Overview of the Recent Experimental Research on the J-TEXT Tokamak

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Recent J-TEXT research has highlighted the significance of the role that nonaxisymmetric magnetic perturbations, so called 3D magnetic perturbation (MP) fields, play in fundamentally 2D concept, i.e., tokamak. In this paper, the J-TEXT results achieved over the last two years, especially on the impacts of 3D MP fields on magnetic topology, plasma disruptions, MHD instabilities, and plasma turbulence transport, will be presented.

On J-TEXT, the resonant MPs (RMPs) system, capable of providing either a static (DC) or a high frequency (up to 6 kHz) rotating (AC) nonaxisymmetric MP field, has been upgraded by adding a new set of 12 in-vessel saddle coils, and the total number of in-vessel RMP coils increases from 12 to 24 (3 rows × 8 columns). The new capabilities advance J-TEXT to the forefront of international magnetic fusion facilities, and allow a flexible study of 3D effects in a tokamak. Both density and plasma rotation dependences of the $m/n = 2/1$ locked mode threshold, $B_{r,(2,1)}$, have been investigated systematically on J-TEXT. Recent experimental results showed the $B_{r,(2,1)}$ scales linearly on the toroidal rotation, and depends weakly on plasma density, $n_e$. The fast rotating RMP field has been successfully applied for avoidance of mode locking and the prevention of plasma disruption. Remarkably, the rotating tearing mode was completely suppressed by the electrode biasing (EB) in addition to the RMP field.

The impacts of 3D magnetic topology on the turbulences have been investigated on J-TEXT. It is found that the fluctuations of electron density, electron temperature, and plasma potential can be significantly modulated by the island structure, and a larger fluctuation level appears at the X-point of islands. The suppression of runaway electrons (REs) during disruptions is essential to the operation of ITER, and it has been reached by utilizing the 3D magnetic perturbations on J-TEXT. The NIMROD simulation indicates that the strong stochastic in the whole plasma cross-section expel out the runaway seed and results in runaway free disruptions on J-TEXT. This may provide an alternative mechanism of runaway suppression for large-scale tokamak and ITER.
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ABSTRACT

Recent J-TEXT research has highlighted the significance of the role that non-axisymmetric magnetic perturbations, so-called 3D magnetic perturbation (MP) fields, play in fundamentally 2D concept, i.e. tokamak. In the paper, the J-TEXT results achieved over the last two years, especially on the impacts of 3D MP fields on magnetic topology, plasma disruptions, MHD instabilities, and plasma turbulence transport, will be presented.

On J-TEXT, the resonant MPs (RMPs) system, capable of providing either a static (DC) or a high frequency (up to 6 kHz) rotating (AC) non-axisymmetric MP field, has been upgraded by adding a new set of 12 in-vessel saddle coils, and the total number of in-vessel RMP coils increases from 12 to 24 (3 rows × 8 columns). The shattered pellet injection (SPI) system has been built in J-TEXT in the spring of 2018. The new capabilities advance J-TEXT to be a forefront of international magnetic fusion facilities, allowing a flexible study of 3D effects and disruption mitigation in a tokamak.

The fast rotating RMP field has been successfully applied for avoidance of mode locking and the prevention of plasma disruption. A new control strategy, which applies pulsed RMP to the tearing mode only during the accelerating phase region, was proved by nonlinear numerical modeling to be effective in accelerating mode rotation and even completely suppressing the mode. Remarkably, the rotating tearing mode was completely suppressed by the electrode biasing (EB) in addition to the RMP field. The impacts of 3D magnetic topology on the turbulences have been investigated on J-TEXT. It is found that the fluctuations of electron density, electron temperature, and plasma potential can be significantly modulated by the island structure, and a larger fluctuation level appears at the X-point of islands. The suppression of runaway electrons (REs) during disruptions is essential to the operation of ITER, and it has been reached by utilizing the 3D magnetic perturbations on J-TEXT. This may provide an alternative mechanism of runaway suppression for large-scale tokamak and ITER.

1 INTRODUCTION

The Joint-TEXT (J-TEXT) tokamak [1-3] is a conventional iron core tokamak, operated at a major radius \( R_0 = 1.05 \) m, minor radius \( a = 25–29 \) cm with a movable titanium-carbide-coated graphite limiter. The typical J-TEXT discharge in the limiter configuration is done with toroidal field \( B_t \) of ~2.0 T, plasma current \( I_p \) of ~200 kA, pulse length of 800 ms, plasma densities \( n_e \) of \( 1–7 \times 10^{19} \) m\(^{-3}\), and electron temperature \( T_e \) of ~1 keV.

