0} R_0$, with Alfvén velocity $v_{\rm A0}$ and major radius R_0. Simulations are underway to simulate an ALE with weaker dissipation ($3\times 10^{-7} v_{\rm A0} R_0$). Our first results on this front indicate that weaker dissipation reduces the threshold in the fast ion pressure gradient at which an ALE can be triggered.

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Stability of Low Frequency Fast-ion Driven Instabilities in DIII-D

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Although the stability of ellipticity, toroidal and reversed-shear Alfven eigenmodes (EAE, TAE, RSAE) is relatively well understood, less is known about the stability of lower-frequency modes such as the beta-induced Alfven eigenmode (BAE), the beta-induced Alfven-acoustic eigenmode (BAAE), and the energetic-particle geodesic acoustic mode (EGAM). Because they are often unstable in present devices and are implicated in fast-ion transport, understanding their stability is vital. To that end, a database of ∼1000 beam-heated discharges has been assembled. Modes are classified based on electron cyclotron emission, beam emission spectroscopy, magnetics, and interferometer data. The database is limited to the initial two seconds of the discharge, where the evolving q profile facilitates identification of RSAEs and provides an effective scan of the dependence of stability upon q. Preliminary analysis indicates that, during the current ramp, TAEs and RSAEs are unstable more often than BAEs and BAAEs. BAEs are more likely to be unstable when the poloidal beta exceeds 0.5 and for particular values of q. BAAEs with a characteristic ”Christmas light” pattern of brief instability as q evolves occur in low beta plasmas with relatively high electron temperature. EGAMs are more common in plasmas in which counter injection and plasma currents between 0.4-0.85 MA cause a significant loss cone. Analysis of representative cases by LIGKA, FAR3D, and GTC is planned. If available, results from a scheduled experiment to determine the relative importance of fast ions and thermal pressure gradients in driving BAE and BAAE instability will also be presented.

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Effects of spatial channeling on the structure of Alfvén eigenmodes

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The energy and momentum transfer across a magnetic field realized by destabilized magnetohydrodynamic (MHD) eigenmodes - the phenomenon named Spatial Channeling (SC) - can be an important factor affecting the plasma performance [1]. It takes place when sources and sinks (s&s) of energy are located in different regions, i.e., when the region where particles (e.g., fast ions) drive the plasma instability does not coincide with the region where the destabilized waves are damped. Depending on the location of these regions, the SC can be directed outwards (see, e.g, [1, 2]) or inwards [3, 4]; the former leads to degradation of the plasma energy confinement, and the latter improves the confinement. The eigenmodes in toroidal systems can be treated as a superposition of two travelling waves, one of them moving outwards and the other moving inwards. In the absence of s&s, the energy flux densities across the magnetic surfaces of the traveling waves exactly compensate each other. The presence of s&s breaks the balance, leading to the flux across the magnetic field, $S_\perp$, which affects the mode spatial structure. The presence of the transverse energy flux, in addition to the longitudinal flux, $S_\parallel$, implies that the total flux is oblique and the wave front is curved. However, when s&s are weak, the mode "survives".

To study these effects of the SC, an equation for TAE modes with the s&s radially separated was solved. It was found that both the mode structure and the mode frequency (ω) changed. In addition, a radial spiral mode structure was obtained, see Fig. 1. This took place even when the plasma was marginally stable ($\gamma/\omega\approx0$, with γ the instability growth rate), but the energy source was sufficiently strong, γ_α^L 0.1 (γ_α^L is the local instability growth rate in the region where drive dominates). It seems possible that the SC might be responsible for the radial spiral mode

structure observed in DIII-D and NSTX [5,6]. The SC can also be a factor playing a role in saturation of Alfvén modes.

![poloidal mode structure][a]

Figure 1: Spiral structure of a driven TAE mode with the mode numbers $m=1/2$, $n=1$, when the region where particles drive the plasma instability does not coincide with the region where the mode is damped. Φ is the scalar potential of the electromagnetic field.

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[a]: http://atyk.lan.ua/spiral.jpg "Figure 1"

MHD spectroscopy of pellet injected plasmas

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In magnetic confinement devices, pellet injection is used to refuel the core of the plasma, control edge localised modes, and mitigate disruptions. These varied applications require drastically different pellets. As a result, the timescales of pellet assimilation can vary significantly depending on the experiment and machine. Diagnosing the effect of the pellet on the plasma represents an important but challenging task because of the short lifetime of the pellet and complexity of the pellet assimilation into the plasma. MHD spectroscopy provides information on the density of ions deposited by the pellet with excellent time resolution.

Alfvén eigenmodes driven unstable by energetic particles are ubiquitous in tokamak plasmas. The frequencies of Alfvén eigenmodes drop significantly during pellet injection, making them an attractive candidate for MHD spectroscopy [1]. We demonstrate how key pellet parameters can be inferred from the observed changes to the Alfvén eigenfrequencies. MHD spectroscopy of pellet injected plasmas was enabled by generalising the 3D MHD codes Stellgap [2] and AE3D [3] to incorporate 3D density profiles. 3D density profiles were generated using a model for the expansion of the pellet wake along a magnetic field line derived from the fluid equations. Thereby, we obtain the time evolution of the Alfvén eigenfrequencies. From the change in mode frequency, we estimate the density of the pellet wake and the timescale for poloidal homogenisation of the wake.

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Fast ion instabilities in DIII-D hybrid discharges

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Significant variations in MHD activity and fast-ion transport are observed in high-beta, steady-state hybrid discharges with a mixture of Electron Cyclotron (EC) waves and Neutral Beam Injection (NBI). For neutral-beam-only heating, many Alfven Eigenmodes (AE) are observed at frequencies of 100-250 kHz that cause a ~35% degradation in the neutron rate. With both NBI and EC, the AE activity is usually suppressed and replaced by low-frequency fishbone-like bursts. It has been suggested that the change in MHD activity occurs because qmin dropped close to unity during EC current drive, and this hypothesis is supported by kinetic/MHD hybrid simulations for a pair of DIII-D hybrid shots [Z. Z. Ren, G. Y. Fu et al., Phys. Plasmas 25, 122504 (2018)]. However, experimental cases exist where the MHD activity changes significantly, but the q profile apparently does not. A recently compiled database shows that change of the perpendicular fast-ion pressure is the main factor responsible for the transition in mode activity. The database suggests that appearance of fishbone-like bursts occur when Phot/Ptot is larger than 0.55, where Phot is the central energetic particle pressure and Ptot is the central total pressure. The gradual decrease of q in some EC cases also facilitates the appearance of fishbones. The simulations with kick model for hybrid shots confirm that the drive for low-frequency fishbones is mainly trapped particles, while AEs resonate with fast ions in a large portion of phase space. An increase of plasma temperature in hybrid discharges generally results in a larger fast ion population, which increases the drive of fishbone instability. The destabilized fishbones redistribute fast ions, and then affect the drive of AEs. This hypothesis is also supported by the observation that fishbone-like bursts are rarely seen in counter-NBI hybrid shots. Kinetic/MHD hybrid simulations are being performed to check the hypothesis.

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Observation of Non-Collisional Bulk Ion Heating by Energetic Ion Driven Geodesic Acoustic Modes in LHD

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In a reversed magnetic shear (RS) plasma produced by tangential counter neutral beam injection (NBI) having high beam energy of ∼160 keV in LHD [1], bulk ion temperature at the plasma center Ti(0) measured by soft X-ray crystal spectrometer (XICS) often increases linearly in time for ∼0.3-0.4 s by a factor of ∼ 1.5-1.7 in the constant electron density and NBI absorbed power phase. The Ti(0)-increase begins when the off-axis minimum of the rotational transform decreases beyond the rational value 1/3. The value reached at the end of the Ti(0)-increase is the same as or slightly above the central electron temperature (Te(0)∼ 1.3 keV). In the latter case, two dimensional XICS shows that the region of Ti > Te extends in the plasma core region of <r>/<a> < 0.5, where <r>/<a> is the normalized minor radius. At the onset of the Ti(0)-increase, plasma potential fluctuation amplitude of energetic-ion-drive geodesic acoustic mode EGAM [2] measured by heavy ion beam probe decreases noticeably (by about ∼30- 40%). The fluctuation amplitude is kept nearly constant having large value of ∼1.3 kV at the plasma center, during the Ti(0)-increase phase. The Ti(0)-increase ceases by a sudden and large jump up of the EGAM amplitude, correlated with sudden drop in the reversed shear Alfven eigenmode (RSAE) and EGAM frequencies. This frequency drop suggests rapid change in the rotational transform profile. Turbulent density fluctuations in the plasma central region measured by CO2 laser phase contrast imaging are not suppressed during the Ti(0)-increase, but are slightly enhanced in the range of k__ _i ∼ 0.7 (k__ : perpendicular wavenumber, _i: bulk ion gyro radius). Density fluctuations in plasma edge region remain unchanged. In this RS plasma, less than 5% of NBI absorbed power is transferred to bulk ions by collisional process. Bulk ion heating power density estimated from experimental data is comparable to the power density generated by ion Landau damping of EGAM excited. In the estimation of EGAM damping rate, the rotational transform at the plasma center is inferred from the observed frequencies of fundamental and 2nd order RSAEs. This ion-temperature-increase observed in the LHD RS plasma is thought to be a clear example of energy channeling from energetic ions to bulk ions via EGAMs.

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Residual Zonal Flows for non-Maxwellian Equilibrium Distribution Function

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Residual zonal flow level R_{ZF} [1] is one of the key relevant quantities which determine turbulence and transport of tokamak plasmas [2]. While there have been various theoretical extensions of the original work in Ref. [1] including the isotopic dependence [3], most previous works have assumed Maxwellian equilibrium distribution function F_{0} with rare exceptions, for instance Refs [4,5]. Neoclassical polarization shielding determines the long term behavior of zonal flows and it can be derived in the context of modern gyrokinetic [6] and bounce-kinetic theories [7]. This approach not only elucidates the underlying physics of residual zonal flows, is but also applicable to an arbitrary F_{0}. Using this method, we show that the long wavelength, high aspect ratio result, $R_{ZF}=\frac{1}{1+1.63q^{2}/\sqrt{\epsilon}}$ derived for a Maxwellian F_{0} in Ref. [1] remains valid for any F_{0} which is isotropic in velocity space. In addition, it is found that presence of high energy ions such as fusion product α-particles described by slowing-down F_{0} can enhance R_{ZF} considerably in the intermediate wavelength regime $k_{r}\rho_{Ti}\sim 0.1$ [4]. This presentation will cover the physics behind the neoclassical polarization shielding and long term asymptotic behavior of zonal flows and the effects of the fusion product α-particles on these.

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Influence of fishbone-induced fast-ion losses on rotation and transport barrier formation in MAST

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Radial currents, which occur when energetic particles are expelled from the core of a tokamak plasma, produce torques on the plasma in both toroidal and poloidal directions, due to return currents that maintain quasi-neutrality [1]. The poloidal component of this rotation is predicted to be damped on the ion-ion collision time [2], whilst the toroidal rotation component relaxes more slowly on the momentum confinement timescale. The resulting change of the flow shear can suppress turbulence and improve transport, leading to an internal transport barrier (ITB). This process has been observed in both tokamaks and stellarators alike (for non-optimized stellarators, flow is expected to be damped in all directions). Since transport barriers play a key role in scenario evolution, understanding the trigger for barrier formation is likely to be an important factor in determining the types of scenarios that can be realised in the Mega Amp Spherical Tokamak-Upgrade (MAST-U) and other machines. We investigate a possible role of fast particle losses and redistribution in this trigger.

In MAST ITBs often formed early in discharges during the current ramp [3] and tended to coincide with the occurrence of Toroidal Alfvén Eigenmode (TAE) bursts, which were eventually replaced with fishbone instabilities as the q profile decreases. The toroidal rotation shear increased as the transport barrier was forming during the early phase of the discharge. However it was difficult to establish a causal link between fast ion instabilities and the flow shear required to produce the transport barrier due to the limited time resolution of charge exchange recombination spectroscopy (CXRS) rotation diagnostics.

A Doppler back-scattering system (DBS) on MAST was used to measure the perpendicular phase velocity of density turbulence ñ (this was generally dominated by ExB drifts), as well as the ñ magnitude, with sub-ms time resolution. Recent careful analysis of DBS data from MAST has revealed that rapid changes in both the phase velocity and fluctuation amplitude coincided with fishbone bursts. The magnitude of the velocity changes will be compared with fast ion losses inferred from fast-ion diagnostics - including a fast ion deuterium-alpha (FIDA) spectrometer system and a neutron camera (NC), and this information will be used to establish the role of fast ion instabilities in transport barrier formation. The full-orbit code HALO, with imposed perturbation fields of the fishbones, will also be used to model the torques and fast ion losses.

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Investigation of beam-ion transport and acceleration during edge localized modes in the ASDEX Upgrade and MAST Upgrade tokamaks

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Observations of beam-ion acceleration during edge localized mode (ELM) crashes have been recently reported in the ASDEX Upgrade tokamak [1, 2]. In this work, fast-ion transport during ELMs is investigated using full orbit simulations with the ASCOT code [3] and measurements from a fast ion loss detector (FILD) [4, 5, 6, 7].

Time-evolving 3D electromagnetic fields have been coded up in ASCOT to compute fast-ion orbits in the presence of fast MHD events such as ELMs, in which the perturbed electromagnetic field changes on fast-ion orbital time-scales. The time-dependent module uses a 4D cubic spline interpolation of the evolving magnetic and the electric field vectors, computed on a uniform cylindrical grid. The module has been successfully tested against a model that describes perturbations using a Fourier decomposition along the field lines. The time-evolving electromagnetic field in ASCOT, together with a 3D model of the tokamak wall, makes it possible to evaluate the velocity-space distribution of the fast-ions impinging on the FILD probe, which is used to construct a synthetic FILD signal during the ELM crash.

Using electromagnetic fields of an ELM crash in ASDEX Upgrade modelled with the hybrid kinetic-MHD code MEGA [8] and a continuous NBI-birth fast-ion distribution from ASCOT, a synthetic signal of the ASDEX Upgrade FILD array is obtained that can be compared with experimental measurements. Similarly, a synthetic signal of the FILD in MAST Upgrade is constructed using the electromagnetic field during an ELM crash simulated with the non-linear resistive MHD code JOREK [9] and the NBI birth distribution from ASCOT, making it possible to investigate the presence of a high-energy component in the signal and giving a first prediction of the fast-ion losses during an ELM crash in MAST Upgrade.

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Explosive Alfven Event in HL-2A H-mode Plasmas

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The nonlinear dynamics of shear Alfv{\'e}nic wave fluctuations have become a major concern in magnetically confined fusion, since they can be driven unstable by energetic particles (EPs).

In the present paper, the nonlinear dynamics of toroidal Alfv{\'e}n eigenmodes (TAEs), including nonlinear wave-particle and wave-wave interactions, have been observed in the HL-2A NBI H-mode plasmas. It is found that there are strong nonlinear mode couplings between TAEs with n=3 and low frequency MHD mode (kink or fishbone) with n=1. The pitch-fork phenomena of TAEs can grow explosively and become an explosive instability. The explosive events have two kind fine structures, i.e., multi-modes and pitch-fork. The two kind structures can coexist, but the strong nonlinear mode coupling induces that the pitch-fork weakens or vanishes and the modes blow-up in finite-time, and this indicates that the nonlinear mode coupling may redistribute energetic-ions, destroy hole-clump pairs in the phase-space, and induce three-wave mixing nonlinearly. As a consequence, the TAE nonlinear dynamics can trigger the onset of ELMs and pedestal collapse within several hundred Alfv{\'e}n times. Following the continuous appearances of rich nonlinear dynamics phenomena, more attentions should be paid to understand the underlying mechanisms, as experimental verification of numerical simulations and analytical theory, that are developed for the predictive ability for future burning plasma scenarios.

Non-linear 3D hybrid kinetic-MHD simulations of ELMs in the ASDEX Upgrade tokamak with MEGA

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A strong interplay between edge perturbations, such as edge localized modes (ELMs) and fast-ions has been observed experimentally [1]. Furthermore, beam-ion acceleration during an ELM was observed for the first time in the ASDEX Upgrade tokamak [2]. All these findings indicate that kinetic effects of fast-ions should be considered in ELM modelling. For this purpose, non-linear hybrid kinetic-MHD simulations of an ASDEX Upgrade reference case [3] have been performed using the code MEGA [4]. First, large type I ELMs are simulated with the code MIPS [5], the MHD component of MEGA, utilising both standard and extended MHD models in a fully 3D and realistic X-point geometry. Standard MHD simulations reveal a linear phase in which medium *n* ballooning modes are the most unstable. In the non-linear phase, lower *n* modes grow due to non-linear coupling between different harmonics until a saturated phase is reached [6]. During this phase, heat flux and particle transport towards the scrape-off layer (SOL) is enhanced. On the other hand, extended MHD simulations including diamagnetic, toroidal and the recently implemented neoclassical flows, show a stabilizing effect on the ballooning modes obtained with the standard MHD model. Preliminary results on the interaction between fast-ions and ELMs will be presented.

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Passing fast ion transport induced by fishbone on the HL-2A

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A newly developed beam emission spectroscopy (BES) diagnostic system has been installed on HL-2A tokamak. Initial 48 channels has been deployed and high spatial (Δr 1 cm, Δz 1.5 cm) and temporal (Δt = 0.5 s) have been achieved. In last campaign, the second neutral beam line has been installed on HL-2A tokamak, providing an opportunity to utilize BES system to study the energetic particle transport on edge region during core plasma instabilities, based on the measurement of passive fast-ion D-alpha (FIDA) signal. Passive FIDA signal means the radiation emitted by charge exchange (CX) between the beam ions and the background neutrals. The BES response suggests that the fishbones ($\sim$20 kHz) in the core region induce the transport of passing fast ions with full energy ($\sim$40 keV) to the edge region. FIDASIM prediction confirms that the reliability of BES measurement. We will carry out the particle tracing code to study the effect of fishbone on fast ion transport in numerical and the comparison between the theoretical and the experimental results.