As of a long-term research program, the J-TEXT experiments aim to develop fundamental physics and control mechanisms of high temperature tokamak plasma confinement and stability in support of successful ITER operation and the design of future Chinese fusion reactor, CFETR. Recent research has highlighted the significance of the role that non-axisymmetric magnetic perturbations, so-called 3D magnetic perturbation (MP) fields, play in fundamentally 2D concept, i.e. tokamak. On J-TEXT, 3D MP fields can be induced by either the application of resonant MPs (RMPs) of the appearance of core MHD modes. In this paper, the J-TEXT results achieved over the
last two years, especially on the impacts of 3D MP fields on magnetic topology, plasma disruptions, MHD instabilities, and plasma turbulence transport, will be presented.

2 PROGRESS OF THE AUXILIARY SYSTEMS

In the past two years, there were two major progresses of the auxiliary systems, i.e. the resonant MP (RMP) system [4, 5] and the shattered pellet injection (SPI) system [6].

In the spring of 2017, the RMP system has been upgraded by adding a new set of 12 in-vessel saddle coils (3 rows × 4 columns × 2 turns), and the total number of in-vessel RMP coils increases from 12 to 24 (3 rows × 8 columns). To date, this RMP system has unique capabilities to provide not only high frequency (up to 6 kHz) ac non-axisymmetric MPs, but also more capable and flexible adjusting its amplitude (up to 3.5 mT of \(m/n=2/1\) RMP) and spectrum (the \(n\) up to 4), where \(m\) and \(n\) are the poloidal and toroidal mode number. These new capabilities advance J-TEXT to be a forefront of international magnetic fusion facilities, allow a flexible study of 3D effects in a tokamak.

In the spring of 2018, the SPI system [6] was built in J-TEXT. FIG. 2 displays the schematic drawing of the whole SPI system, which is about 3.5 m long. A pellet is formed with 5 mm diameter and 1.5-10 mm length at a temperature of 64 K. The pellet is formed with argon and the amount of injected Argon particles is from \(0.7 \times 10^{20}\) to \(5.0 \times 10^{21}\) atoms. Helium gas or Argon gas, as the propellant gas for pellet, accelerates the pellet to 150-300 m/s with a pressure of 0 ~ 20 bar (the max is 80 bar). The pellet will be shattered before entering the plasma by impacting on a strike plate situated at the entrance to the tokamak vacuum chamber. Normally, the time interval between injection cycles is about 8 minutes.

3 CONTROL OF TEARING MODES

Tearing modes (TMs), especially the \(m/n = 2/1\) TM, deteriorate the confinement performance significantly. In addition, the TM could be decelerated to a non-rotating state, leading to the so called locked mode (LM). The LM usually grows to a very large amplitude, and it is one of the most common causes of major disruption in a tokamak. Therefore, active control of the TM is an important issue for future fusion reactors, e.g. ITER and CFETR.

Previous experimental and theoretical studies showed that the RMP influences both the rotation and the width of the TM [7], with accelerating (decelerating) the TM when \(\pi < \xi < 2\pi \) (\(0 < \xi < \pi\)) and stabilizing (destabilizing) the

![FIG. 1 The in-vessel RMP coils on J-TEXT, consisting of 12 single-turn coils (blue) [4] and 12 double-turns coils (red) [5].](image1)

![FIG. 2 The 3D layout diagram of the SPI system for the J-TEXT tokamak:1 – cryocooler, 2 – pellet acceleration system, 3 – pellet injector, 4 – gas tube system, 5 – electrical system, 6 – flange of pump, 7 – guide tube, 8 – gate valve, 9 – measurement system, 10 – high and low vacuum sensors, 11 – vacuum gate valve, 12 – buffer chamber, 13 – J-TEXT tokamak. [6]](image2)
TM when \(0.5 \pi < \xi < 1.5 \pi\) (-0.5 \(\pi < \xi < 0.5 \pi\), where \(\xi\) is the phase difference between the RMP and the TM. As a result, the static RMP could apply a net stabilizing and braking effect on a rotating TM. This section briefly summarizes the recent studies on TM control by applying rotating or modulated RMP field and by biased electrode, while a detailed description is presented in Ref. [8].

### 3.1 Control the TM rotation by applying rotating RMP field

The electromagnetic torque applied by RMP on the TMs can be used as an effective tool to control the rotation of TMs and the background plasmas. The application of a static RMP field always leads to the deceleration and locking of rotating TMs, followed by a major disruption [7, 9]. By applying a RMP field rotating faster than the TM, the rotation acceleration of a TM in J-TEXT was first observed in 2013 [10]. It is shown later that the TM could either be accelerated or decelerated, if the initial slip frequency \(f_s = f_{TM} - f_{RMP}\) is negative or positive [11]. Meanwhile, the particle confinement is improved if the TM is accelerated, which is unlike the density decrease for TM-locked to static RMP [12].

Recently, the plasma rotations were measured by the spectrometers both in the edge \((r/a = 0.6 \sim 0.9)\) for CV (C\(^4+\)) [13] and in the core \((r/a < 0.4)\) for helium-like argon (Ar\(^{16+}\)) [14], during the application of the RRMP. By locking the TMs to RRMP, the toroidal rotations of the impurities were also accelerated or decelerated depending on the sign of \(f_s\) [15], as shown in FIG. 3. With the modification of high frequency power supplies, the change of the RMP frequency within one discharge was achieved [16]. As shown in FIG. 4, the frequency of the RMP were reduced by \(-1\ \text{kHz}\) within \(1\ \text{ms}\) at \(0.321\ \text{s}\) and \(0.371\ \text{s}\). The frequency of the TM is also reduced after a short time lag, which is needed for the locking of TM to the RRMP.

![FIG. 3 The dependence of the toroidal rotation frequency of the impurities in the core, \(f_{CV}\), and edge, \(f_{CV}\), on the tearing mode frequency with (open) and without (filled) rotating RMP. [15]](image)

![FIG. 4 Control of the TM frequency within one discharge by applying RRMP with varying frequency. Top, RMP coil current; Bottom, the frequency of RMP field (red) and TM (green). [16]](image)

According to the observation in Ref. [10], the TM could be suppressed by maintaining the frequency of RRMP slightly higher than that of the TM, so that the RRMP could apply a net stabilizing effect on TM without locking. Preliminary studies show that the frequency response of this hopping-frequency PS is not fast enough to avoid mode locking and to keep a small \(f_s\). A new PS, which is capable of varying frequency continuously, has been built [17] and will be applied for this control strategy in the following campaign.
3.2 Control of the locked modes by applying rotating RMP field

The capacity of RRMP in accelerating TMs can also be used to control the LMs. The RMP, rotating at a few kilo Hertz, was applied and unlocked the TMs successfully in J-TEXT [18]. It is found that the unlocking threshold of RRMP is smaller at lower static error field or lower RRMP frequency. Further analysis reveals that the phase of the LM is forced to oscillate by the EM torque applied by RRMP [19] and that the LM is unlocked with large amplitude of the phase oscillation. To set-up reproducible LMs, these discharges were carried out with non-disruptive LMs which were maintained by a small static RMP.

Recently the disruptive discharges induced by the intrinsic mode locking were performed by increasing the plasma current and hence reducing the edge safety factor from 3 towards 2, as shown by discharge #1052960 in FIG. 5. The braking of TM lasted for ~ 5 ms and the disruption followed about ~ 10 ms after the mode locked. The RRMP applied after the mode locked was not strong enough to unlock the LM, hence the disruption occurred. Triggered by the mode locking warning system, the 3 kHz RRMP was applied before the mode locked in discharge #1052963 (blue lines in FIG. 5). The TM was accelerated to 3 kHz and the intrinsic mode locking was avoided. As a result, the disruption was prevented [8].

3.3 Suppressing magnetic island and accelerating its rotation by modulated RMP

The above control strategy applies a rigid rotating RMP field, hence the TM undergoes acceleration/deceleration or stabilizing/de-stabilizing effects successively within a TM rotation period in the RRMP rest frame. To enhance the good effect (also to reduce the bad effect) of RMP on TM, a new control is proposed to apply pulsed RMP to the TM only during the accelerating phase region, i.e. within $\pi < \xi < 2\pi$, or during the accelerating and stabilizing phase region, i.e. within $\pi < \xi < 1.5\pi$ [20]. By nonlinear numerical modelling, it was proved to be efficient in accelerating the mode rotation and even completely suppresses the mode, as shown in FIG. 6.