Effects of the non-perturbative mode structure on energetic particle transport

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Energetic particle (EP) transport in the presence of Alfvenic mode determines the EP profiles and plays a crucial role in confinement. In order to model the EP transport efficiently, mixed linear-nonlinear recipes are used in various codes [1,2,3], in which the mode structure is from linear simulation and is used in the EP transport calculation. For "perturbative" approach, the linear mode structure is calculated without taking into account the EP effects [4]. In this work, the effects of non-perturbative mode structure are studied by considering EP's effects on the mode structure and in turn, the effects on EP transport. In particular, the mode structure with symmetry breaking properties in terms of net radial propagation or parallel propagation is adopted [5]. The radial mode structure $A(r)=exp

Design optimization of a fast-neutron detector with scintillating fibers for triton burnup experiments at fusion experimental devices

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Time-resolved triton burnup studies have been carried out to estimate the behavior of alpha particles in DD fusion experimental devices. In those studies, 14 MeV neutrons emitted through DT reactions in DD plasmas should be measured selectively in the backgrounds of DD neutrons and gamma rays. For that purpose, a scintillating fiber (Sci-Fi) based fast-neutron detector has been adapted because of its advantages such as fast response, design flexibility in detection efficiency by changing the number of Sci-Fi and discrimination property against 2.4 MeV neutrons produced through DD reaction and gamma rays. However, as an optimization study of its design parameters to meet the requirements as 14 MeV neutron detector has never been done, its length had conventionally set to around 10 cm. In the present study, we tested three types of Sci-Fi detectors with three different lengths and compared with the simulated results of energy deposition, through which we tried to understand the phenomena in the detection process of fast neutrons. From the results, it has been shown that, due to the self-shielding of neutrons by Sci-Fi and the attenuation of scintillation photons during the transmission process to the photomultiplier tube, the optimal length of Sci-Fi is concluded to be about 6 cm.

Validation of the Imaging Neutral Particle Analyzer via Pitch Angle Scattering of Injected Beam Ions*

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The pitch angle scattering rates of deuterium beam ions in low density, nearly MHD-quiescent plasmas are measured using an imaging neutral particle analyzer (INPA) in DIII-D. The INPA is a scintillator-based diagnostic that provides energy and radially resolved measurements of confined fast ions [1]. The main purpose of this study is to validate this novel diagnostic system during classical fast ion behavior. The pitch angle scattering rate is manipulated by varying the electron temperature using electron cyclotron heating (ECH) and by changing Zeff through neon gas puffing. To compare with the experimental data, a series of synthetic INPA images are simulated through the following steps: (1) the time evolution of the fast ion distribution is obtained by the NUBEAM module of the TRANSP code; (2) the neutral flux towards the INPA is estimated by the FIDASIM code; (3) the INPASIM code simulates the neutral-foil interaction and traces the ions to the strike position of the INPA phosphor [2]. Preliminary results show agreement within 25% error in signals produced by the probing beam. In addition, a sensitivity study on the INPA phase space was performed by artificially varying the pitch angle scattering rate (through Zeff) to observed the change in signal detected. It was found that in general, the signal levels decreased as the pitch angle scattering rates increased and vice versa.

Signals produced by sources other than the fast ion interaction with beam neutrals are also investigated. The charge exchange process between confined fast ions and edge cold neutrals is modelled and compared to the measurement. The result can partially account for the image deficit. A separate set of signals that are unaccounted for in the simulation are distinctly observed and are thought to be asymmetric signals produced by newly born fast ions on the first few orbits for three reasons: (1) the energy of the particle corresponding to the signal matched the energy of a single neutral beam; (2) the temporal appearance of the signal is strongly correlated with the timing of the specific beam; (3) the signal does not appear to change in magnitude with different pitch angle scattering rates. To investigate this further, simulated fast ion orbits are followed in reverse and evaluated on whether they passed through the beam footprint and have the correct velocity space requirements. Preliminary statistical results show that this is a reasonable possibility.

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Role of fast-ion transport to sustain the high q min profile in KSTAR discharges

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Recently, a high q min scenario has been developed in KSTAR by controlling the plasma current ramp-up rate and the heating/shaping timing. An interesting finding is that a steady-state high and broad q profile has been sustained even without strong off-axis current drive scheme. Time-traces of magnetics/ECE spectrogram clearly show that Alfvenic kind activities appeared as the high/broad q profile is formed. In this study, the effect of Alfvenic modes and accompanying fast ion transport on the formation of the broad current profile is explored. Making high safety factor scenario in 2018 campaign has been succeeded with combination of different perpendicular component NB sources and all of them show similar MSE and spectrogram diagnostic patterns. Consequently, those shots are chosen as the main analysis target. The frequency of the magnetics/ECE spectrogram and the electron temperature fluctuation pattern of the ECE / ECEI were compared with the NOVA analysis to determine which series of Alfvenic modes are active. Then, the kick-model is applied to potential modes, and used to estimate how fast ion transport and beam driven currents are varied. By comparing the reconstructed current profile from the kinetic EFIT with the beam-driven current profile estimated from the kick-model, it was evaluated how much energetic particle transport affects maintaining the high q min profile. In conclusion, high and broad q profiles are obtained in the KSTAR plasma with a moderate non-inductive fraction when off-axis NBCD profile is produced from the fast-ion transport due to by Alfvenic modes. A positive aspect of Alfvenic mode driven fast ion transport in the KSTAR is the generation of favorable q-profile modification.

Observation of neutron emission anisotropy by neutron activation measurement in beam-injected LHD deuterium plasmas

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Information of confined energetic ions can be obtained by the neutron measurement because neutrons are mainly emitted from the reactions between energetic and thermal ions in current deuterium plasmas.

The large helical device (LHD) has several neutron measurement systems, and energetic-particle physics studies have been performed based on the neutron measurement.

When the deuteron velocity distribution functions are anisotropic, the neutron emission spectrum also has an anisotropic angular distribution because the $\rm D(d,n){^3He}$ reaction has a large anisotropy against the deuteron incident direction.

The neutron emission anisotropy may provide further understanding of energetic-particle physics in helical/stellarator devices; for instance, interaction between energetic ions and instabilities could be discussed from the point of view of the anisotropy of the energetic-ion velocity distribution function.

Energetic deuterons generated by neutral beam (NB) injection form the anisotropic slowing-down distribution function because NB is injected in a particular direction.

The LHD has three tangential and two perpendicular NB injectors.

We can produce some different anisotropic neutron emission spectra by changing combination of the NB injectors.

The shot-integrated neutron yield is measured with the neutron activation system (NAS) in LHD deuterium plasmas by exposing the activation foils and counting gamma-rays emitted from the irradiated foils.

The activation foils are sent by the pneumatic transfer system to two irradiation ends located at horizontal and lower ports.

The indium foil is employed for measurement of fast neutrons emitted by the $\rm D(d,n){^3He}$ reaction by using the $\rm {^{115}In}(n,n'){^{115m}In}$ reaction which has a threshold energy of 336 keV.

Thermal neutrons can simultaneously be measured by using the $\rm {^{115}In}(n,\gamma){^{116m}In}$ reaction.

When neutrons are anisotropically emitted, the ratio of the neutron flux at the horizontal port to that at the lower ports should be different from the case when neutrons are isotropically emitted.

In this study, we have observed the neutron emission anisotropy by the NAS in NB-injected LHD deuterium plasmas and performed numerical analyses.

We have conducted experiments to investigate the dependence of the neutron emission anisotropy on the NB-injection direction by comparing three injection patterns: use of only three tangential, only two perpendicular, and all NBs.

The clear difference of the ratio of the fast neutron flux [the reaction rate of $\rm {^{115}In}(n,n'){^{115m}In}$] at the horizontal to that at the lower ports between the cases of tangential and perpendicular injections was observed, whereas no difference of the ratio of the thermal neutron fluxes [the reaction rate of $\rm {^{115}In}(n,\gamma){^{116m}In}$] was not seen.

We have calculated the reaction rates of $\rm {^{115}In}(n,n'){^{115m}In}$ and $\rm {^{115}In}(n,\gamma){^{116n by the MCNP-6 code.

The double-differential neutron emission spectra as the source spectra for the neutron transport analysis were calculated from the deuteron velocity distribution function and the differential cross-section of the $\rm D(d,n){^3He}$ reaction.

The distribution function of energetic deuterons generated by NB injection was evaluated by following the guiding-center orbits of test particles.

The obtained numerical results is consistent in the dependence of the neutron anisotropy on the NB-injection direction with the observed experimental data.

Effects of 3D magnetic field on fast ion loss and Alfvenic activities in KSTAR

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We report observation and numerical analysis of fast ion loss and Alfvenic activities driven by 3D magnetic field in KSTAR. Experimental observation in KSTAR indicates a sudden increase of fast ion prompt loss by resonant magnetic perturbation (RMP) when the applied RMP field exceeds a threshold amplitude. Full orbit simulation with 3D perturbed equilibrium computed by the ideal plasma response reproduces the experimentally observed feature of RMP-induced prompt loss of fast ions and the existence of threshold RMP amplitude. Phase space analysis suggests that trapped and intermediate pitch passing particles modified from initial high pitch passing ones are responsible for the threshold behavior of the fast ion loss in the simulation. It is found that the phase space distribution of lost particles depends on the RMP field configuration. Another observation in KSTAR suggests that non-resonant 3D magnetic field can excite Alfvenic activities. In those discharges, up to 70% reduction of core toroidal rotation was achieved by 3D field driven magnetic braking, while change of kinetic profiles was not significant. Excitation of Alfvenic activities by 3D field is likely to depend on bulk plasma parameter and degrade confinement through enhancing fast ion loss and/or decreasing neutral beam power absorption. Role of 3D field in driving Alfvenic modes and correlation to plasma response will be discussed.

Impact of Suprathermal Ions on Neutron Yield at Pre-DT Phase of ITER Operation

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ITER Organization

The neutron and tritium production at pre-DT phase of ITER operation need to be quantified in view of the plans for commissioning and operation of the heating systems, as discussed in the ITER Research Plan (IRP) [1]. An assessment of neutron production has been carried out for the whole set of scenarios foreseen by the IRP for the pre-DT phase, Pre-Fusion Plasma Operation, (PFPO-1 and PFPO-2) with the application of H0-NBI, ECRH and ICRH H and He3 minority and 3-ion heating schemes. Fast ions originated from NBI and minority ICRH react with intrinsic Be impurities producing neutrons and fast deuterons. For protons, the reaction rate is affected by the synergistic acceleration of H0-NBI ions by ICRH when both systems are applied simultaneously. This deuteron source produces secondary neutrons and tritium from interaction of the thermal deuterium ions with fast and thermalized deuterons. To address the neutron production by fast particles, simulations have been performed for L-mode and H-mode scenarios in hydrogen and helium plasmas for a range of toroidal field values (1.8-5.3 T) as foreseen in these phases in the IRP. The simulations include nonlinear effects, such as synergy of H0-NBI and IC waves in a hydrogen minority heating scheme, as well as the 3-ion ICRH scheme. The ICRH power absorption and distribution function of ICRH-generated suprathermal ions for plasma scenarios are calculated with the SSFPQL-TORIC suite of codes [2]. The ECR wave absorption, heating and current drive is calculated with the OGRAY code [3]. Profiles of plasma parameters are calculated self-consistently with heating and current-drive by 1.5D transport simulations in the ASTRA framework [4]. The beam energy and NBI power are adjusted to fulfil the shine- through power load limits in ITER. It is shown that the main source of neutrons for the plasma parameters expected in PFPO is due to the interaction of Be impurity with suprathermal ions produced by NBI and ICRH, fast deuterium from the Be(p,d)2a reaction and further secondary fusion reactions. Local fractions of the NBI and ICRH fast ion pressures and their gradients at PFPO are higher than those of fast alphas in the ITER Q = 10 baseline scenario, making AEs unstable. The AE stability analysis of PFPO plasmas is performed using the perturbative NOVA suite of codes with rich kinetic physics [5, 6]. It is shown that sawtooth oscillations and excitation of AEs can noticeably reduce the neutron rate. The total upper estimate of the integrated neutron emission for the two PFPO phases will be provided.

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ECCD effect on the Helitoron J and LHD plasma stability

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The aim of the study is to analyze the stability of the Energetic Particle Modes (EPM) and Alfven Eigenmodes (AE) in Helitron J and LHD plasma if the electron cyclotron current drive (ECCD) is applied. The analysis is performed using the code FAR3d that solves the reduced MHD equations describing the linear evolution of the poloidal flux and the toroidal component of the vorticity in a full 3D system, coupled with equations of density and parallel velocity moments for the energetic particle (EP) species, including the effect of the acoustic modes. The Landau damping and resonant destabilization effects are added via the closure relation. The simulation results show that the n=1 EPM and n=2 Global AE (GAE) in Heliotron J plasma can be stabilized if the magnetic shear is enhanced above a given threshold, due to a decrease of the rotational transform at the magnetic axis caused by a ctr-ECCD injection. In addition, the simulations mimicking the effect of a co-ECCD injection also indicate a stabilizing effect on the EPM/GAE, caused by an enhancement of the magnetic shear due to an increase of the rotational profile at the magnetic axis. The stabilization of the n=1 EPM/GAE and n=2 Toroidal AE (TAE) in LHD discharges with ctr-ECCD injection is caused by an enhancement of the continuum damping in the inner plasma. Nevertheless, if the NBI injection intensity (EP) is large enough to overcome the continuum stabilization, the growth rate of the unstable EPM/AE is larger in the simulations for a ctr-ECCD discharge.

Effects of anisotropic energetic particle distributions on the residual zonal flow

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In tokamak plasmas, the interaction among the microturbulence, the zonal flow (ZF) and the energetic particles (EPs) can affect the turbulence saturation level and the consequent confinement quality and thus, is important for future burning plasmas. The zonal flow residual for isotropic particles has been studied [1, 2, 3]. For tokamak plasmas, anisotropic EPs can be produced by NBI or ICRF and their effects on zonal flow residual and the consequent effects on turbulence are not so well understood. In this work, the effects of anisotropic EPs on the ZF residual level are studied. By choosing the EP distribution function as $f=C_p exp{-\bar{E}((\lambda-\lambda_0)/\Delta\lambda)^2 }$, where $\lambda=v_\perp^2 B_0/(v^2 B)$, $E\equiv(mv^2)/2T$, it is shown that EPs have more significant effect on long wavelength ($k_r \rho_t<0.1$) ZFs than on short wavelength ($k_r \rho_t>1$) ZFs where $\rho_t=\sqrt{2T_i m_i}/eB$. In the long wavelength range, small to moderate $\delta\lambda$ leads to more significant ZF residual level change compared with pure thermal ions. In addition, barely passing, barely trapped and deeply trapped EPs can enhance the ZF residual level, while well passing and intermediate trapped EPs suppress the ZF residual level. Along with these theoretical analyses in our previous work [4], the EP distributions from ASDEX Upgrade experiments are used and the anisotropic EP effects on ZF residual is analyzed. Two cases with well-passing EPs or barely trapped EPs at the specific radial location are compared and mitigation or enhancement of ZF residual is obtained respectively from the calculation. The possibility of applying ICRF or NBI for ZF enhancement is discussed.

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The LHD Neutron Diagnostics

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Neutron diagnostics have played an essential role in magnetic confinement fusion, in particular, in terms of enhancement of energetic-particle (EP) physics studies. To explore a new confinement regime utilizing isotope effects and obtain deeper understanding of EP-related physics in the Large Helical Device (LHD), the deuterium operation has been conducted in LHD since March, 2017. An integrated set of neutron diagnostic systems based on leading-edge technologies was established before the start of the deuterium operation [1]. In the first deuterium campaign, the system consisted of a wide dynamic range ex-vessel neutron flux monitor, a neutron activation system, a vertical neutron camera, scintillating-fiber detectors, and fast-neutron scintillation detectors. These have provided much new information, e.g., total neutron emission rate, i.e., global confinement of beam ions, effect of beam-ion-driven magnetohydrodynamic (MHD) instabilities on neutron emission profile, i.e., beam ion profile, triton burnup ratio, etc [2]. In LHD, enhancement of neutron diagnostics is steadily continuing. The second vertical neutron camera characterized by high-neutron-detection efficiency and high-time resolution has been operated since the second deuterium campaign and measured rapid change of neutron emission profile with higher accuracy. An ion cyclotron resonance heating (ICRH) antenna is now being installed for the next campaign. To prove production of high-energy tail of deuteron perpendicular to magnetic field and investigate confinement property of high-energy deuteron tail, an advanced neutron spectrometer called TOFED [3] is being constructed in the collaboration with Peking University, China. A single crystal CVD diamond detector will be also employed to measure secondary 14 MeV neutron. In this paper, current status of LHD neutron diagnostics and representative results will be described.

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Effects of Electron Cyclotron Heating on the Toroidal Flow in Helical Plasmas

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Recently, spontaneous toroidal flows have been observed in electron cyclotron heating (ECH) plasma in many tokamak and helical devices such as JT-60U, LHD, and HSX. To clarify the underlying mechanism, many experimental [1] and theoretical [2] studies have been undertaken. Particularly, in LHD, when ECH was applied into the neutral beam injection (NBI) heated plasma, the radial profile of the toroidal flow velocity changes drastically and the direction is reversed in the core region. This change of the toroidal flow by ECH has not yet been understood well.

ECH can drive the radial electron current j_e due to the radial motion of suprathermal electrons [3]. The net current in the steady state should be canceled to maintain the quasi-neutrality, so the return current, $j_r (= - j_e)$, must flow by the bulk ions. Therefore, the bulk plasma feels the $j_r \times B$ force due to the return current. On the other hand, the suprathermal electrons drift toroidally due to the precession motion. During the slowing down of the suprathermal electrons, they transfer their obtained momentum to the bulk plasma due to collisions.

In this study, we investigate the behaviors of energetic electrons by ECH, which can generate the radial current making the $j_r\times B$ torque in the LHD plasma. Also, we evaluate the collisional torques, by the collision between energetic electrons and bulk plasma. We apply the GNET code, which can solve a linearized drift kinetic equation for energetic electrons by ECH in 5-D phase space[3]. Then, we calculate the toroidal flow by solving the radial diffusion equation including the toroidal component of the $j_r\times B$ torque, collisional torques, and the NBI torque, which is evaluated by FIT-3D code[4].