A dedicated pulsed power supply (PS) [21] and the corresponding real time control system [22] with the measurement of island locations [23] have been built on J-TEXT. The first experimental attempt with the pulsed RMP has demonstrated the acceleration effect with a relative low amplitude of RMP [22]. The TM frequency could be increased by ~ 0.3 kHz with 1 kA of RMP coil current. A new pulsed PS [17], with a maximum current of 3 kA, has been built to further testify the impact of pulsed RMP on the frequency and width of the TMs. The preliminary experiment shows

FIG. 5 Disruption avoidance by the feedback application of RRMP. Red: without RRMP; Blue: RRMP applied by feedback control.

FIG. 6 Complete suppression of a TM and accelerating its rotation by applying a modulated RMP in the acceleration and stabilizing phase region. $[\pi, 1.5\pi]$ [20]
that the TM could be accelerated from 4.5 kHz to 7 kHz [8]. Further commissioning will allow higher operation frequency of this PS, and perhaps lead to further rotation acceleration of TMs.

3.4 Control of the tearing mode by biased electrode

The biased electrode is an efficient method to change the plasma parameters and flows. An electrode, inserted 2 cm inside the plasmas, was biased either positively or negatively to investigate its impact on the TM in J-TEXT [24]. It is found that for a negative bias voltage, the TM amplitude is reduced, and the mode frequency is increased accompanied by the increased toroidal plasma rotation speed in the counter-\(i_p\) direction. For a positive bias voltage, the mode frequency is decreased together with the change of the rotation velocity towards the co-\(i_p\) direction, and the mode amplitude is increased. FIG. 7 displays the statistic results that the variations in the toroidal rotation speed, \(\Delta V_b\), the 2/1 mode frequency, \(f_{MHD}\), and its amplitude, \(\delta B_{\theta, nor}\), depend linearly on the bias voltage, \(U_{EB}\).

Remarkably, the TMs were completely suppressed [24] by the negative biasing with a threshold voltage of -300 V at \(q_a = 3\), while the TMs were locked if the positive biasing was above 100 V. The experimental results suggest that applied electrode biasing is a possible method for the avoidance of mode locking and disruption, which will be investigated in the future.

4 PROGRESS ON THE DISRUPTION MITIGATION

The disruption-generated high energy runaway electrons (REs) is a great threat to the safe operation of a fusion reactor. It is of great importance to understand the mechanisms responsible for RE generation, the confinement of REs, and to find reliable methods to control or suppress the REs. In this section, we summarize the recently J-TEXT studies on the RE generation [25, 26] and the RE suppression by actively driven magnetic perturbations [27-31] in the disruptions triggered by the massive gas injection (MGI). The first result on the disruption mitigation by using the SPI system is also presented [6].

4.1 Runaway electron generation during MGI triggered disruptions

A systematic study of disruption-generated REs has been performed in J-TEXT [25]. During the intended disruption by MGI of argon in J-TEXT, the RE plateau is more easily obtained with a higher loop voltage and shorter onset time of high loop voltage. Magnetic fluctuations are observed at the beginning of the current quench during the disruptions. RE currents are only obtained in the region of low electron density and low magnetic

![FIG. 7 The statistical results of (a) the variation of rotation at \(r/a = 0.74\), (b) TM frequency \(f_{MHD}\) and (c) normalized poloidal magnetic perturbation \(\delta B_{\theta, nor}\) versus bias voltage. \(\delta B_{\theta, nor} = \delta B_\theta/\delta B_{\theta0}\), \(\delta B_{\theta0}\) and \(\delta B_\theta\) are the initial and steady amplitude of \(\delta B_\theta\) before and during the application of \(EB\), respectively. [24]

![FIG. 8 I_{RE}/I_p in J-TEXT disruptions as function of normalized magnetic fluctuation level and pre-disruption electron density. [25]
fluctuation. FIG. 8 displays $I_{RE}/I_P$ as a function of the maximum magnetic fluctuation amplitude during the CQ, $\delta B/B_t$, and the electron density, $n_e$, before the disruptions. In J-TEXT the RE plateau is not visible unless the product of $\delta B/B_t$ and the square of $n_e$ is lower than a threshold. For shots with lower product than the threshold it is found that $I_{RE}/I_P$ decrease with the product for a wide range of $B_t$ and $I_p$.

Experimental evidence supporting that the theory of hot tail RE generation might be playing a role has also been found. With higher temperature before the disruption, more REs are generated via the hot tail mechanism during the thermal quench. By increasing the hot tail RE generation by increasing the temperature, an obvious RE plateau is observed even with a low toroidal magnetic field (1.2 T).

4.2 MHD activities and the cooling process during MGI triggered disruptions

In the disruption mitigation by injecting impurities, the deposition of impurities at the center of the plasma is the key for the radiation of plasma energy and runaway suppression. Recent J-TEXT experiments show that the injection of a massive amount of argon can cool the plasma from edge to core region, and the cooling process is accompanied by different MHD modes when the gas jet reaches the corresponding rational surfaces [32]. After the argon atoms are injected, a high-\( m\) MHD mode is initiated. As the impurity cools the plasma deeper, the MHD mode changes to a lower-\( m\) mode until a 2/1 mode is initiated and a thermal quench (TQ) started.

A pre-existing large 2/1 TM can significantly increase the penetration speed of a gas jet across the rational surfaces as shown in FIG. 9. The cooling process lasted ~ 1.4 ms in #1049676, where no large TM existed before MGI. With the pre-existing large TM in #1050281, the cooling from the edge to the core occurred at the same time. These results indicate that the 2/1 mode plays an important role in the penetration process. It will be shown in section 4.3 that the SMBI or RMP triggered magnetic island could assist the suppression of RE currents.

4.3 Suppression of runaway electrons by RMP and SMBI

The RE confinement can be influenced by the magnetic topology change from the nested flux surfaces, hence the RE generation can be significantly impacted. In J-TEXT, the formation of magnetic island or even stochastic layer can be actively driven by supersonic molecular beam injection (SMBI) [30] and RMP fields [27-29, 31] before the MGI triggered disruptions, and the RE can be suppressed.

The SMBI excites magnetic islands, as long as the injected hydrogen quantity is above a certain threshold in J-TEXT [33]. Moreover, the RE loss increased rapidly if large TMs were excited [30]. By applying SMBI to induce TMs with

![FIG. 9 The time evolution of MHD instability and thermal quench due to MGI, without (#1049676) and with (#1050281) a pre-existing 2/1 TM. [32]](image-url)

![FIG. 10 The REs generation impacted by the SMBI at different times, which led to different mode amplitudes.](image-url)
sufficient amplitude, the generation of REs can be completely suppressed during the MGI triggered disruptions, as shown by discharges #1041920 and #1041921 in FIG. 10. The later injection of SMBI in #1041922 led to smaller mode amplitude at the CQ and the RE was partially suppressed. Applying hydrogen SMBI at the same time with argon MGI also demonstrates a complete suppression of RE current generation.

A large 2/1 locked island can be formed due to the locking of a pre-existing rotating island or the RMP penetration. The RE generation can be completely suppressed, if the locked island is formed with enough time ahead of the MGI [28, 29], as shown in FIG. 11. It is found that the threshold time of RE suppression is longer for RMP penetration than that for mode locking. This is related to the fact that the width of the locked island grows faster in the case of mode locking than that of RMP penetration. Note that this observation does not have to contradict the previous observation, where the RE production was enhanced by RMP [27]. In the previous case, the RMP amplitude was so low that no locked mode was excited before the MGI. Recent experimental results show that the RE production decreased again [31] at higher RMP amplitude due to the RMP penetration.

![FIG. 11: Dependence of the runaway current on the time of (a) mode locking and (b) mode penetration before the disruptions. The Ar MGI trigger time is corresponding to t = 0 s.](image)

The NIMROD simulation has also demonstrated that the large magnetic islands have the ability to enhance REs seed loss during disruptions. The simulation result of the ratio of REs left during disruptions is illustrated in FIG. 12. The REs are lost quickly in the case of larger islands than the case of small islands during disruption. These results suggest that the magnetic perturbation can act as an alternative way to mitigate runaway electrons in tokamak disruptions.