The toroidal components of the $j_r\times B$ and collisional torques cancel each other in axisymmetric plasma[5]. We, first, calculate the torques in the axisymmetric magnetic configuration and obtain this cancellation of the toroidal torques. Next, we study the behaviors of energetic electrons and evaluate the torques assuming the LHD plasma. As a result, we find that the obtained torque by ECH is almost the same order as that by NBI, and that its direction is opposite to NBI torque direction in the inner region. Finally, we solve the radial diffusion equation to evaluate the toroidal flow in plasmas with ECH and/or NBI, and compare with the experimental observations.

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Characterization of Intermittent Fast Ion Transport in DIII-D

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Fast ion loss detector (FILD) measurements indicate intermittent bursts of losses associated with Alfvén Eigenmode (AE) induced critical-gradient transport [1]. During the current ramp phase of a DIII-D inner wall limited, oval shaped, L-mode plasma with reversed-shear magnetic safety factor profile, the total AE activity increases with neutral beam injected (NBI) power. A mix of both frequency sweeping reversed-shear Alfvén eigenmodes (RSAEs) and near-constant frequency toroidicity induced Alfvén eigenmodes (TAEs) are also observed. As the beam power increases from 2.4 to 9.2 MW, the frequency and amplitude of fast-ion fluctuations increases, and a skewed tail emerges in the distribution of loss events. The addition of electron cyclotron heating changes the types of AEs present, increases the measured fast-ion density, and alters loss behavior [2]. New fluctuation measurements from an upgraded bank of FILD, fast-ion D-alpha, and imaging neutral particle analyzer diagnostics will be presented. In theory, intermittency is associated with the domino effect, where avalanches of global redistribution and losses can occur when many overlapping modes provide a channel for particle transport over a larger portion of phase space [3]. Quantification of intermittent transport is important for model validation, particularly for simplified critical gradient transport models that do not account for time dynamics. Furthermore, these experiments suggest that losses can be altered, or perhaps 'smeared out' using active control to manipulate AE mode activity.

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Gyrofluid Studies on Avalanche-like Transport and Formation of Transport Barrier

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Recent experiments in KSTAR have exhibited the evidence of the non-diffusive avalanche-like electron heat transport events from the L-mode and the weak internal transport barrier (ITB) plasmas without magnetohydrodynamic instabilities[1]. During the events, corrugated profiles of electron temperature are observed, which suggest the existence of $E\times B$ staircase. Based on Self-Organized Criticality(SOC) dynamics, $E\times B$ staircase is known to strongly correlate with corrugated mean profile and regulate the avalanche events by the formation of micro-barriers[2]. Moreover, a model based on Hasegawa-Mima equation showed that those mesoscale structures can merge and become a global structure in the self-organized process, achieving an enhanced confinement state[3]. Inspired by previous works, we analyze the evolution of structures using gyrofluid code developed by Yagi[4], which adopts the 3-field equations with neoclassical poloidal flow damping. With the condition similar to the ITB plasma in KSTAR[5], the weak transport barrier formation is observed. Before the formation of transport barrier, corrugated structures rise and evolve in the way described in Ref. 3, resulting in the creation of global structure in the self-organized process.

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Suppression of Toroidal Alfvén Eigenmodes by the Electron Cyclotron Current Drive in KSTAR Plasmas

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Advanced operation scenarios such as high poloidal beta ($_P$) or high ${q_{min}}$ and so on are the promising concepts to achieve the steady-state high beta fusion plasmas. Those scenarios, however, are prone to excitation of the strong Alfvénic mode activities causing fast-ion transport and losses due to its fast-ion pressure gradient and broad current profile as the heating power and the confinement increase. Recent experimental studies on KSTAR under the advanced scenario attempts have shown that the electron cyclotron current drive (ECCD) is able to suppress the beam-ion driven toroidal Alfvén eigenmodes (TAEs) successfully for over several tens of confinement time. Experiments have been performed by scanning the injection angle of the electron-cyclotron (EC) wave. The off-axis ECCD is found to be effective to mitigate or suppress the TAEs, while the on-axis or far off-axis ECCD has shown no visible effect. Intermediate off-axis co-current directional ECCD lowers the central safety factor slightly and tilts the central *q*-profile shape so that the Alfvén continuum gap (NOVA calculations) is elevated and the gap width becomes slightly narrow in the core region, hence the TAEs at the core region become damping. In addition, rise of plasma beta at the transition and suppression phase contributes to TAE stabilization, too. While the TAEs are suppressed, neutron emission rate and total stored energy increase by approximately 50% and 25%, respectively. Fast-ion transport estimated by TRANSP calculations approaches to the classical level during the TAE suppression period. Substantial reduction in neutron deficit and fast-ion loss is also observed. Enhancement of fast-ion confinement by suppressing the TAEs leads to increase of non-inductive current fraction, indicated by loop-voltage reduction, and will be beneficial to the sustainment of the long-pulse high-performance discharges.

Electrostatic potentials generated by NBI fast ions in tokamak and helical plasmas

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Neutral beam injection (NBI) is one of the trusted methods of plasma heating and is widely used in the present-day tokamaks and stelalrator experimental devices, as well as ITER. The fast ions produced by NBI generally have strongly anisotropic velocity distribution depending on the injection direction. A perpendicular NBI produces fast ions in the trapped orbit that are trapped and localized in the outer side of the torus where the magnetic field is weak, creating non-uniform density distribution of fast ions on the flux surface. As a consequence, NBI generates equilibrium electrostatic potential that varies on the flux surface [1].

Electrostatic potential varying on flux surface may affect radial transport of the high-Z impurity ions because the ratio of parallel electrostatic force to the magnetic mirror force becomes larger for high-Z impurity ions, as numerically investigated in [2] for several stellarator devices. In the previous numerical study, it has been found that the electrostatic potential generated by a perpendicular NBI has three-dimensional structure even in axisymmetric tokamaks [3]. We also have studied the electrostatic potential generated by a perpendicular NBI in the helical plasma of the Large Helical Device [4] and found that the generated electrostatic potential can alter the neoclassical transport of carbon impurity ion. These previous studies were focusing on perpendicular injection case. On the other hand, the electrostatic potentials generated by tangential NBI, which also generates non-uniform fast ion density distribution due to the radial drift of fast ions, has not been clarified.

In this study, we investigate the fast ion distributions and electrostatic potentials associated with NBI in tokamak and helical plasmas for a variety of injection conditions including tangential injection case using the global neoclassical code GNET [5]. GNET is based on Monte Carlo technique and can accurately evaluate the five-dimensional distribution function of the fast ions in general magnetic configuration. The fast ion birth points are evaluated using the FIT3D code considering geometry of plasma and beam injector. By using the fast ion distribution function obtained with GNET, we evaluate the electrostatic potential assuming the quasi-neutrality condition. The effect of the electrostatic potential on transport of the impurity ions such as carbon will be investigated using Monte Carlo method.

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Modeling of Supra-thermal Electron Flux and Toroidal Torque by ECH in Non-Axisymmetric Toroidal Plasmas

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Spontaneous toroidal flows have been observed during ECH without direct momentum input in tokamak and helical plasmas[1-3]. In LHD, when we applied ECH to the NBI heated plasma, the toroidal velocity profile changed drastically. We assume that the radial flux of supra-thermal electron enhances the bulk ion canceling current. This current generates the JxB torque, which would play an essential role in causing a toroidal flow. We have studied the JxB torque due to the radial current of supra-thermal electrons and the collisional torque by the supra-thermal electrons in the LHD using GNET[4] code, which can solve the 5D drift kinetic equation for supra-thermal electrons. As a result, we have found that the JxB torque generated by ECH is the same order as the NBI torque, and its direction is an opposite (same) direction to NBI torque in the inner (outer) region[5]. Also, we have evaluated the toroidal torque by ECH in the non-axisymmetric tokamaks (finite toroidal field ripples and magnetic perturbations) and have found significant net toroidal torques by ECH due to the radial motion of ripple trapped electrons.

In this study, we study the radial flux of suprathermal electrons assuming a drift convection model and estimate the radial profile of the JxB toroidal torque by ECH in a rippled tokamak. We find that the maximum toroidal torque which is proportional to 3/2/n, where and n are the ripple amplitude and plasma density, respectively. We find that the obtained model fluxes show relatively good agreements with the numerical results by GNET.

Also, we extend this drift convection model in the case of LHD and HSX. We find that the larger JxB toroidal torques are obtained in helical plasmas than that in the rippled tokamak due to the large fraction of trapped electrons. The drift convection model results are compared with the numerical results by GNET code.

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Evaluation of beam-beam fusion reaction rate considering local beam profile in toroidal plasmas

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NBI heating is a reliable method to heat the plasma to high-temperature. Energetic beam ions are generated, and nuclear fusion occurs if we choose the deuterium as a beam ion. Many D-D fusion reaction experiments have been performed in tokamaks[1] and helicals[2]. The neutrons by D-D fusion reactions are measured to study the confinement of energetic beam ions and neutron counts are compared with the numerical simulation considering the beam-thermal, thermal-thermal, and beam-beam fusion reactions. On the other hand, trapped beam ions locally distributed on the flux surface, and it is necessary to evaluate the beam-beam fusion reaction considering the local distribution of the beam ions if the beam density increases.

We study the beam-beam fusion reaction in toroidal plasmas (a simple tokamak and LHD) considering the local beam ion distribution on the flux surface. We apply the GNET code, which can solve the drift kinetic equation for the beam ions in 5D phase space. We evaluate the velocity space distributions in 5D phase space, then, estimate the D-D reaction rate; the neutron and tritium emission rate.

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STABILITY ANALYSIS OF TJ-II STELLARATOR NBI DRIVEN ALFVÉN EIGENMODES IN ECRH AND ECCD EXPERIMENTS

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In stellarators, low levels of plasma current induced by neutral beam injection or EC heating may cause non-negligible modifications of the plasma equilibrium and, therefore, of the shear Alfvén waves spectrum. Experiments carried out in the TJ-II stellarator [1] and other helical devices [2, 3] have addressed this issue clearly illustrating this effect.

Numerical analysis of TJ-II (B0=1 T, R=1.5 m, a=0.22 m) experimental results studying the impact of electron cyclotron resonant heating (ECRH) and electron cyclotron current drive (ECCD) on NBI driven Alfvén activity has been performed using the FAR3D code [4]. The code solves the reduced linear resistive MHD equations and the moment equations governing the evolution of the energetic ions density and their parallel velocities, including resonance effects to account for damping/growth of the MHD perturbations. The simulations, aiming at understanding the experimental variations observed in the spectrum of Alfvén Eigenmodes (AEs) measured by magnetic diagnostics and the heavy ion beam probe (HIBP), have been carried out taking into account the equilibrium modified by plasma currents and the fast ion pressure profiles calculated in the different plasma conditions. In principle, FAR3D results allow us to identify the modes with highest growth rate compatible with the variable experimental conditions.

The shots analyzed were obtained with a combination of ECRH/ECCD and hydrogen co-NBI in deuterium plasmas. Furthermore, experiments making use of additional ECRH power allow us to increase plasma temperature with no noticeable variations in plasma density. Changes in electron temperature profile (from 1.6 to 2.0 keV central temperature) are accompanied by an increase in mode frequency (from 240 to 260 kHz), which could be explained by changes in plasma resistivity or in the energetic particle slowing down time. Although the result of the simulations also shows strong variations of the predicted activity, several uncertainties related to the experimental determination of mode number and mode location precludes precise identification of the observed instabilities.

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Modelling of toroidal ripple field and fast ions in the COMPASS Upgrade tokamak

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The COMPASS Upgrade tokamak [1] will be a tokamak of major radius R0∼0.894 m with high-field (Bt∼5 T) and high-current (Ip∼2 MA). The machine should be completed by 2022. It will be located in Prague, Czech Republic and is currently in design phase. The main auxiliary heating system used to access H-mode will be 4 MW of Neutral Beam Injection (NBI) power with an injection energy of 80 keV. This will create a population of well-confined energetic D ions. In this contribution, the modelling studies the effects of the toroidal ripple induced by the 16 TF coils: a Biot-Savart solver is used to calculate the intensity of the perturbation (BTFR/Bt∼10^-3 at outermost mid-plane positions).

Detailed integrated modelling with the METIS code [2] yields the pressure and current profiles in various planned scenarios (Bt from 2.5 T to 5 T and Ip from 0.8 to 2 MA). These profiles are an input to the FIESTA code [3] that derives a complete mapping of the poloidal flux using realistic positions of the various shaping coils. These maps are then used to follow during a few ms the fast particles in the 3D field using the EBdyna_go orbit solver [4] with a precision of order 10^-4 on the value of p (radial position) of each trajectory. We quantify the amount of NBI ions in the edge region, in the Scrape Off Layer and in the divertor. Initial distributions of ions are either uniform or obtained from BBNBI code [5]. Results for various engineering parameters indicate the losses on the Plasma Facing Components for co- and counter- injection.

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Fast-ion D alpha diagnostic with enhanced FIDASIM in the Large Helical Device

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A magnetic confinement fusion reactor requires the sustainment of plasma by energetic alpha particles from fusion reaction. Therefore, it is important to understand the behavior of energetic particles in the magnetic confinement device. To investigate the behavior of energetic particles, a Fast-Ion D Alpha (FIDA) diagnostic system was installed on the Large Helical Device (LHD) [1,2]. In LHD, we have conducted hydrogen experimental campaigns since March, 1998. To understanding physics of energetic particles and obtain isotope effects, the deuterium experimental campaigns has been started in LHD since March, 2017. In the FIDA diagnostic, the Doppler-shifted D alpha lights from fast neutrals are utilized as signals of energetic particles, where these fast neutrals are produced by the charge exchange process between fast ions in plasmas and actively induced neutrals by injected Neutral Beam (NB) [3,4]. The advantages of the FIDA diagnostic are the local measurement at the crossing point between its line of sight (LOS) and incident line of NB. An enhanced FIDASIM, which is improved to simulate in a three dimensional magnetic configuration device such as stellarator and helical types, was applied on LHD to analyze the FIDA diagnostic. The FIDASIM was originally developed in an axisymmetric configuration for a two-dimensional magnetic configuration device such as a tokamak type [5]. The FIDASIM requires the distribution function, plasma profiles, magnetic equilibrium and diagnostic geometry. For LHD, a code is developed to produce the inputs files needed to run the enhanced FIDASIM in a three-dimensional magnetic configuration device. We inputted the distribution functions which were calculated by GNET, MORH and MEGA which were the code to simulate the energetic particle behavior. In order to validate the enhanced FIDASIM, measurement of radial profile of fast ions using the FIDA diagnostic was performed in MHD-quiescent plasmas. As a result of the comparison, the FIDA diagnostic results and the enhanced FIDASIM calculation results obtained good agreement on LHD. In the presentation, we will describe current status of the FIDA diagnostic and the enhanced FIDASIM on LHD and representative results.

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Fast-ion D spectroscopy diagnostics in KSTAR

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Fast-ion D (FIDA) diagnostics has been widely employed to investigate fast-ion characteristics in many fusion devices. In KSTAR FIDA diagnostic system has been developed and the commissioning has been performed since 2018 KSTAR experimental campaign. The system consists of the grism, two tele-lens sets, blocking strip and EMCCD. A narrow neutral density filter (transmittance $<$ 0.1%) strip was utilized for blocking the main D emission peak in order to increase signal-to-noise ratio of the peripheral emission intensity. The temporal, spectral and spatial resolutions of the spectrometer are 20 msec, 0.0215 nm and 4-10 cm respectively. Presently, there is only active view which is blue-shifted from the main D line (656.1 nm). The weight functions of FIDA view have been calculated with geometric information of KSTAR neutral beam and FIDA line of sights for evaluating the diagnostic coverage and sensitivity of the fast-ion phase-space. FIDASIM calculations have been commissioning with KSTAR spectrometer data to precisely evaluate FIDA signal.

Study on particle pinch mechanism for DEMO

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The particle transport is an important research topic for burning control in DEMO reactors. For example, the hollow density profile is often seen after pellet injection or gas-puff. In such a case, the inverted density gradient appears in the edge region which produces the particle pinch. To understand particle pinch mechanism, we have performed local gyrokinetic simulation using DEFEFI code[1, 2] with the inverted density gradient (dn/dr > 0). We have observed inward particle flux for such condition. To understand the mechanism of particle pinch, we have revisited the ion-mixing mode theory proposed by B. Coppi[3]. It is found that the electron drift wave contributes to the particle pinch rather than the ion-mixing mode for the inverted density gradient.

In this paper, we introduce the trapped electron response which is not considered in the previous analysis. In DEMO, we expect trapped electron mode (TEM) is dominant in the core region with the normal density gradient (dn/dr <0) . However, for the inverted density gradient in the edge region, it should be stabilized so that the particle pinch may come from the passing electron response rather than trapped electron response. We will clarify parameter regime in which the particle pinch is produced by passing or trapped electron response relevant to DEMO.

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Spatially resolved measurements of the tail temperature of RF accelerated deuterons at JET

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Energetic deuterons leave pronounced signatures in the neutron emission spectrum from fusion plasmas. In this work, this is exploited in order to obtain information about the properties of ICRF-accelerated deuterons using the neutron camera system at JET. By combining data from the ten horizontal, and nine vertical lines of sight, a spectroscopic analysis of each detector's pulse height spectra has been used to determine the spatial profile of the effective tail temperature of fast deuterons.

The procedure entails fitting parametrised models of the neutron energy spectra to the pulse-height spectra measured by the neutron camera detectors. Fitting the parametrised models gives an estimation of the model parameters, including the temperature of the hot ion-tail.

The analysis method is validated and benchmarked on synthetic data. We demonstrate that pulse-height spectra from the camera's liquid scintillator detectors provide enough spectroscopic information to estimate the line-of-sight averaged fast-ion temperature. Using a model of the ICRF resonance-layer, which includes a resonance height and width, we show that the neutron camera at JET can be used to determine the spatial and energy distribution of fast RF-accelerated ions in a Tokamak.

The developed method is then applied to various ICRF-scenarios at JET, including 2nd and 3rd harmonic acceleration of deuterium ions, as well as the "3-ion" scenario. The results clearly show how the tail temperature profile peaks in the vicinity of the resonance position, where the most energetic ions are located.

The potential for using this method to study rapid transient phenomena, such as redistribution of fast ions during MHD instabilities, is also discussed.