**4.4 First result on the disruption mitigation by the SPI system**

FIG. 13 displays a successful dissipation of MGI-induced runaway current by SPI, with $I_p = 180$ kA, $n_e = 1.5 \times 10^{19}$ m$^{-3}$, $B_t = 2.2$ T and $q_a = 3.6$. Following the trigger of the MGI valve at 0.42 s, about $5 \times 10^{19}$ argon atoms were injected into the plasma and cooled the plasma from 0.422 s to 0.423 s. The current quench happened at 0.423 s following a large loop voltage induced. Then a runaway current plateau about 100 kA was formed at 0.424 s. The increase of the ECE signal was caused by the generation of non-thermal electrons during the runaway current plateau. The shattered argon pellet with 4.5 mm length, 5
mm diameter was injected into the plasma with a speed of 250 m/s at 0.405 s. About 23 ms later, the shattered pellet started to dissipate the runaway beam, while the radiation measured by soft x-ray and AXUV signals started to increase. The argon SPI dissipated the runaway current at a rate of approximately 12 MA/s.

4.5 Disruption prediction and avoidance

To achieve the successful mitigation of disruption, a reliable disruption prediction is needed with sufficient warning time. In the previous works on J-TEXT, two predictors based on neural networks were developed to predict the locked mode disruption [34] and density limit disruption [35]. The previous networks were trained and tested by off-line data. Recently, an on-line density limit disruption prediction and the avoidance system based on a neural network has been built on J-TEXT [36]. The neural network has been improved from a simple multi-layer design to a hybrid two-stage structure. The first stage is a custom network which uses time series diagnostics as inputs to predict plasma density, and the second stage is a three-layer feedforward neural network to predict the probability of density limit disruptions. It can predict the plasma density as well as the density limit disruption. It is found that hybrid neural network structure, combined with radiation profile information as input can significantly improve the prediction performance, especially the average warning time ($T_{\text{warn}}$). In particular, $T_{\text{warn}}$ is eight times better than that in previous work [35] (from 5 ms to 40 ms). In off-line tests, the system can achieve a performance of Successful Alarm Rate $> 90\%$, False Alarm Rate $< 10\%$ and Average Warning Time $> 30$ ms in a specific threshold range. The on-line density limit disruption avoidance system consists of an on-line density limit disruption predictor, by implementing the hybrid neural network on LabVIEW-RT platform, and a plasma density feedback control system based on the POLARIS [37]. This system can predict the plasma density as well as a density limit disruption, as shown by a density ramp-up discharge in FIG. 14. The density limit disruption is successfully avoided by closing the gas puffing control (GPC) valve immediately when the disruption is predicted (FIG. 14). These results demonstrate the successful prediction and avoidance of density limit disruption on J-TEXT.

5 TURBULENCE AND TRANSPORT STUDY

The impacts of 3D magnetic topology on the turbulences, and interplay between the turbulence and plasma rotation have been investigated on J-TEXT. It is found that the fluctuations of plasma potential [38], electron density [39] and electron temperature [40] can be significantly modulated by the island structure, and a larger
fluctuation level appears at the X-point of island. By applying SMBI, the multi-channel non-local transport (electron temperature, particle, and momentum), possibly due to turbulence spreading, has been observed for the first time on J-TEXT [41]. For understanding the physics of intrinsic rotation, a new mechanism named turbulent acceleration has been developed [42-45].

5.1 Impact of magnetic island on the turbulence

The temporal-spatial structures of turbulence and plasma flows near 3/1 magnetic islands are investigated by using Langmuir probe arrays and Mirnov coils in the edge plasmas of J-TEXT tokamak. The long-range correlation analysis is utilized. The structures of the flows are similar to those observed in the magnetic islands as m/n = 3/1. At q = 3 surface, the reversal of the potential fluctuations for the flows is observed and the reduction of the powers is pronounced. FIG. 15 (a) and (b) show the spatial-temporal distributions of the potential fluctuations and the turbulence envelopes, respectively. Here, the dashed curves indicate the magnetic islands. The reversal of the sign for the m/n = 3/1 electrostatic potentials at Δr = -1.5 cm is appeared. The position of q = 3 surface is indicated by the horizontal-dashed lines. The island width is evaluated as w ~ ∂B_r,0.5 ~ 1.5 cm from the magnetic measurements. The X-points and O-points of magnetic islands are identified from the sign of potential fluctuations, considering that the flows are toward the X-points. Based on the measurements of the q = 3 surface, island width and X-points, and assuming the ‘separatrix’ is satisfied with a sine or cosine function, the location of the magnetic islands is evaluated. The flows are concentrated near the separatrix and have quadrupole structures. The measurements are in good agreement with the prediction of theory. The turbulence is concentrated near the X-points and partly trapped inside the islands (FIG. 15(b)).