Simulation study on impact of pedestal height on energy loss process with resistive ballooning mode turbulence during pedestal collapse

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In future tokamak reactors such as ITER and DEMO, the intermittent heat flux released by edge localized modes (ELMs) should be avoided or mitigated to low level enough to remain within heat load constraints on plasma facing components. One of the critical issues is therefore to understand nonlinear dynamics underling ELMs and resultant energy loss process. For simulation studies on impact of fluctuation driven toroidally axisymmetric flows called convective cell modes (CCs) [1] on energy loss process during ELM crash, JOREK simulations reveal that strongly sheared CCs generated by the residual of force balance between $J\times B$ force and pressure gradient shear density filaments and suppress the energy loss level [2,3]. On the other hand, our numerical study on interplay between CCs and resistive ballooning mode (RBM) turbulence during pedestal collapse using BOUT++ code [4] shows that a secondary instability accompanied by a damped oscillation among pressure gradient, CCs and turbulence intensity rises and enhances energy loss level after the suppression of energy loss level by strongly sheared CCs [5]. This work is however limited to a nonlinear simulation with one parameter set and a further parameter scan varying resistivity, pedestal height and so on is required to get more generalized understanding on a role of CCs on energy loss process during pedestal collapse. In the present paper, we will report a sensitivity analysis on energy loss level during pedestal collapse in the presence of RBM turbulence against pedestal height using a series of shifted circular equilibria increasing plasma pressure.

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Hybrid kinetic-MHD simulations of TAE active control using RMPs in the ASDEX Upgrade tokamak

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Experiments in the ASDEX Upgrade (AUG) tokamak have shown that externally applied 3D fields may be used to control Toroidally Induced Alfven Eigenmodes (TAE) in neutral beam heated discharges with elevated q-profile and low collisionality [1]. TAEs have been fully suppressed or excited in identical discharges with n=2 3D fields by varying their poloidal spectrum.

The non-linear hybrid kinetic-MHD MEGA code has been applied to model these discharges to identify the underlying mechanism in a fully 3D geometry, including realistic equilibrium, beam geometry and plasma response to externally applied 3D fields. MEGA simulations using the ${\delta}$f method reproduce some key aspects of the experiments such as the TAE frequency, the dominant n number and the dependency of mode structure on the radial fast-ion profile generated by the applied NBI configuration. The simulated TAE growth rate is observed to depend on the poloidal spectrum of the externally applied 3D fields following the experimentally observed trend. 3D continuum calculations, using the Alfvén gap stability code STELLGAP, are used to study the impact of externally applied 3D fields on TAE continuum damping and compare it against fast-ion drive. Calculations of the particle variation of toroidal canonical momentum ${\delta P_\phi}$ induced by the applied 3D fields as a function of the poloidal spectrum shows that 3D fields transport is resonant and edge-localized [2]. Non-linear resonances between fast-ions and applied 3D fields overlap with wave-particle resonances responsible for TAE drive, enabling TAE control by populating or depopulating these resonances. The possibility of optimizing this TAE control method by using different toroidal periodicity on the externally applied 3D fields is discussed. The conclusions of these experiments and their implications towards ITER are examined.

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Fast ion driven electron drift instability in reversed shear plasmas

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It is shown that trapped fast ions can destabilize the electron drift wave because fast ions reverse their precession direction in RS plasmas to electron diamagnetic direction and can resonate with electron drift wave.[1] A local stability analysis of this new instability is performed and consequent quasi-linear transport is calculated using gyrokinetic equations in toroidal geometry [2,3] under fusion reactor condition. The new instability occurs when the temperature gradient of fast ions peaks sufficiently compared to the density profile and the linear growth rate is linearly proportional to the temperature gradient length of fast ions which is the free energy source of the instability. Strongly negative shear plasmas are more favorable for the new instability. The resulting quasi-linear particle flux of fast ions is outward while the particle flux of main hydrogenic ions is inward. These results show that the new instability might be beneficial for burning plasma operation because it can expel lower energy He ions preferentially while keeping the ion working gas inside.

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Impact of externally applied 3D fields on plasma rotation and correlation to fast-ion losses

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Externally applied magnetic perturbations (MPs) are amongst the most effective tools to mitigate and suppress edge localized modes [1]. Recent experiments have highlighted that the plasma response to the externally applied 3D fields plays a key role in the ELM suppression mechanism [2,3]. In this work, we study how changes in the plasma density and rotation correlate with the orbit topology of the lost fast-ions due to MPs. The study is based on a new analysis technique, which allows us to characterize the coupled temporal evolution of plasma density, toroidal rotation and fast-ion losses. The technique relies on the calculation of the correlation (based on the linear Pearson coefficient) between the signals. The correlation ranges between [-1,1], such that -1, 1 and 0 indicate inverse, coupled and decoupled temporal evolution, respectively. A detailed correlation study was performed for two low collisionality H-mode discharges at the ASDEX Upgrade tokamak. In these experiments, the application of static n=2 MPs produce impurity toroidal rotation braking, electron density pump-out and enhanced fast-ion losses. The first correlation patterns resolved in energy and pitch angle (owing to the resolution of the fast-ion loss detectors) and radius (given that density and rotation measurements are well localized) are presented. The correlation becomes more intense towards the plasma edge, in agreement with the observation that the lost fast-ions are born at the edge and can have a stronger impact on rotation there. There is also an abrupt change of sign in the correlation due to a variation in pitch angl, which coincides with the trapped/passing boundary. This observation suggests the effect of the accumulation of resonances in the trapped/passing boundary, which can affect the confinement of fast-ions. This result is in line with previous observations of the existence of an edge resonant transport layer [4]. Possible mechanisms responsible for the experimental observations are discussed. The ASCOT [5] code will be used to analyze the changes in the fast-ion torque profile due to MPs. An estimation of the radial current induced by fast-ion losses and its impact on Er is assessed.

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Extensions of FIDASIM capabilities: Passive signals, 3D geometry and neutron collimator signals

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FIDASIM is a synthetic diagnostic code that simulates fast ion D-alpha (FIDA) and neutral particle analyzer (NPA) signals produced by charge exchange (CX) with neutrals. The experimental configuration and a theoretical distribution function are inputs to the code. Previously, FIDASIM only simulated CX with injected neutrals in axisymmetric devices. However, the magnitude of passive signals produced by CX with edge-cold neutrals can be of comparable magnitude to active signals. Therefore, FIDASIM is modified to accept a cold neutral population, calculate their atomic states and predict passive signals. The effect of 3D magnetic fields on fast ion confinement is important in stellarators and in tokamaks with ELM-control coils. Also, the cold neutrals that produce passive signals often vary toroidally. Thus, FIDASIM is improved to predict signals in 3D geometry. Neutrons emitted in beam-thermal reactions depend upon the fast-ion distribution function. To model FIDA, NPA and neutron collimator signals in a common framework, forward models for neutron collimator signals are incorporated into the code. This poster discusses the improvements made to FIDASIM and their benchmarks.

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1 MeV triton confinement study on KSTAR

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The behavior of 1 MeV triton in KSTAR deuterium plasma is studied using triton burnup neutron (TBN) diagnostics and classical burnup calculation code. In KSTAR, TBN is measured by neutron activation system (NAS) and scintillation detectors. Shot-integrated TBN yield is evaluated by NAS with silicon sample. Two kinds of scintillation detectors, stilbene and scintillating-fiber detectors, provide TBN emission rate. Measured TBN emission is analyzed using classical burnup calculation code. The code evaluates expected TBN emission by considering prompt loss rate and Coulomb drag in certain plasma condition. The amount of prompt loss is statistically evaluated using full orbit following code LORBIT. In addition to prompt loss and Coulomb drag, finite confinement time effect can be considered by volume averaged effective diffusion coefficient. Measured and calculated TBN emission are compared in two timing of Alfvén eigenmodes control experiment, with and without Alfvénic activity. Without Alfvénic activity, calculated TBN generally matched with measured value within experimental error. During the Alfvénic activity however, measured value is about half of the calculated value. The amount of confinement degradation due to Alfvénic activity is estimated in terms of volume averaged effective diffusion coefficient.

Observation of rapid frequency chirping driven by runaway electrons in DIII-D

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We report the first observation of chirping instabilities driven by runaway electrons (REs) in a tokamak. Energetic particles often drive instabilities through wave-particle resonances. The frequency of an instability can sweep gradually as background plasma parameters evolve or it can change rapidly (known as "frequency chirping") due to nonlinear evolution of the energetic-particle distribution function. Chirping instabilities driven by REs in two distinct frequency bands are observed for the first time in the DIII-D tokamak. In addition to their intrinsic interest, these observations could be of practical importance, as kinetic instabilities that modify the RE distribution function may mitigate damage by runaways in a tokamak reactor.

REs are often generated during tokamak disruptions due to large induced electric fields accelerating suprathermal electrons up to relativistic energies. In the present experiments the disruptions with generation of a hundreds kA RE beam are deliberately triggered by an injection of an argon pellet in DIII-D. The resultant post-disruption plasma is cold, dense, with a large fraction of the high-Z impurity. To extend the runaway stage and reduce the transformer flux required to run the current, argon is purged from the plasma by a secondary injection of deuterium gas. This provides access to a RE beam at low collisionality lasting more than a second and a large variability of an applied voltage.

The RE energy distribution function is constrained via hard x-ray bremsstrahlung measurements using the Gamma Ray Imager. It has a non-monotonic feature (bump) at about 5 MeV suggesting the presence of free energy to drive kinetic instabilities. The chirping instabilities driven by REs are observed when a negative (decelerating) loop voltage is applied.

The frequency chirping is detected in two distant frequency bands: 1-10 MHz and 45-75 MHz. The frequency typically changes by 0.5-1 MHz on a timescale of 1 ms. Modification of the RE distribution function is directly measured during the chirping in the low-frequency band. The low-frequency instability also correlates with an increase of an intermittent RE loss from the plasma. Distinct modes chirping upward and downward are observed during the high-frequency instabilities. The frequency of instabilities in both frequency bands increases nearly linearly when the toroidal magnetic field sensed by the RE beam increases. The instabilities are hypothesized to be compressional Alfven eigenmodes since their frequency lies between Alfven and ion cyclotron frequencies for given plasma parameters. They are supposedly driven by a non-monotonic RE distribution function, likely lead to a pitch-angle scattering of REs and increase RE radial transport. Similar frequency range instabilities are also observed shortly after the disruption without deuterium injection, opening the possibility of excitation of these modes at higher collisionality.

The observations of RE-driven frequency chirping provide a novel experimental platform for fundamental studies of nonlinear chirping. They also support a continued research effort to understand the RE loss driven by the instabilities and how to benefit for RE mitigation in ITER.

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Kinetic Aspects of High-Z Pellet Modeling for Disruption Mitigation

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Injection of high-Z pellets is now a part of the disruption mitigation strategy for ITER. Pellets are seen as favorable to massive gas injection due to deeper penetration of the impurity material into the plasma and the ability to adjust the cooling properties via mixing fractions.

The ablated material surrounding the pellet contains electrons that are much colder

and denser than the ambient background plasma. Hot electrons entering the cloud from the background collide with the cold electrons in the cloud. The electron-electron collisional time scales are much shorter for the cold-cold collisions than for the hot-cold collisions. Because of that, the cold electrons can be viewed as thermalized, whereas the hot electron distribution function in the cloud can deviate from Maxwellian significantly. This situation requires a kinetic description of the hot electron distribution function as they slow down and scatter in the ablation cloud.

This talk presents a kinetic model for the power deposition from energetic electrons into the neutral gas shield of an ablating high-Z pellet. For high-Z pellets, the velocity distribution of the hot electrons is nearly isotropic, and we use this feature to develop rigorous solutions to the kinetic equation. We consider a combined effect of elastic scattering and gyro-motion and of the hot electrons. The hot electrons diffuse longitudinally along the field lines when the gyro-frequency is much greater than the elastic collision frequency, and they diffuse radially in the opposite limiting case. In both limits, we calculate the power deposition kinetically as a function of the line integrated gas density. We also show that the sheath potential required to maintain ambipolarity in the cloud scales as \$1/Z\$^1/3.

When combined with pre-existing fluid models for the ablated flow, our power deposition model gives an ablation rate that scales as \$1/Z\$^7/6, which is different from the \$1/Z\$^2/3 scaling reported by other authors.

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Runaway electron driven high frequency kinetic instabilities during quiescent phase of KSTAR discharge

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In a reactor level device such as ITER, a disruption mitigation system is necessary because a considerable level of magnetic energy is transferred to runaway electrons (REs), which seriously damages the tokamak device. Massive material injection techniques considered as a disruption mitigation method in ITER are based on pitch-angle scattering through the Coulomb collision. However, this method has many technical difficulties because it must achieve a high level of density in a plasma disruption situation. As an alternative to this, research on pitch-angle scattering based on wave particle interaction has been actively conducted recently [1][2]. In KSTAR, high frequency kinetic instabilities of several GHz range caused by REs were measured through electron cyclotron emission (ECE) and radio frequency signals in low density Ohmic discharges where a significant amount of REs were present. These instabilities were observed to cause instantaneous scattering of REs in ECE signal. In this work, we will present the characteristics of these kinetic instabilities such as their frequency, frequency gap, and wave number. Possible mechanisms of excitation condition will be discussed as well.

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Deuterium experiment on LHD and its contribution on Energetic Particle Physics in Toroidal Plasmas

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Deuterium experiment was started since March, 2017 on the Large Helical Device (LHD). One of the objective of the deuterium experiment is to explore the physics of energetic particles (EPs) in helical plasmas, but the experiment is also beneficial to the comprehensive understanding of EP physics in toroidal devices.

The EP physics study on LHD is characterized by the use of negative-ion based energetic (180keV) and powerful (15MW) Neutral Beams (NBs). The wide operational range in magnetic field strength (0.5T-3T) and operational electron density (1017-1021 m-3) also characterize the LHD as a good platform for EP physics study. These features enable us to explore the EP driven instability study in wide area of EP velocity normalized by the Alfvén velocity and EP beta value [1]. Although LHD has these nice character, the EP studies on LHD during its hydrogen-phase experiment [2,3] was limited because the global EP confinement evaluation was not possible and the validation of EP simulation codes, such as GNET, MORH and etc [5,6], with experimental data were limited. The neutron diagnostic, which becomes possible by starting deuterium experiment, is a powerful tool for evaluating the EP confinement property because the cross section of D(d,n)3He reaction is monotonically increasing with the relative energy between reactant particles up to 1MeV.

In the deuterium experiment on LHD, the maximum neutron emission rate of 1.9x1016 n/s is expected and the most of the neutrons are emitted by the reaction between bulk ions and energetic particles produced by NBs[4]. Using the benefit of neutron diagnostics, the validation of EP simulation codes was started and the database construction using diffusive model of EP transport was also started for the integrated simulation code, TASK3D [7]. These activities are beneficial not only for the community of stellarators but also for that of tokamaks because the LHD is the only machine where the high energy Negative-ion based NBs (N-NBs) are in operation, which will be the main heating device in ITER and/or future DEMOs, and can be used as a platform to evaluate the heating, the current drive and diagnostics using N-NBs if these codes are validated.

In the presentation, the current status of LHD deuterium experiment and the results related to EP physics studies will be shown.

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Energetic particle transport in NSTX/NSTX-U multi-mode scenarios through integrated simulations

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In magnetically confined plasmas, energetic particles from Neutral Beam injection, fusion reactions or RF acceleration are susceptible to enhanced transport by several classes of instabilities, thus potentially leading to degraded plasma performance. Depending on its properties (e.g. frequency, mode number spectrum and radial structure), each type of instability can affect the fast ion population differently, for instance in terms of modification of the radial vs energy gradients. This work investigates modifications of the fast ion distribution in NSTX/NSTX-U scenarios featuring simultaneous low-frequency MHD (kink and fishbones) and Alfvénic modes (AEs) such as Toroidal and Reversed-shear AEs. Interpretive analysis is performed through the TRANSP tokamak transport code, enhanced by the reduced-physics 'kick model' for fast ion transport by instabilities [M. Podestà et al., Plasma Phys. Control. Fusion **59** (2017) 095008]. It is shown that the different instabilities can affect each other's evolution through modifications of the fast ion distribution function, which in turn affects the mode drive and overall stability. For example, core-localized kink modes can redistribute fast ions outward and either reduce or enhance the drive for AEs, depending on the relative reduction of the fast ion pressure and increase in its gradient around the AE location. Marginally stable kinks can also undergo three-wave coupling with AEs, thus favoring the synchronized evolution of the AE mode amplitude in large bursts (or *avalanches*) with enhanced fast ion transport. An important result of this "multi-mode" analysis is the necessity to retain all relevant time scales in the simulation, from the rapid AE growth to the NB ion slowing down that replenishes the fast ion distribution. In general, it is concluded that accounting for the evolution of the fast ion distribution over (at least) a slowing down time is critical for quantitative simulations of mode stability/saturation and resulting fast ion transport. As a consequence, estimates of the expected unstable AE spectrum based on linear AE stability analysis from single time slices can result in inaccurate predictions, since the results are extremely sensitive to any prior relaxation of the fast ion distribution in both energy and real space. *(Work supported by the US Department of Energy, Office of Science, Office of Fusion Energy Sciences under contract number DE-AC02-09CH11466)*.

Analysis of TAEs and FBs induced fast ions redistribution and losses in MAST using a reduced fast ion transport model

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In MAST dedicated experiments were carried out to study the redistribution and loss of neutral beam injected fast ions due to their interaction with Toroidal Alfvén Eigenmodes (TAEs) and Fish-Bones (FBs) by integrating observations from Fast Ion D-alpha diagnostics, a multi-channel Charged Fusion Product Detector (CFPD) and a Neutron Camera (NC) [1]. The experimental observations were modelled in TRANSP/NUBEAM using a combination of the "ad-hoc" time-dependent anomalous diffusion coefficient and the FB model available in NUBEAM. The main limitations of this study were the lack of a physical justification for the level of anomalous fast ion diffusion required to match predictions and observations and the fact that it was not possible to identify a fast ion distribution that was simultaneously in agreement with both FIDA and NC observations.

In this work, these experimental observations are now revisited using the "kick model" [2] in which spatial diffusion coefficients emerge from the estimate of the fast ion diffusion in pitch and energy phase space estimated by Monte Carlo simulations of test particle trajectories in presence of perturbations of the plasma equilibrium. The Probability Density Function (PDF) of the "kicks" in energy and pitch is estimated using the ORBIT code in which the perturbation(s) eigenfunction(s) and amplitude(s) are provided in input. The perturbation eigenfunctions are estimated using NOVA and MISHKA codes while amplitude is proportional to root mean square value of the magnetic field perturbation at the edge measured by Mirnov coils, with the proportionality constant as the single free parameter. The fast ion distribution calculated in TRANSP/NUBEAM on the basis of the "kicks" PDF is then compared with FIDA, CFPD and NC observations.

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Fast-ion loss simulation with MEGA code in the Large Helical Device

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The evaluation of fast-ion confinement is indispensable for the prediction of the heating efficiency in fusion reactor. The fast-ion confinement depends not only on the collisional transport but also on the fast-ion driven magnetohydrodynamics (MHD) instabilities such as Alfvén eigenmodes (AEs) which induce the fast-ion transport and losses. Therefore, it is an important issue to identify the fast-ion driven MHD instabilities and clarify the lost fast-ion distribution due to the instabilities.

In the Large Helical Device (LHD), which is one of the largest heliotron/stellarator devices with non-axisymmetric three-dimensional magnetic configuration, the fast-ion driven MHD instabilities such as the toroidal Alfvén eigenmodes (TAEs) were observed[1]. In addition, the AE-induced fast-ion losses were measured by a scintillator-based fast-ion loss detector (FILD)[2]. The relationship between the amplitude of the instabilities and the fast-ion losses are investigated.

On the other hand, since there is a toroidal dependence of fast-ion loss in the LHD even with no AE instabilities, it is difficult to achieve an overall understanding of fast-ion loss process only by the local measurements. A computer simulation is a powerful tool to investigate the interaction between fast ions and fast-ion driven AE instabilities leading to the fast-ion losses.

A hybrid simulation code for nonlinear MHD and fast-ion dynamics, MEGA, has been developed to simulate recurrent bursts of fast-ion driven AE instabilities including the fast-ion source, collisions, and losses in non-axisymmetric three-dimensional magnetic configuration like the LHD[3]. In order to validate a reproducibility of AE, the MEGA code was applied to the LHD experiment[1]. It was found that two groups of AEs with frequencies close those observed in the experiment are destabilized alternately. The alternate appearance of multiple AEs is similar to the experimental observation[3].

In order to validate the hybrid simulation on the interaction between fast ions and AEs, we apply the MEGA code to the LHD experiment with the AE-induced fast-ion losses measured by the FILD. A numerical fast-ion loss detector with Lorentz orbit (Numerical FILD) has been developed in the MEGA code. The velocity space region of lost fast-ions measured by the Numerical FILD is similar to the FILD measurements during the AE bursts. The fast-ion losses brought about by the AE bursts are proportional to the square of the AE amplitude, which reproduces well the LHD experiment. In addition, the characteristics of the AE induced fast-ion loss are clarified.

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Experiments on Control of TAEs in ASDEX Upgrade and TCV plasmas with ECRH / ECCD

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*See author list of S. Coda et al 2017 Nucl. Fusion 57 102011

**See author list of H. Meyer et al 2017 Nucl. Fusion 57 102014

In present-day magnetic fusion experiments, energetic particles produced by neutral beam injection (NBI) and/or ion cyclotron resonance heating (ICRH) often excite Alfvén Eigenmodes (AEs) [1]. The wave-particle momentum and energy exchange and accompanied non-classical transport of energetic particles can cause degradation in the plasma performance and particle loss threatening the plasma facing components. In view of the next step burning plasma experiments in ITER, possible control techniques are being developed for AEs driven by the fusion-born super-Alfvénic alpha-particles [2-4].

On ASDEX-Upgrade (AUG) tokamak, the very flexible and powerful electron cyclotron resonance heating (ECRH) system that was previously shown to facilitate Toroidal AE (TAE) excitation by ICRH ions [3], was used as electron cyclotron current drive (ECCD) for affecting magnetic shear at the position of TAEs. It was found that counter-ECCD applied just inside TAE decreases the magnetic shear strongly enough for the pressure suppression of TAE. This effect makes TAEs cease to exist in plasmas with plasma pressure high enough for the second ballooning stability zone. Further AUG experiments with four (out of six) gyrotrons delivering ECCD with mirror-controlled power deposition moving across the TAE structure have shown remarkable changes in TAE spectrum. In particular, depending on the ECCD power deposition along the vertical Z axis, TAEs of certain type disappeared, and TAEs of more core-localised type appeared, and time intervals free of TAEs

were also seen. The mirror-controlled ECCD was then incorporated into the TRANSP code so modelling of the time-dependent evolution of magnetic shear and other plasma profiles and fast ions became possible. The pressure effect and TAE damping effects are investigated in these AUG discharges, and extrapolation to ITER baseline scenario with ECCD is given.

On the TCV tokamak, a recently installed 1 MW 25 keV NBI combined with the existing ECRH allowed to join the study of ECRH/ECCD on beam-driven instabilities [5]. Plasma scenarios for Energetic Geodesic Acoustic Modes and TAEs were obtained on TCV, in the presence of simultaneous off-axis NBI and off-axis ECRH. No beam-driven instabilities were observed without ECRH, and the beam velocity was just above one third of Alfven velocity. The talk presents the status of the data analysis and the strategy for continuation of the experiments in view of the planned installation of the second high energy (50-60 keV) NBI.

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Experimental assessment of Toroidal Alfvén Eigenmode control using externally applied resonant magnetic perturbations in the ASDEX Upgrade tokamak

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In magnetically confined fusion devices, super-thermal particles must be well confined until they slow down to the plasma bulk. Fusion born alpha particles as well as energetic particles produced by external heating systems such as neutral beam injectors (NBI) or ion cyclotron resonance heating (ICRH) are, however, a source of free energy that can destabilize a rich spectrum of Alfvén Eigenmodes (AEs) through resonant wave-particle interactions. A net wave-particle energy and momentum exchange is often accompanied by a particle radial transport that can affect the plasma fusion performance as well as threaten the vacuum vessel integrity. Toroidally induced Alfvén Eigenmodes (TAEs) are one of the most deleterious AEs in present tokamaks and are thought to pose some threats in next step fusion devices such as ITER. Several TAE control techniques are currently being developed in tokamaks and stellarators [1]. Among others, externally applied Resonant Magnetic Perturbations (RMPs) have shown their potential to mitigate or even suppress TAEs in present tokamaks [1, 2]. A robust theory that allows us to predict their capability to control TAEs in ITER still needs to be developed.

We present here the experimental assessment of the RMP capability to control TAEs via dedicated experiments in the ASDEX Upgrade (AUG) tokamak with different RMP toroidal and poloidal spectra, energetic particle distributions, equilibrium helicities and plasma collisionalities. RMPs with n=1, 2 and 4 are applied to low collisionality plasma discharges with a differential phase ($\Delta\Phi$UL) scan between the upper and lower set of the AUG RMP coils and different energetic particle distributions. The energetic particle distribution is produced by NBI beams with variable energies and injection geometries and ICRF minority heating. RMPs with n=1 have the strongest impact on the energetic particle distribution and related AE activity. In agreement with the Edge Resonant Transport Layer (ERTL) theory [3], a narrow RMP $\Delta\Phi$UL window has been observed to have a clear impact on the observed TAE activity. The ERTL properties for different scenarios will be presented together with the most recent experimental and modelling results. Based on these results, the capability to control the energetic particle distribution and related AE activity in ITER will be discussed.

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Simulations of Alfven Eigenmode Destabilized by Energetic Electrons and Energetic Electron Effects on Energetic-Ion Driven Alfven Eigenmode

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Energetic electron driven toroidal Alf$\rm {\acute{ven}}$ eigenmodes (TAEs), which have been observed in many devices (COMPASS-D[1], C-MOD[2], HL-2A[3]) with high-power ECW and LHW heating, are investigated using a hybrid simulation code MEGA in a tokamak plasma [4]. Considering the interaction between energetic electrons and Alf$\rm {\acute{ven}}$ eigenmodes, energetic electron effects on TAE excited by energetic ions are further investigated, as active control of Alf$\rm {\acute{ven}}$ eigenmodes using ECH can also produce a considerable number of energetic electrons. Firstly, an energetic electron driven TAE propagating in the electron diamagnetic drift direction is found using MEGA. The resonance condition for energetic electrons shows both passing and trapped energetic electrons can resonate with TAE. However, the energy transfer from energetic electrons to bulk plasma shows that only trapped energetic electrons contribute to the mode destabilization. Main reasons for little energy transfer of passing energetic electrons are the spatially localized resonance region and small orbit width. Only those passing energetic electrons located closely to rational surfaces can resonate with the mode. In order to investigate the energetic electron effects on energetic ion driven TAE, both energetic ions and energetic electrons described by kinetic equations are included in the simulation model. An obvious stabilization of TAE is found when an off-axis peaked energetic electron beta profile is employed. Further increasing the energetic electron beta can even fully suppress the energetic ion driven TAE. It is found that the stabilizing effect comes from the energetic electron beta profile, as shown in Fig. 1. The decrease of the linear growth rate is mainly due to the decrease of energetic ion driving rate, rather than the increase of the damping rate. Besides, the energetic electron beta profile can also affect the TAE frequency. Both downshift and upshift of mode frequency are found, which is dependent on the gradient of energetic electron beta profile.

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![Kinetic energy evolution of energetic ion (EI) driven TAE with the effect of energetic electrons (EEs).][5]

[5]: https://i.postimg.cc/cJF7jqhS/kt2571-ekin-EEkin-EEbulk-new.png

NBI fast ion modelling of the LHD heliotron and W7-X stellarator with the ASCOT code

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The two leading helical confinement devices, Wendelstein 7-X (W7-X) and the Large Helical Device (LHD) use neutral beam injection (NBI) heating to produce fast ions. The ASCOT code is now equipped to model NBI ions in both devices.

The proposed contribution compares fusion rates and NBI wall loads in the two machines. Neutron rates are only measured in LHD, which started deuterium operation in 2017, while until now W7-X has been operated only with hydrogen plasmas. The assessment of fast ion wall loads focuses on W7-X, where wide-angle IR cameras provide a comprehensive coverage of the fast ion orbit losses to the walls.

Study of Alfvénic modes driven by energetic particles using the code HYMAGYC for the NLED AUG testcase and DTT equilibria

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The code HYMAGYC [1] is a hybrid code suited to study the interaction between energetic particles (EPs) and Alfvénic modes. The thermal plasma is described as a single fluid by fully, resistive, linear MHD equations written in general curvilinear coordinates, while the EPs are described by nonlinear gyrokinetic Vlasov equations [2]. The code capabilities will be fully exploited: realistic shaped plasma cross section, finite magnetic compression, and Finite Larmor Radius (FLR) effects will be considered [3]. The so-called NLED-AUG testcase will first be assumed, both with monotonic and nonmonotonic energetic particle density profile, considering a Maxwellian EP distribution function. The experimental equilibrium has been reconstructed using CHEASE [4] in order to compute the specific equilibrium quantities required by HYMAGYC; moreover, the Alfvén continuous spectra have been evaluated by the linear stability eigenvalue code MARS [5]. Linear dynamics results for modes driven by EPs and characterized by different toroidal mode numbers will be considered, as well as the dependence of the growth-rate and frequency on parameters characterizing the EP distribution function. First results showing nonlinear saturation will also be presented. Moreover, preliminary results of Alfvénic modes in presence of EPs generated by Neutral Beams and/or ICRH in the recently proposed DTT experiment will also be presented.

![NLED-AUG case, n=1: (left) frequency spectrum for the electrostatic potential and monotonic EP density profile (black solid curve, see the right frame), and (centre) frequency spectrum for nonmonotonic EP density profile (red dashed curve, see the right frame); Maxwellian EP distribution function with temperature TH=0.093 MeV.][7]

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[6] Ponti G et al 2014 Proc. 2014 Int. Conf. on High Performance Computing and Simulation, HPCS 2014 pp 1030–3 art. no. 6903807

[7]: http://www.afs.enea.it/vlad/Miscellaneous/Figure-abstract.jpg

Frequency chirping of an energetic particle driven mode in the presence of kinetic thermal ions

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In the present work, the extended hybrid MHD-gyrokinetic code (XHMGC) [1,2] with both energetic particles and thermal ions treated kinetically is used to study the frequency chirping of a single toroidal number mode. Anisotropic slowing-down distribution with single pitch angles are used to describe the energetic ion velocity space distributions, and isotropic Maxwellian distribution is used to describe the thermal ions. In our simulations, we found mode frequencies can chirp across the shear Alfvén continuum. The down-chirping is dominant. Saturation level scales differently from both resonance detuning and radial decoupling scaling for fixed mode structure and constant frequency modes [3]. During chirping, mode structure is strongly modified. Each poloidal harmonic essentially attaches to its own shear Alfvén continuum branch. As a consequence, large particle redistribution in phase space is observed. By varying thermal ion beta or energetic particle density, modes are found to chirp down to the kinetic thermal ion induced gap. When the mode chirps down, it can transfer energy to thermal ions. Down-chirping modes can transfer energy to thermal ions in an easier way, as the ion Landau damping is more effective at low frequency.

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Global electromagnetic gyrokinetic simulations of TAEs in ITER

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For a long time, direct initial value gyrokinetic simulations of Alfvén eigenmodes with global structures in realistic tokamak conditions have proven very challenging. While MHD-kinetic hybrid models have been able to simulate these modes with varying reductions in the model, global gyrokinetic codes have struggled with electromagnetic simulations using realistic plasma beta and in realistic geometry. Recent work (1) has improved the mitigation of the so-called cancellation problem in electromagnetic particle-in-cell codes, allowing simulations of global large-scale modes at high plasma beta. In this work, building upon some recent developments, we present simulations performed of TAEs in the ITER 15MA baseline scenario using the gyrokinetic code ORB5 (2,3).

By starting with several simplifications to the problem, the impact of which are investigated individually, we are able to show that robust simulations can be obtained, results which we are able to compare to hybrid simulations and to linear gyrokinetic eigenvalue calculations obtained with LIGKA (4), and results which allow some limited parameter scans. Having learnt lessons from running these simplified cases, we are also able to run simulations keeping as few simplifications as possible.

With these simulations, we can study the effect of several physical processes, including the effect of the background profiles on global modes, kinetic Alfvén waves, the damping due to finite electron mass, subdominant instabilities, and the presence and interaction of modes across multiple TAE gaps with a single toroidal mode number.

![(a)][1]

![(b)][2]

Figures 1 & 2: Snapshots of the potential for: (a) a global $n=12$ TAE and (b) a core-localized $n=26$ TAE. R and Z are in units of ρ_s

(1) A. Mishchenko et al. CPC 2019 (2) S. Jolliet et al. CPC 2007 (3) E. Lanti et al. CPC 2019 (submitted) (4) Ph. Lauber PPCF 2015

[1]: https://home.mpcdf.mpg.de/~thay/fig_n12_crop.png

[2]: https://home.mpcdf.mpg.de/~thay/fig_n26_0.985_crop.png

Gyrokinetic investigation of the dynamics of Alfvénic instabilities in ASDEX Upgrade

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In the present work, Alfvén modes are investigated by means of simulations performed with the global, gyro-kinetic, particle-in-cell code **ORB5**. The obtained results are compared with the outcomes from the gyro-kinetic, non-perturbative, eigenvalue solver **LIGKA**.

Results of global, collisionless simulations with both analytical and experimental Tokamak magnetic equilibria are discussed. Comparison with analytical predictions is shown for equilibria with small and realistic inverse aspect ratio. The principal studies performed have been focused on the understanding of the two main damping mechanisms of the Alfvénic instabilities, i.e. the continuum damping and the Landau damping.

The dependence of the dispersion relation and of the damping rate on the finite electron mass has also been analyzed. As an application, the experimental magnetic equilibrium and plasma profiles of the **NLED AUG case** have been considered. The frequency spectra of the Alfvén modes have been investigated with **ORB5**. The energetic particle's density profile has been modified, considering both on-axis and off-axis profiles and varying their slope. Toroidal Alfvén Eigenmodes (TAE) and energetic-particle-driven modes (EPM) have been observed. The study of their main damping mechanisms is also discussed.

Analytical estimation of drift-orbit island-width for passing ions in static magnetic perturbation

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The fast ion transport plays a key role in the simulation for developing operational scenarios. But the transport of fast ions in the perturbed field, such as a resonant magnetic perturbation or MHD, is complex compared with that of thermal ions. The transport depends on energy and pitch angle as well as a spatial coordinate. The Monte-Carlo approach can handle the transport in the straight forward way, however the approach is computationally expensive and is not suitable for integrated codes used for the operational scenario development. Thus, we need reduced transport models. In the model, the island structure in the phase space can be a characteristic scale of the transport and can be an important factor. Thus, a simple method to determine the width of the island structure are useful. In the previous work[1], we proposed a method to map a magnetic-field island-width onto a drift-orbit island-width for passing particles in the presence of static magnetic perturbations. We assumed the orbit perturbation is dominated by the magnetic perturbation with the same toroidal and poloidal mode number. But the method has deficits. One deficit is the assumption on the perturbation. Another deficit is a cost to calculate a Poincaré map for the magnetic perturbation though it is much smaller calculation than the Monte-Carlo approach. A smaller calculation is better for reduced models. In this paper, we present a better method to estimate the drift-orbit island-width from the velocity perturbation on a resonant canonical angular momentum surface. We have derived an expression for the drift-orbit island-width in the similar way how we estimate the magnetic island width from the magnetic perturbation on a resonant magnetic poloidal flux surface. The derived expression is an analytic form using velocity perturbation. Thus, we can avoid the issue on the difference between the magnetic perturbation and velocity perturbation. We can also eliminate the cost for the Poincaré-map calculation of the magnetic perturbation. The estimated drift orbit island widths were compared with those from Poincaré maps obtained from a drift-orbit-following calculation. The estimated island widths well correlate with those from Poincaré maps. The island overlaps are also explained by the estimated island position and its width. The estimation method can provide an indicator to evaluate an overlapping threshold for chaotic orbits in the same way with the magnetic perturbation.

[1] K. Shinohara et al., Nucl. Fusion 58 (2018) 082026

Numerical investigation of energetic particle driven interchange mode in LHD

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The Energetic particle driven Interchange mode (EIC) is a mode that was observed reccently [1] in the Large Helical Device (LHD) in the presence of strong perpendicular Neutral Beam Injection (NBI). The EIC is a magnetohydrodynamic (MHD) instability with m/n=1/1 (where m and n are the poloidal and toroidal mode numbers respectively) that occurs in bursts and causes losses of energetic ions from the core plasma. It was found that the frequency was consistent with the helically trapped energetic ions precession frequency. The fast ion losses are observed through the drop in neutron emission in deuterium experiments and are deleterious for the energy confinment and plasma heating. An important feature of this mode is that it experiences a frequency down-chirping during each burst.

For the study of this mode, the code MEGA [2] is used. It is a fully nonlinear hybrid MHD-kinetic code where the bulk plasma is treated using the fluid MHD description and the energetic particles are treated using a drift kinetic description. This code uses a realistic geometry and equilibrium, and has been used successfully on both tokamak and stellarator configurations for energetic particle driven modes.

The mode is investigated using an equilibrium reconstructed from a deuterium shot where EIC was observed. The role of the energetic ion β, profile and pitch angle is investigated. Preliminary results on destabilization, nonlinear saturation, chirping, and pressure profile redistribution, are presented.

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effects of trapped energetic particles on double tearing modes

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The effects of trapped energetic ions(TEI) on double tearing modes (DTMs) are studied by hybrid simulation. It is shown that TEI have a stabilizing effect on DTMs for small energetic ion beta. A new energetic particle driven mode is found when energetic ion beta larger than a threshold. This mode is an ideal mode, which is a fishbone-like mode. The threshold increases with resisitivity, and the resistivity tends to reduce the growth rate. The dependence of TEI effects on energetic ion beta, gyro-radius and speed is studied systematically. It suggests that a fishbone-like mode will be triggered with a reversed shear q profile.

Alfvén Eigenmode evolution in NBI-heated plasmas with dynamic magnetic configuration in the TJ-II stellarator

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Alfvén Eigenmodes (AEs) were studied in low magnetic shear flexible heliac TJ-II (B0=1 T, <R>=1.5 m, <a>=0.22 m). The modes were excited by hydrogen co-NBI in L-mode hydrogen plasmas (P_NBI=0.56 MW, E_NBI=32 keV), and diagnosed with Heavy Ion Beam Probe (HIBP) [1], Mirnov probes and bolometer arrays. An earlier published paper [2] shows that for any observed AE, its frequency fAE could be well described by a simple expression based on local AE dispersion relation including a linear iota dependence on plasma current Ipl in the k term. Taking advantage of the unique TJ-II capabilities, a dynamic magnetic configuration experiment with iota variation during discharge was performed via inducing net plasma current. This experiment has shown a strong effect of the iota value on the mode frequency. A drastic frequency change from 50 to 250 kHz was observed for some AEs when plasma current as low as ±2 kA was induced by small (10%) changes in the vertical field. It was also found that no AE exists with fAE < fmin 50 kHz, which indicates the GAM/ EGAM effect on AEs at lowest frequency in TJ-II. On top of the conventional linear link between fAE and plasma current Ipl, which could explain via k interplay why the local extrema of fAE coincide with the extrema of Ipl, a new type of fAE dependence on Ipl has been observed in TJ-II. In this new type cases, the local minima of fAE are seen not at extremum points of the current, but at certain Ipl values along linear evolution of the current. To describe this type of fAE behavior, the model [2] was modified by adding the fmin correction caused by the GAM/EGAM effect and a finite pressure gradient effect. It was found with the modified model, that when the iota evolving due to the temporal evolution of Ipl, passes values equal to the ratio of toroidal and poloidal mode numbers, iota = n/m for a specific AE, thus turning k to zero, fAE reaches fmin then. With further Ipl evolution, the value of k changes its sign, so that fAE changes the directivity of its evolution from the frequency decrease to the frequency increase.

It was also found that in some discharges the evolution of AE from a steady frequency mode to a chirping one and back takes place when the plasma current reaches certain values or changes its evolution from raise to decay. Amplitudes of the perturbations in the form of plasma potential and density, as well as the mode location were measured by HIBP.

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Correlation between Beam Power and Knock-on Effect of Energetic Protons on Slowing-down Deuterons Observed in the Large Helical Device

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Energetic ions knock the thermal ions in the higher energy range via nuclear elastic scattering (NES) [1], and create knock-on tails in ion velocity distribution functions. A large fraction of the energetic-ion energy is transferred to the bulk ion in a single NES event, and the energetic-ion slowing-down properties are affected by the collisional energy-transfer process as well as Coulomb collision. Owing to the NES effect, fractional energy deposition transferred from energetic ions to bulk ions tends to increase compared with when we only consider Coulomb collision. The NES causes distortion of both energetic and bulk distribution functions, and sometimes fusion reaction rate coefficients are changed from the values for Maxwellian plasma. These phenomena could be appreciable in a thermonuclear plasma and the understanding with experimental validation would be necessary.

On the large helical device (LHD), we attempted to observe the knock-on effect by looking at a decay time of the DD neutrons after deuterium beam was terminated for several beam conditions. We devoted our attention to measure the neutron decay times produced by the DD reactions between the ~60-keV deuterium beam and bulk deuterons. During the decay process the ~180-keV hydrogen beams were continuously injected, and the decay times were compared for several hydrogen beam-injection patterns. We expected that the neutron decay process would be disturbed by the knock-on effect of energetic protons. We observed that the decay process was actually delayed (decay time increases) with increasing the intensity of the injected hydrogen beam power. Numerical simulations are carried out to understand the observed phenomena on the basis of the Boltzmann-Fokker-Planck model [2]. The simulations reproduced the experimentally measured phenomena with several parameters. In the presentation we will discuss the influences of the parameters assumed in the simulation and the particle loss process in the LHD plasma.

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The systematic investigation of energetic particle driven geodesic acoustic mode channeling using MEGA code

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The energy channels established during the energetic particle driven geodesic acoustic modes (EGAMs) in the Large Helical Device (LHD) plasmas are investigated using MEGA code. MEGA is a hybrid simulation code for energetic particles interacting with a magnetohydrodynamic (MHD) fluid. In the present work, both the energetic particles and bulk ions are described by the kinetic equations. A realistic 3-dimensional equilibrium generated by HINT code is used for the simulation.

The properties of EGAM channeling are systematically investigated for the first time. Five conclusions are found as follows. First, during the non-chirping EGAM activities, EGAM channeling occurs in the linear growth stage but terminates in the nonlinear saturated stage; while during the chirping EGAM activities, EGAM channeling occurs continuously in both linear growth stage and nonlinear saturated stage. Second, the bulk ion heating power increases with the EGAM amplitude, because stronger mode activity transfers more energy to the bulk ions. But the energy transfer efficiency (E_{ion}/E_{EP}) is not sensitive to the EGAM amplitude, because both the energy absorption of bulk ions and the energy loss of energetic particles changes together. Third, lower frequency EGAMs make higher energy transfer efficiency as shown in Fig. 1, because the interactions between lower frequency mode and bulk ions are stronger. The EGAM mode frequency decreases with the increase of energetic particle pressure, while the EGAM energy transfer efficiency increases with energetic particle pressure. Also, the EGAM mode frequency increases with neutral beam injection velocity, while the EGAM energy transfer efficiency decreases with the increase of neutral beam injection velocity. Fourth, in the case of deuterium plasma and deuterium beam, the energy transfer efficiency is lower than that of the hydrogen plasma and hydrogen beam. Last, the energy transfer efficiency increases with the decrease of dissipation coefficients. Less energy dissipates by decreasing the dissipation coefficients, and thus, more energy can be transferred to the bulk ions. After the resistivity decreases by 78% from $8.16 \times 10^{-5} \Omega \cdot m$ to $1.81 \times 10^{-5} \Omega \cdot m$, the energy transfer efficiency increases from 40% to 55%.

![The energy transfer efficiency (triangles) and EGAM frequency (circles) versus the energetic particle pressure (left panel) and beam energy (right panel).][1]

[1]: https://i.postimg.cc/bwsx2qBd/IAEA-TM-EP-2019.png

Long-term Alfvén instability nonlinear simulations and high-bandwidth linear eigenmode surveys

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Fast ion driven Alfvén instabilities are often observed to persist at sustained/steady amplitudes in experiments for 105 to 106 Alfvén times ($\tau_{Alfvén}$ = $R_0/\vee_A$). Nonlinear saturation effects and mechanisms that lead to self-organized states are important since they influence the mode intermittency and associated fast ion transport levels. Gyro-Landau fluid models (TAEFL/FAR3D) have achieved very long simulation times for these instabilities (up to 50,000 Alfvén times). This model uses predictor-corrector time stepping to achieve numerical stability and projects the 5D phase space of the fast ion kinetic problem down to 3D to attain good efficiency and turn-around times. The sustained nonlinear state requires a balance between transport of the fast ion component into the resonance regions and transport out by nonlinear flattening of the distribution function; also, zonal flows (with neoclassical damping) and currents aid in regulating the amplitudes. The following figures show two examples of the simulated time variation of the fluctuating poloidal magnetic field at the plasma edge from an RSAE instability. In (a,b) no external source of fast ions is imposed, and the nonlinear density profile flattening, zonal flows and currents achieve a balance which allows sustained fluctuations. In (c,d) a fast ion density source is used that freezes the fast ion profile at its initial state; this leads to bursting in the nonlinear amplitudes with limit cycles. In the linear regime, gyrofluid models can also be solved as eigenvalue problems, facilitating mode surveys over wide frequency ranges and parameter variations. Applications to low frequency (BAE/BAAE) instabilities have been made; such techniques are also useful in understanding nonlinear dynamics and mode couplings.

![ ][1]

Figure 1 - Nonlinear Alfvén mode evolution of $\delta$$B_{\theta}$/$B_0$ (a,c) and spectrograms (b,d) for a steady saturated state (a,b), and a pulsating saturated state (c,d).

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[1]: http://s000.tinyupload.com/?file_id=37863156144769090530

Investigation of the effective confinement time of energetic ions in LHD by using neutron measurement and simulation

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Enhancement of the plasma heating efficiency is one of the most important issue for magnetically confined fusion devices. In general, the plasma heating in fusion devices is achieved by the kinetic energy transfer from fast ions, which are generated by the neutral beam (NB) injection, the radio frequency waves, and the fusion reactions, to bulk plasmas through Coulomb collision. To obtain the high efficiency of the plasma heating, fast ions should be confined in plasmas until its kinetic energy is transferred sufficiently. Unfortunately, however, the fast ion confinement often degrades due to several transport mechanisms. For this reason, there are numerous researches, which have performed to clarify the fast ion transport mechanisms.

This paper aims to investigate the fast ion confinement in the Large Helical Device (LHD). Generally, the accurate description of the fast ion transport is very difficult because the fast ion transport mechanism includes several phenomena, which have wide range of time and spatial scale. Therefore, in this paper, we have estimated the effective fast ion confinement time by using neutron measurement and simulation codes.

In LHD deuterium plasmas, fast neutrons are yielded owing to the deuterium-deuterium (D-D) fusion reaction. In present magnetically confined fusion devices including LHD, the fusion reaction between fast ion and thermal ion is dominant. For this reason, we can evaluate the fast ion confinement from the neutron emission rate measurement. We have performed the series of the short pulse NB injection experiment to investigate the effective fast ion confinement time τ_n. The neutron emission rate decays exponentially after NB is turned off. This decay can be explained by two reductions. One is the reduction of the fusion cross-section due to the fast ion slowing down. The other is the reduction of the fast ion density due to the fast ion transport. For this reason, we obtain the following relation: $\tau_n^{-1}=\tau_s^{-1}+\tau_c^{-1}$, where τ_s and τ_c denote the time constant of the neutron decay due to the slowing down and transport. The time constant τ_n can be obtained by the neutron measurement and τ_s can be obtained by the Fokker-Planck simulation. Analysis result with several magnetic configurations and plasma parameters will be presented.

Numerical analysis of two-fluid and finite Larmor radius effects on reduced MHD equilibrium with flow

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Effects of two-fluid and ion finite Larmor radius (FLR) effects on equilibrium with flow in reduced MHD equations for high-beta toroidal plasmas are investigated numerically. Equilibrium flow plays an important role in the suppression of instability and turbulence in fusion plasmas. In the region of steep gradient in the improved confinement mode achieved by the flow shear, small scale effects such as two-fluid effects and ion FLR effects are not negligible. Plasma flows induced by the neutral beam injection has strong pressure anisotropy. Since fusion plasmas become high temperature and low collisionality, non-Maxwellian component is important. The macroscopic behaviors of fusion plasmas including above-mentioned multiscale effects are described by extended MHD equations. Equilibrium solution in the presence of flow for the extended MHD equations is needed to study stability and for initial conditions of nonlinear multiscale simulations. The equilibrium equations for extended MHD are expanded with respect to the inverse aspect ratio of a torus for high-beta tokamaks to obtain the Grad-Shafranov (GS) type equations [A. Ito and N. Nakajima, Nucl. Fusion **51** (2011) 123006]. The toroidal and poloidal flows are assumed to be comparable to the poloidal sound velocity. This order of flow is included by taking higher order terms of expansions. The coupling of the equations for the parallel flow and pressure, the characteristic of the slow magnetosonic wave appears. The interaction between the poloidal flow and slow magnetosonic wave causes singularity. By including two-fluid and ion FLR, the effects of diamagnetic drift is induced. The ion FLR effect is included as gyroviscosity in the fluid moment equations. Since, in low-collisionality plasmas, non-Maxwellian component is not negligible, pressure anisotropy and parallel heat flux are also taken into account with a closure model. The expanded GS equations include complicated effects, but can be solved easily. We solve the GS equations numerically by using the finite element method. We obtain equilibrium structures such as the magnetic flux surfaces and isosurfaces of anisotropic pressures and stream functions for ions and electrons. The numerical solutions show the key features of such multiscale equilibrium that the pressures and stream functions are not constant. Since the poloidal flow consists of $E\times B$ and diamagnetic drifts, the equilibrium depends on the direction of $E\times B$ flow. Application to the stability analysis is also discussed. Since this equilibrium includes toroidicity and compressibility, it is applicable to study the effect of flow and the small scale effects on the ballooning and geodesic acoustic modes (GAM).

Parametric Study of Linear Stability of Toroidal Alfvén Eigenmode in KSTAR and JET

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Toroidal Alfvén Eigenmodes (TAEs) driven by energetic ions play a critical role in the transport of the resonant energetic ions by relaxing their pressure gradient. It is important to predict the linear stability of TAE in various conditions for optimizing burning plasma scenarios. However, it requires considerable computational resources for MHD/gyrokinetic simulations to explore the diverse conditions and find the stability conditions. In this work, we performed parametric studies using analytic formulae for the linear growth rate derived from the eigenmode equation with suitable assumptions. First, we calculated the criteria of TAE destabilization by beam ions. We found that the beam damping becomes dominant when the beam-ion orbit width becomes narrower. This shows good agreement with KSTAR experiments. Second, we modelled the TAE resonance with ICRH-heated ions using a bi-Maxwellian for the fast ion distribution, in order to apply this stability analysis to RF-driven TAEs in JET. Then we checked the time-varying linear stability of TAE in a JET discharge using the analytic formulae. We could see that TAE is excited by ICRH, and damped as beam beta increases and the plasma density exceeds the critical value for the resonance. The strong interaction of TAE with the beam occurs only in plasmas with rather high density so that ${v_A}$ is low enough for the resonance condition ${v_{ b}=v_A/3}$. In JET plasmas with densities lower than the one required for such resonance, the interaction of TAE with the beam is small. Finally, we predicted the alpha particle contribution to TAE destabilization for a future DT campaign in JET. This fast modelling tool can be used for extensive parametric studies in order to optimize TAE scenarios in JET and ITER.

Gamma ray measurements of the runaway electron distribution function in disruption mitigation experiments at the ASDEX Upgrade and JET tokamaks

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The mitigation of runaway electrons (RE) that may be generated in disruptions is among the key priorities for the safe operation of the ITER tokamak. The most pursued mitigation techniques are currently based on the injection of a high Z impurity in the plasma (predominantly Argon) as a way to achieve RE dissipation. Examples are experiments based on Massive Gas Injection (MGI) at the ASDEX Upgrade tokamak, or on Shattered Pellet Injection (SPI), such as those recently conducted at JET. In both cases, the aim of the experiments is to gain detailed physics insight on the mechanisms that drive the RE mitigation, which is achieved by comparing data from a broad range of RE diagnostics to currently available codes. The goal is to possibly validate the theoretical models so that the results of present experiments can be reliably extrapolated to ITER.

The RE distribution function is one of the most interesting parameters for validation, but this is also challenging to measure experimentally. A possibility comes from time resolved spectral measurements of the hard x-ray emission from REs at typical energies in the MeV range, which has recently been made possible by the development of gamma-ray spectrometers with MHz counting rate capabilities and, hence, millisecond time resolution.

In this contribution we present an overview of measurements of the RE distribution function by the detection of bremsstrahlung spectra in the MeV range in MGI and SPI experiments at the ASDEX Upgrade and JET tokamaks, respectively. At ASDEX Upgrade two spectrometers observe the plasma along two toroidally separated, radial lines of sight. At JET, instead, the plasma is viewed simultaneously along a vertical and tangential lines of sight, together with an array of compact detectors (cameras) that make it possible to infer information on the RE spatial profile.

We further discuss the deconvolution methods that are used to obtain the RE distribution function from hard x-ray measurements and, in particular, to retrieve the maximum energy Emax of the RE beam and its evolution in the post-disruption phase. For the MGI scenario, we finally compare the time evolution of Emax with a one-dimensional model that, albeit simplified, is capable to capture the gross features of our experimental findings.

Feasibility of using Orbit Tomography to infer the Runaway Electron Distribution Function from Bremsstrahlung Measurements

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During a disruption event a strong electric field is generated, causing supra thermal electrons to reach relativistic speeds. Due to the severe damage the runaway electrons can inflict upon ITER's plasma facing components and cooling systems, developing strategies to both prevent the formation of and to safely dissipate the runaways is critically important to ITER's success. However, development of mitigation strategies is hindered by the difficulty of measuring the runaway electron's distribution function as most runaway-electron diagnostics can only provide partial information about the runaway-electron phase-space. Fortunately, using Orbit Tomography, a technique developed in the fast-ion community, multiple measurements can be combined to infer the runaway electron distribution function to unprecedented dimensionality.

DIII-D's Gamma Ray Imager (GRI) provides multiple spatially and energy resolved

bremsstrahlung measurements of the runaway electron distribution. Calculations of the GRI's orbit weight functions i.e. phase-space sensitivities shows favorable conditions for doing Orbit Tomography. In this work we will explore the feasibility of doing Orbit Tomography with GRI measurements. Orbit weight functions for the GRI calculated by the SOFT code will be presented along with reconstructions of the runaway electron distribution function from synthetic measurements.

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Ion species mix, magnetic field, and distribution function dependence of instabilities in the ion cyclotron range of frequencies

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A Frontier Science experiment in the DIII-D tokamak explored the compressional Alfvén eigenmodes (CAEs) and coherent ion cyclotron emission (ICE) dependence on the plasma ion species mix, magnetic field strength, and energetic ion species and their phase space distribution. The results from this experiment advance understanding of energetic ion-driven instabilities in the radiation belts—electromagnetic ion cyclotron (EMIC) and "equatorial noise"—that resemble the CAEs and ICE seen in tokamaks. The flexible neutral injection beam capability of DIII-D was used to explore ten different combinations of energetic ion species and their phase space distributions. Energetic ion species included hydrogen (H+) and deuterium (D+), and the highly anisotropic distributions were varied in terms of the direction (co- vs. counter current), pitch (v||/v), energy (81/55 kV) and radial location (on- vs. off-axis) of the energetic ions at birth. The background plasma was D+ with H+ and helium (3He++) in different mixtures throughout the experiment. The instabilities of interest were measured using toroidal magnetic loops with a digitization range of 1–100 MHz. Spectroscopy, neutron rate, and toroidicity-induced Alfvén eigenmode (TAE) frequency were all used to determine the species mix of the plasma, as well as to cross-check calculation outputs.

The addition of H+ and 3He++ to the plasma introduces emission bands below their respective cyclotron frequencies reminiscent of those seen in H+, He+, and oxygen (O+) plasmas in space. Emission below the deuterium cyclotron frequency (fcD) has a higher dB amplitude for on-axis co-current D+ injection, magnetic fields at or below 1.25 T, and high concentrations of H+ in the thermal plasma. Low-energy, off-axis, and/or counter-current D+ injection and high magnetic field strengths are detrimental to this lower-frequency emission. Above fcD, 81 keV counter-current D+ injection produces the strongest emission, followed closely by high-energy on-axis injection. In this frequency range, increasing H+ in the plasma inhibits emission and magnetic field has no effect. The distribution functions that drive these instabilities are calculated by NUBEAM [A. Pankin, Comp. Phys. Comm. 2004]; compared with fast-ion D-a (FIDA), imaging neutral particle analyzer (INPA), and neutron data; and analyzed for bump-on-tail features. The effects of species mix on the distribution function are considered.

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HALO : A GPU code for calculating the non-linear evolution of fast particle driven eigenmodes in Tokamaks

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The full abstract with figures can be found here:

https://docs.google.com/document/d/17Fvahzdj03hl4ligouFJladkZVHlq1ij7Kafp3g9kJo/edit?usp=sharing

The text of the abstract is reproduced below:

HALO : A GPU code for calculating the non-linear evolution of fast particle driven eigenmodes in Tokamaks

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HALO (HAGIS-LOCUST) is a recently developed code for predicting the non-linear evolution of MHD eigenmodes driven unstable by fast particle populations in tokamaks. HALO is built on top of the LOCUST fast particle tracking code which exploits modern GPU technology to rapidly track the full gyromotion of millions of particles in realistic tokamak geometries. LOCUST has been used extensively to model heat loads on first wall components in various reactors, including components under the divertor dome on ITER [1]. Fig. 1 shows a LOCUST calculation of the heat load on in-vessel components due to residual gas-stripping in the MAST-U Double Beam Box. HALO leverages the high performance of LOCUST to calculate the non-linear response of a set of prescribed eigenmode fields to a given fast particle population. The code can deploy either guiding centre or gyro-orbit tracking and particles can be tracked outside the separatrix.

HALO exploits a perturbative approach, assuming that the eigenmode shapes are constant as the modes evolve. This is applicable to a large number of physically relevant scenarios, most notably TAEs. HALO tracks particles via solution of the Lorentz force law, calculates the work done by the particle population on the wave fields and then solves a complex ODE for each mode to determine the evolution of its amplitude and phase. HALO, like HAGIS, also exploits a delta-F scheme for noise reduction.

HALO has been validated using a near cylindrical geometry case with a single TAE and has been observed to conserve the invariant K=E-(omega/n)P to an accuracy of 1 part in 10**5. Growth rate comparisons with HAGIS show excellent agreement when HALO is run in 'drift order' mode as well as a disparity consistent with theory when full orbit effects are included. HALO also successfully reproduces the chirping behaviour expected when ad-hoc mode damping is included (Figure 3).

HALO is now starting to be used for realistic studies of TAE losses on JET in preparation for DTE2. Development work is ongoing and is currently focussed on further parallelisation of the code with MPI and coupling the code with MISHKA3 to allow studies with ion cyclotron modes as well as low frequency modes. Another key research goal is the incorporation of collisional effects which are presently absent.

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Long range Alfvenic frequency chirping in tokamaks

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Unstable Alfvén eigenmodes (AEs) can lead to frequency chirping

events and enhanced particle transport in magnetic fusion devices. Refs. [1, 2] explain the frequency sweeping events in terms of evolution of coherent structures (holes and clumps), in the energetic particles (EPs) phase-space using a perturbative method. This method implies small deviations of frequency from the initial eigenfrequency of the linear mode, as the spatial structure of the mode is fixed. A nonperturbative adiabatic model was then developed in Ref. [3] to study the long range frequency chirping [4, 5] of a plasma wave whose spatial structure is notably affected by EPs. The model was subsequently extended to describe the effects of EPs collisions [6, 7] and equilibrium drift orbits [8].

In the present work, we use a Lagrangian formalism and finite element method to study the hard nonlinear frequency sweeping of a Global Alfvén eigenmode (GAE). We focus on the evolution of the radial structure of the eigenfunction. The eigenfunction is represented by a single poloidal and toroidal mode number. Toroidal effects are retained on EPs dynamics in a high aspect ratio tokamak limit. The evolution of the frequency is tracked using the balance between the energy extracted from the EPs distribution function and the energy deposited into the bulk plasma. For later evolution, we have found a region where the frequency chirps even faster than the square root dependency in time. Due to MHD properties of this mode, the impact of frequency change on the radial profile is more significant at the earlier stages of chirping.

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The electron drift effect on the axi-symmetric global Alfven eigenmodes

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The axi-symmetric Alfvenic perturbations were observed on TFTR almost two decades ago and on JET more recently. They are global Alfven eigen-modes (GAEs) with characteristic frequency like that in cyclindrical plasmas, and the dominant poloidal mode number m=+/-1. The ellipticity of cross section is invoked to explain the splitting of the cylindrical ideal MHD Alfven continuum in a recent research. In this work, we studied the axi-symmetric GAEs using the two-fluid model. The simple geometry with concentric circular cross section is adopted. The cylindrical Alfvenic continuum splits into two branches due to the drift effect from the electron temperature gradients alone, without taking into account the non-circular shaping of cross sections. For profiles of the safety factor, electron temperature and density in a typical tokamak plasma, the two separate accumulation points are near the edge region of the plasma. It gives an interpretation of the two axi-symmetric Alfven modes observed on TFTR. The toroidal coupling of the m=1 and m=-1 components results an up-shift of the continuum, but has no effect on its splitting. The radial mode structure is similar to that predicted from ideal MHD codes.

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Hybrid Simulation of Global Alfvén Eigenmode and Energetic Particle Mode in Heliotron J, a Low Shear Helical Axis Heliotron

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Magnetohydrodynamic (MHD) and energetic particle hybrid simulation code, MEGA, is applied to Heliotron J, an advanced stellarator/heliotron device with low magnetic shear, helical axis, and finite vacuum magnetic well. Due to the low magnetic shear, the global Alfvén eigenmode (n/m=2/4) has been dominantly observed, along with the energetic particle mode (n/m=1/2) in the experiment. In a recent experiment, a low frequency mode has also been observed when the plasma current is ramped up to a certain threshold. A bump at the high energy tail of the energetic particle distribution is observed in Heliotron J experiment for particles with low pitch angle, due to the significant charge-exchange loss at the ![enter image description here][1]peripheral region. It is gradually changed to the slowing-down distribution for particles with high pitch angles. The objective of this paper is to clarify the interaction between energetic particles and magnetohydrodynamic waves in the experiment and present the dependency of the energetic particle-driven mode on the equilibrium energetic particle distribution function. In this calculation, MHD equilibrium is based on the low bumpiness (low toroidal magnetic mirror) configuration. The slowing-down and the bump-on-tail distributions are utilized to study the dependency of energetic particle mode and global Alfvén eigenmode on the energy distribution. The n/m=1/2 energetic particle mode and the n/m=2/4 global Alfvén eigenmode have been successfully reproduced in the simulation. Both the n/m =1/2 and 2/4 modes are dominantly destabilized by two velocity ranges of the passing energetic particles, which are 7 to 14 keV, and 20 to 24 keV, where the injection energy is 28 keV. This results in no significant difference in the linear growth rate of the mode, despite changing the location of the distribution peak in energetic particle energy distribution. The discrepancies between the simulation and the experiment will be discussed for further improvement.

[1]: https://postimg.cc/7Cm71F5d/69da931f

The impact of anisotropy on ITER scenarios and Edge Localised Modes

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We report on the impact of anisotropy and flow to tokamak plasma configuration and stability in several different regimes.

First, we conduct a preliminary analysis of the impact of anisotropy on ITER pre-fusion power operation 5MA, B=1.8T ICRH scenarios, where a RF calculation gives the fast ion distribution function. To model ITER scenarios remapping tools are developed that iterate the anisotropy-modified current profile to produce the same q profile with matched thermal energy. We find characteristic detachment of flux surfaces from pressure surfaces, and an outboard (inboard) shift of peak pressure $T\_{||}>T\_\perp$. Differences in the poloidal current profile are evident, albeit not as pronounced as for the spherical tokamak. We find that the incompressional continuum is largely unchanged in the presence of anisotropy, and the mode structure of gap modes is largely unchanged. The compressional branch however exhibits significant differences in the continuum. We report on the implication of these modifications, and scan over a wider set of ITER scenarios.

Second, we explore the impact of anisotropy on ballooning mode, one of the instabilities believed to be responsible for ELMS. The investigation was conducted using the newly-developed codes HELENA+ATF[1] and MISHKA-A[2], which adds anisotropic physics to equilibria and stability analysis. We have examined the impact of anisotropy on the stability of an $n=30$ ballooning mode, confirming results conform to previous calculations in the isotropic limit. Growth rates of ballooning modes in equilibria with different levels of anisotropy were then calculated using the stability code MISHKA-A. The key finding was that the level of anisotropy had a significant impact on ballooning mode growth rates. For $T\_\perp > T\_{||}$, typical of ICRH heating, the growth rate increases, while for $T\_\perp < T\_{||}$ typical of neutral beam heating, the growth rate decreases.[3] Experimentally, values of $p\_\perp / p\_{||} >> 2.5$ and $p_{||} / p_\perp >> 1.7 $ have been identified in JET [4] and MAST [5] plasmas, respectively. This suggests that the impact on growth rates may be significant, and indeed offer the possibility that higher ELM-free performance might be achieved by increasing $p\_{||}/p\_\perp$ in the pedestal region.

Finally, we explore the impact of toroidal flow on both the magnetic equilibrium and stability for an increasing rotation profile. We explore this for a low (n,m) modes resonant with the core plasma, and for gradually increasing rotation. This work is done ahead of benchmarking the impact of rotation on stability using the HELENA+ATF and MISHKA-A code combination.

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Impact of poloidal convective cells on transport processes with kinetic electrons

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Recently, a lot of attentions have been paid to the role of poloidal asymmetries of electrostatic potential in magnetic confined plasmas. It is known that poloidal asymmetries of the $E\times B$ plasma flow are instrumental in neoclassical transport. Nevertheless, this kind of structures are often neglected in standard neoclassical theory, since the amplitude of poloidal asymmetries is expected to be small according to standard neoclassical theory. There are however, several situations where poloidal asymmetries cannot be negligible. For instance, a centrifugal force due to toroidal rotation and RF heating of minor impurities can generate poloidal asymmetries. Even without them, plasma turbulence which is intrinsic in fusion plasmas, can drive flows that are not poloidally symmetric, due to their ballooned feature. These poloidally non-symmetric structures are called poloidal convective cells herein.

Although there are some experimental evidences that poloidal convective cells could have significant impacts on transport processes, particularly on impurity transports, further theoretical studies are needed for understanding complicated transport processes. In order to investigate the impact of poloidal asymmetries on the transport processes, we have introduced a new hybrid kinetic electron model in full-F global gyrokinetic code GT5D [Y. Idomura et al, Comput. Phys. Commun. 179, 391-403 (2008)]. Contrary to the original hybrid electron model in GT5D [Y. Idomura, J. Comput. Phys. 313, 511-31 (2016)] where convective cells are filtered out, the new hybrid electron model keeps convective cells with a new assumption in the passing electron dynamics. If the convective cells interact with both neoclassical and turbulence dynamics, this may be the most reliable approach, since full-F global gyrokinetic code can model neoclassical and turbulence transport processes consistently.

In order to verify the new model, we carry out neoclassical simulations and zonal flow damping tests using both original and new hybrid electron models. We show that the particle flux induced by magnetic drift is enhanced with the presence of convective cells and the frequency and damping rate of zonal flows are changed following the theoretical estimate in the new model. Finally, we compare the flux-driven simulation results with both hybrid electron models. It is shown that the particle, momentum and energy transport driven by magnetic drift are enhanced with the presence of convective cells, while they tend to be cancelled by their counterparts induced by $E\times B$ drift of convective cells. This behavior agrees with our previous work [Y. Asahi et al, PPCF 61, 065015 (2019)] qualitatively. As shown in our previous work, the impact of convective cells on equilibrium profiles are quite limited even with kinetic electrons.

Relativistic guiding-center motion of runaway electrons

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To investigate energetic runaway electron dynamics we developed a code that is solving relativistic guiding-center equations of motion. Relativistic high parallel velocities may cause the zero parallel component of the effective magnetic field, so we adopt the toroidally regularized guiding-center theory [1] to avoid that singularity. Because there is a discrepancy between the standard guiding-center coordinates and the toroidally regularized coordinates, we examined the transformation between the two coordinate systems. Using this code, we performed a computational analysis of the characteristics of runaway electron orbits.

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The collisional resonance function in discrete-resonance quasilinear plasma systems

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A method is developed to analytically determine the resonance broadening function in quasilinear theory, due to either Krook or Fokker-Planck scattering collisions of marginally unstable plasma systems where discrete resonance instabilities are excited without any mode overlap. It is demonstrated that a quasilinear system that employs the calculated broadening functions reported here systematically recovers the nonlinear growth rate and mode saturation levels for near-threshold plasmas previously calculated from kinetic theory. The distribution function is also calculated, which enables precise determination of the characteristic collisional resonance width.

Validating the LOCUST-GPU fast ion code

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The controlled and reliable generation of a high-power burning plasma in ITER requires an understanding of energetic particle (EP) dynamics and subsequent wall heat loads [1]. Detailed studies must however include realistic 3D magnetic equilibria, which are widely thought to worsen EP confinement; this is particularly true for the interaction between edge-localised NBI ions and RMP fields [2][3]. In ITER plasmas, EP slowing-down timescales are long ($\sim$ 1s) and plasma-facing component (PFC) geometry is complex (e.g. pipework under the ITER divertor dome). Therefore generating smooth, high-fidelity EP distribution functions and wall heat loads require a high-performance computing approach.

LOCUST-GPU has been designed in response to this challenge. The Monte Carlo algorithm solves the Lorentz equation of motion for millions of EP markers in a static or rotating 3D magnetic field together with a collision operator and high-precision PFC model. This is achieved in hours by utilising GPGPU cards, each controlled by OpenMP threads, to track markers in parallel.

Current efforts to validate LOCUST-GPU against similar fast ion codes are presented here, and a close match with TRANSP predictions is shown. Additionally, preliminary studies of the effects of DIII-D RMP fields on EP confinement are also presented.

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Quasi-periodic frequency sweeping in electron cyclotron emission of mirror-confined plasma sustained by high-power microwaves

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The complex dynamics have been observed in the spectra of the electron cyclotron emission of a nonequilibrium plasma created by powerful microwave radiation of gyrotron (37.5 GHz, 80 kW) under electron cyclotron resonance (ECR) conditions and confined in a tabletop mirror trap [M.E. Viktorov, et al. // EPL V.116, P.55001 (2016)]. The dynamic spectrum of the emission is a set of highly chirped radiation bursts with both increasing and decreasing frequencies which are repeated periodically. Such patterns are not described in the frame of a quasilinear approach which is standard for the description of a broadband plasma emission. On the other hand, the simultaneous observation of several chirping bursts in the same frequency range is typical for the formation of nonlinear phase-space structures in proximity of the wave-particle resonances of a kinetically unstable plasma, also known as the “holes and clumps” mechanism [H.L. Berk, et al. // Phys. Lett. A V.234, P.213 (1997)]. Our data provide the experimental evidence for the spontaneous formation of self-consistent structures in the new frequency domain (a few GHz) linked to the electron cyclotron frequency in a laboratory mirror-confined plasma.

Microwave emission is observed at a plasma decay stage with a delay of 0.1-1 ms after ECR heating switch-off. The microwave emission is observed only in a few frequency bands ($f = 1–10$ GHz) which are independent of the experimental conditions and the emission frequency is always less than electron cyclotron frequency in the trap center. We assume that the emission frequency is downshifted with respect to the electron cyclotron frequency due to the relativistic effects. The frequency shift corresponds to the energies of resonant electrons of up to 300 keV which is in a good agreement with experimental measurements of energy distribution function of electrons escaping the magnetic trap. Within every frequency band the emission spectrum is a set of fast narrowband chirping bursts ($df/dt \approx 30\,$MHz/sec, $\Delta f / f \approx 10^{-3}$) with a duration up to $10\,\mu s$, while the duration of a burst series can be up to 1 ms. Frequency change $\delta f_{\mathrm{chirp}}$ in a chirp at a single mode is in the range 100-300 MHz which corresponds to the ratio $\delta f_{\mathrm{chirp}}/ f = 0.05–0.1$. Following the model [H.L. Berk, et al. // Phys. Lett. A V.234, P.213 (1997)], the frequency drift within each wave packet is proportional to the instability growth rate and has a predetermined time dependence. Resulting from the analysis of the microwave emission spectrum, the value of the growth rate is consistent with previous studies of excitation of extraordinary waves at the stage of plasma decay, which confirms the applicability of the discussed model.

In the present work, we review the available experimental data and discuss applicability of the “holes and clumps” paradigm to our case. We show that separate nonlinear wave-particle resonances are indeed possible in the described experiment in spite of the huge variation of the magnetic field typical of a mirror magnetic trap [A.G. Shalashov, E.D. Gospodchikov, M.E. Viktorov // arXiv:1903.05218 (2019)].

Analysis of velocity distribution of D-D fusion products driving ion cyclotron emission on JT-60U

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Non-thermal ions can drive waves in ion cyclotron range of frequency (ICRF). Excitation of ICRF waves has been observed in several tokamaks and stellarators when fast ions are produced. This emission is called ion cyclotron emission (ICE). A possible driving source for ICE is the ion velocity distribution having significant non-thermal components, such as a bump-on-tail structure and strong anisotropy. Such a non-thermal distribution can be formed near the outer midplane edge due to the magnetic drift. Identifying characteristics of the ion distribution driving ICE is important to understand its emission mechanism. On JT-60U, ICEs thought to be driven by deuterium-deuterium (D-D) fusion produced ^{3}He ions [ICE(^{3}He)], H ions (protons) [ICE(H)] and T ions (tritons) were detected, and their toroidal wavenumbers were quantitatively measured. Here, ICE(H) was identified by not only comparing its measured frequency with H ion cyclotron frequency, but also comparing its measured toroidal wavenumber with that of 2nd harmonic deuterium ICE [1]. ICE(H) was observed mainly in weak and reversed magnetic shear plasmas. In the previous study [2], fast ^{3}He ion velocity distribution driving ICE(^{3}He) is first evaluated under realistic condition by using OFMC code. In this simulation, birth spatial and velocity distribution of fusion produced ^{3}He ions is evaluated from orbit calculations of fast D ions injected by neutral beams. As the results, it was found that fast ^{3}He ions on the bump-on-tail structure can resonate with waves in the same frequency as the ICE(^{3}He). In addition, the emission condition for the ICE(^{3}He) strongly depends on the bump-on-tail structure in the distribution at the outer midplane edge. On the other hand, necessary characteristics of the fast H ion distribution to drive ICE(H) are not understood since the distribution was not evaluated under such realistic conditions so far.

The purpose of this study is to identify the characteristics of the D-D fusion produced ion distributions driving ICE. Fast H ion velocity distributions have been evaluated under the realistic conditions for the first time by using OFMC code. As the results, it was found that the evaluated fast H ion velocity distribution at the outer midplane edge has the pitch-angle anisotropy and the bump-on-tail structure in the coordinate of the energy. In addition, this bump-on-tail structure is formed only near the outer midplane edge. The ICE(H) would be excited locally in the major radius direction since its observed frequency spectrum width is very narrow ($<$ 1 MHz). Hence, the localization of the formation of the bump-on-tail structure is reasonable. There is a possibility that the emission mechanism for the ICE(H) can be explained by destabilization of ICRF waves by the bump-on-tail structure as well as ICE(^{3}He).

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First investigation of fast-ion-driven modes in Wendelstein 7-X

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The 2018 operation phase (OP 1.2b) of the stellarator Wendelstein 7-X (W7-X) included, for the first time, neutral beam injection (NBI) to heat the plasma. During longer phases of NBI injection, with the primary purpose to study the heating efficiency of this system, Alfvén eigenmodes (AEs) were observed by a number of diagnostics, including the phase contrast imaging (PCI) system, the magnetic pick-up coils (Mirnov and Rogowski coils), and the soft X-ray multi-camera tomography system (XMCTS).

Alfvén eigenmodes are of great interest for future fusion reactors as it has been shown that the resonant interaction of fast ions with self-excited AEs can lead to enhanced transport of fast ions and potentially to energy losses. This is especially true for so-called gap-modes, Alfvén eigenmodes with frequencies in gaps of the continuous spectrum, since they lack continuum damping.

In this contribution we present a first analysis of the observed mode numbers and frequencies from the theoretical side. The calculation of shear Alfvén wave continua for selected cases and the assignment of observed frequencies to the gaps of the continuous spectra are presented. We emphasize the crucial role of the Doppler shift arising as a consequence of the radial electric field in W7-X. Furthermore, the ideal-MHD code CKA [A. Könies et al., *10th IAEA TM on Energetic Particles in Magnetic Confinement Systems* (Kloster Seeon, 2007)] has been used to compute mode structures which are compared to experimental measurements.

The Monte-Carlo particle-following code ASCOT [E. Hirvijoki et al., *Comput. Phys. Commun.* **185** 1310-1321 (2014)] is used to compute the slowing-down distribution function of the fast ions. This information is used by the gyro-kinetic codes CKA-EUTERPE [T. B. Fehér, Ph.D. thesis, *University of Greifswald* (2013)] and EUTERPE to assess the fast-ion drive and to answer the question whether the fast-ion drive is sufficient to destabilize the modes. This question is of particular importance since mode activity has also been observed in other experimental programs without NBI heating. These findings indicate the existence of other destabilizing mechanisms, e.g. associated with the electron pressure gradient [T. Windisch et al., *Plasma Phys. Control. Fusion* **59** 105002 (2017)].

Validation of the TGLF-EP+Alpha critical-gradient model of energetic particle transport in DIII-D scenarios for ITER

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The TGLF-EP [1] and Alpha [2] codes for the critical-gradient model (CGM) of energetic-particle (EP) transport have been unified and verified by nonlinear gyrokinetic simulations and validated against five DIII-D H-mode scenarios for ITER. This reduced model predicts the degree to which Alfvén eigenmodes (AEs) destabilized by EPs—in this case fast ions from neutral beam injection—radially flatten the classical slowing-down EP profile. It finds the steady-state solution of a local 1D radial transport equation under a stiff critical gradient approximation for AE transport with an estimated (small) contribution from microturbulence [3] and including the physical source and sink profiles. While such a reduced CGM neglects phase-space dynamics, finite orbit effects [4], and nonlinear effects such as transport intermittency and frequency chirping, kinetic simulations [5,6] combined with experimental evidence for EP profile resiliency [7] strongly suggest AE-EP transport is clamped to a critical gradient. Our validation study confirms broad applicability of the unified TGLF-EP+Alpha code in predicting the time-averaged density profile in DIII-D. The critical gradient, the model's key input, comes from linear solutions of the TGLF [8] gyro-Landau fluid code, optimized for EP-AE physics, automated, and highly parallelized by the TGLF-EP wrapper code. TGLF-EP+Alpha, under development by the SciDAC ISEP center as an EP module for the future fusion whole-device-modeling project, is fully physics based, requiring only the equilibrium and beam source as inputs. It is computationally inexpensive enough (<30 minutes turnaround time versus over one month for first-principles models) to perform scoping studies needed for scenario optimization. DIII-D cases considered represent a wide range of EP transport, with observed neutron production near classical predictions down to an 80% deficit. TRANSP simulations using the EP diffusion coefficient predicted by TGLF-EP+Alpha find neutron deficits within 20% of experimental observations in applicable cases. Predicted AEs are consistent with previous studies [9].

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High-Resolution Imaging Neutral Particle Analyzer Measurements of the Local Fast Ion Distribution Function and Instability Induced Transport in DIII-D

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The recently developed imaging neutral particle analyzer (INPA) on DIII-D enables fast ion velocity-space tomography of unprecedented fidelity, as well as resolution of local phase space dynamics under the action of classical and non-classical transport mechanisms. The INPA itself measures charge-exchanged energetic neutrals by viewing an "active" neutral beam through essentially a 1D pinhole camera with a rear collimating slit that defines the neutral particle collection sightlines. The incident neutrals are ionized by stripping foils and the local tokamak magnetic field acts as a magnetic spectrometer to disperse ions on the scintillator. A fast camera provides 2D images of the escaping neutrals mapped to energy and radial position in the plasma – thus providing energy-resolved radial profiles of confined fast ions in DIII-D. The local phase space measurements enabled by the INPA are ideally suited to studies of instability-induced fast ion transport, and recent data clearly show transport due to sawteeth and Alfven eigenmodes (AEs). Measurements in reversed magnetic shear experiments have revealed large AE induced preferential transport of different orbit classes at nearby radii, something that would be impossible to distinguish with fast ion diagnostics that weight broad regions of phase space such as fast ion D-alpha (FIDA) or neutron emission.

The 10,000 simultaneous INPA measurements allow velocity space tomography computation of the local distribution function with unprecedented accuracy in the plasma at the INPA measured pitch. To accomplish this, the weight function of the INPA is calculated by FIDASIM [2] and INPASIM [3]. FIDASIM computes the spatial and energy distributions of neutral flux towards the carbon stripping foils and INPASIM simulates the diagnostic response to this flux, including the foil-particle interactions, the particle trajectory towards the phosphor, phosphor response on the incident ion flux and camera imaging. The computed tomography, using the Ridge regression method, benefits from the very localized phase space weights of each pixel and remarkable signal to noise of the system. In test cases, the inversion is able to successfully reconstruct fine-scale velocity-space structure produced by multiple neutral beams at different voltages. Using the technique, the impact of sawtooth crashes on passing fast ions is studied and the inverted data reveal a prompt phase-space dependent redistribution across the q=1 flux surface. At full beam energy, a transition from originally peaked profiles to a flattened profile occurs, however, at half energy, a hollow profile after the crash is found. Fast ion distributions computed by combining tomographic analysis with the INPA data can significantly advance the understanding of phase-space dynamics of fast ions and related model validation, which is a crucial effort for predicting the fast ion behavior in future fusion reactors.

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Observation of Hole-Clump Pair Using an Upgraded E//B-NPA during TAE Burst in LHD

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Toroidal Alfvén eigenmode (TAE) bursts are often observed in the low magnetic field (B_t<1T) experiments in LHD with tangential neutral beam (NB) injection [1-4]. In order to measure the behavior of the energetic particles (EPs) during the TAE bursts, a tangential E-parallel-B type neutral particle analyzer (E//B-NPA) has been used. In the experiments with the E//B-NPA, the hole-clump pair formation was observed in the energy spectra of EPs. The observation indicates the radial transport of the EPs by the TAE bursts, and the energy of the clumped neutral particles were decreased after the bursts [3, 4]. During the TAE burst, the energy decrease which is much faster than the classical slowing down process was also observed by the NPA, but the detailed analysis was difficult due to the lack of time resolution. In order to investigate the behavior of the EPs during the burst, we have upgraded the E//B-NPA to improve its sampling time, which correspond to the minimum time resolution, down to 5 ns by adapting modern electronics to its measurement electronic circuits [5]. With this improvement, the energy change of hole-clump pairs were observed more clearly. It turned out that the clump appeared at high energy region and stayed at almost same energy at the initial phase of the burst. The large energy drop of the clump after the mode amplitude reached its maximum was observed more clearly than before. We will report the detailed investigation of the observed hole-clump pair.

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Energetic-particle Transport and Loss Induced by Helically-trapped Energetic-ion-driven Resistive Interchange Mode in the Large Helical Device

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Understanding of interplay between energetic particle (EP) and EP-driven magnetohydrodynamic mode is of the greatest importance in order to reduce the anomalous transport and/or loss of EPs in current fusion machines and in a fusion reactor. In high-ion-temperature discharges performed in relatively low-density plasma on the Large Helical Device (LHD), helically-trapped energetic-ion-driven resistive interchange mode (EIC) is often excited due to the intensive injection of positive-ion based perpendicular neutral beams (P-NBs) [1]. Study of EIC mode-induced EP transport/loss has progressed by starting the deuterium operation of LHD by using neutron diagnostics because neutrons emitted from NB-heated LHD deuterium plasma are produced mainly from so-called beam-thermal reactions. The effect of EIC mode on beam ion confinement has been studied by total neutron emission rate (S$_n$) measured with the neutron flux monitor and by the neutron emission profile obtained with first vertical neutron camera (VNC) based on stilbene detectors with automated pulse-shape discrimination capability[2]. Loss of helically-trapped beam ion due to EIC mode was reported by comparing S$_n$ and the radial neutron emission profile before and after the EIC mode excitation [3]. The second VNC based on fast-neutron scintillator EJ410 characterized by high-detection efficiency operated with current mode is newly installed in order to obtain neutron emission profile with high-time resolution. By using second VNC, it is found that decay time of neutron signal due to EIC mode in central and edge cords is almost the same, whereas rise time of neutron signal after EIC event is different in central and edge cords. The decrements of S$_n$ and neutron signal in the central cord linearly increase with EIC amplitude suggesting that the convective process is dominant. Orbit following simulation using guiding center orbit following code in the Boozer coordinates (DELTA5D) including magnetic fluctuation [4] is performed to understand the effect of EIC fluctuation on beam ion confinement. In this simulation, EIC perturbations are taken into account as the form δB=∇×(αB) including the frequency sweeping from 10 kHz to 5 kHz within 2 ms as observed in experiments. The width and the location of the magnetic fluctuation are decided to be r∼0.06 m and r/a∼0.87, respectively, based on the experimental observation [1]. Time evolution of S$_n$ obtained by DELTA5D simulation shows that S$_n$ decreases significantly within ∼5 ms by including the magnetic fluctuation. In addition, it is found that the drop rate of S$_n$ increases with the increase of EIC amplitude, as observed in the experiment. Detailed comparison of time evolution of neutron emission profile and transport/loss process of beam ion due to EIC mode will be presented.

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Excitation of elliptical and toroidal AE modes by 3 He - ions of the MeV energy range in hydrogen - rich JET plasma

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Excitation of Elliptical AEs (EAEs) and TAEs has been observed in hydrogen-rich (nH/nH+nD ~70-90%) JET discharges of so-called "three-ion scenario", i.e.D-(3He)-H three ion ICRH scenario [1]. This scenario is characterized by a strong absorption of radio frequency waves at very low concentrations of the resonant 3He-ions. In the experiments, core localized TAEs with frequency f_TAE 280 kHz were observed. Following the phase with the TAE excitation, EAEs at higher frequencies, f_EAE 550-580 kHz, and with mode numbers n=±1, ±3, ±5 were seen. These high frequency modes indicate that a MeV range population of trapped energetic ions was present in the plasma interacting with the modes via the trapped particle resonances. The experimental evidence of the existence of the MeV-energy 3He-ions able to excite the AEs is provided by neutron and gamma-ray diagnostics as well as fast ion loss (FILD) measurements. It was found that the anomalous DD neutron rate in the ICRF-only heated plasma is provided by population of energetic deuterons formed via elastic head-on scattering of the MeV 3He-ions on deuterium (the knock-on effect): D(3He,3He)D knock-on=> D(D_knock-on,n)3He. Gamma-ray diagnostics [2] show that some neutrons are also generated in the nuclear reaction 9Be(3He,n)11C, which takes place with 3He-ions in the MeV-range. The fast ion loss detector [3] indicates that the MeV-range 3He-ion losses related to the core localized TAEs ended with a spike associated with a monster sawtooth, after which the losses correlated to the EAE modes were observed. Analysis of FILD data indicates that the lost 3He-ion energies exceed 2 MeV. The back-in-time orbit analysis of the FILD data shows that the TAE-induced losses of 3He-ions are localised in the plasma centre (R 3.0 m). However, the losses of 3He-ions associated with the EAEs are coming from R 3.2-3.4 m. Results of MHD analysis are consistent with the experimental data showing that the MeV 3He ions are resonant when interacting with TAEs and EAEs.

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Predator-prey paradigm for Alfvén instability dynamics in realisitc RBQ simulations

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To understand the dynamics of multiple Alfvén Eigenmode (AE) instabilities excited simultaneously by energetic beam ions we developed a heuristic Predator-Pray (PP) model where two PP systems each consisting of a predator (AE) and a prey (resonant ions) are coupled together. The first PP system works as a source of particles for the second system which in its turn plays a role

of a sink of those particles. Our model helps to understand multiscale intermittencies observed in

Resonance Broadened Quasi-linear (RBQ) code simulations [N.N. Gorelenkov, V.N. Duarte, M. Podesta, H.L. Berk, Nucl. Fusion 58, 082016 (2018)]. The PP model is different from

the fishbone PP model developed earlier [D. Borba, M.F.F. Nave., F. Porcelli, Theory of Fusion Plasmas (Commission of the European Communities, Brussels, 1992) , 285 (1992)] by demonstrating the presence of the saturated state with finite AE amplitudes.

An interplay between the growth, damping rates and the effective scattering frequency in RBQ simulations is demonstrated in Fig.1, which exhibits a PP behavior in the presence of a single RSAE. ![Intermittancy figure][1]

Figure 1. Single n = 5 RSAE intermittent dynamics with clearly resolved interplay between the net growth rate L − | d |, damping rate d and the pitch angle scattering parameter, scatt .

RBQ model adapts the quasi-linear (QL) approach [H.L. Berk, B.N. Breizman, et al. Phys. Plasmas 3, 1827 (1996)] and generalizes it for a realistic problem near marginal state of unstable AEs. The diffusion equation is solved simultaneously for all particles together with the evolution equation for mode amplitudes by going beyond the perturbative-pendulum-like approximation for the wave particle dynamics. It is likely that once the instability is too strong

(i.e linear theory is sufficiently above the instability threshold) quasi-linear relaxation will keep the system near the marginal stability conditions.

Hence, having a QL theory capable of describing the conditions close to threshold should be an important tool for fusion burning plasma scenarios.

We apply the RBQ code to a DIII-D plasma with elevated q-profile where the fast beam ions show stiff transport properties [C.S. Collins, W.W. Heidbrink, et al. Phys. Rev. Letters 116, 095001 (2016)]. The sources and sinks are included via the Krook operator. The properties of AE driven fast ion distribution relaxation are studied in self-consitent simulations. Initial results show that the model is robust, numerically efficient, and can predict fast ion relaxation in present and future burning plasmas.

[1]: http://www.princeton.edu/∼ngorelen/gnsct5.png

Experimental Progress

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Summary presentation

Theoretical Progress

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Summary presentation