The influence of the m/n=2/1 magnetic island on density fluctuations [39] has been investigated by an eight-channel Doppler backscattering (DBS) reflectometer diagnostic [46]. The 2/1 islands were formed due to the penetration of the static RMP, and their phases with respect to the DBS measurement were scanned by varying the RMP phases between discharges. The island phases are indicated by the phase of \( r = 1 \) radial magnetic field, \( \phi_{B_r,M} \) measured by locked mode detectors. It is found that density fluctuations reduced inside the island and elevated at the island boundary, as shown in FIG. 16, in agreement with the variations of temperature gradient induced by the magnetic island topology.

The influence of a rotating m/n=2/1 magnetic island on electron temperature fluctuations has been investigated by an eight-channel correlation electron cyclotron emission (CECE) diagnostic [40], as shown in FIG. 17. The 5 kHz rotating 2/1 island modulated both the original CECE signal, measured inside the island, and the Mirnov...
FIG. 17 Impact of a rotating 2/1 island on the $T_e$ fluctuations measured by CECE. (a) original CECE signal, (b) Mirnov signal, (c) the CECE signal within 50-500 kHz (blue) and its envelop (green). The spectra are compared in (d) for the Mirnov signal (red), the positive envelop of (c) shown in yellow and the cross power spectrum of two band-pass filtered CECE signals near the $q = 2/1$ surface (blue).

FIG. 18 The waveforms of cold pulse discharge with multi-pulse SMBI; (a) line-averaged electron density, (b) sawtooth period, (c) core $T_e$, (d) edge $T_e$ at $r/a=0.79$, (e) SMBI pulse. [41]

FIG. 19 The detail time evolution of core $n_e$ and $T_e$ for the first SMBI pulse in FIG. 18. [41]

5.2 Observation of multi-channel non-local transport

The non-local transport (NLT) was triggered by applying multi-pulse SMBI as cold pulse source in J-TEXT [47, 41]. In the recent cold pulse experiment, not only rapid electron temperature increases in the core are observed, but also steep rises in the inner density are found [41], as shown in FIG. 18. The typical NLT effect in electron channel (core $T_e$ rises while edge $T_e$ drops in FIG. 18(c) and (d)) appeared in all 5 SMBI pulses. On the other hand, the prompt increasing of $n_e$ due to SMBI is clearly shown in FIG. 18(a). FIG. 19 displays more accurate characters for the particle transport during NLT from the local density response, where two different time scales of the core $n_{e0}$ evolution appeared. One was the steep rise of $n_{e0}$ in serval milliseconds in the beginning. The other was the slow increase and sustainment in the following tens milliseconds. Moreover, the steep rise of $n_{e0}$ was synchronous with the fast increase of $T_{e0}$. For the J-TEXT SMBI experiments, the neutral penetration of SMBI mainly concentrated in plasma edge region ($r > 23$ cm). If the steep rise of $n_{e0}$ was caused by local transport process, the averaged convection velocity from edge to core should be more than 40 m/s ($\sim 0.2$ m/5 ms), which is astounding high value. The steep rise of $n_{e0}$ should be also caused by some NLT process. One notable point during NLT is that the sawtooth period $\tau_{sawtooth}$ (FIG. 18(b)) also increased clearly for all 5 SMBI pulses. The increasing pace of $\tau_{sawtooth}$ was coincident with the core $T_e$ rise. It is shown in
that the experimental $\Delta n_e$ during NLT was much lower than the value needed to explain the prompt increase of $\tau_{\text{sawtooth}}$. An acceleration of core $V_\Phi$ at around 1.4 km/s is estimated according to the scaling relation between $V_\Phi$ and $\tau_{\text{sawtooth}}$. The J-TEXT results are the first experimental discovery of simultaneous fast NLT responses in multichannels transport (electron temperature, particle, and momentum) in magnetic fusion plasma, and suggest that turbulence spreading [48] is a possible mechanism for the NLT dynamics.

5.3 Theoretical study on the turbulence

Both the intrinsic rotation and the intrinsic current driven by micro-turbulence are important for magnetic confinement plasmas. However, the mechanisms for the origin of intrinsic rotation drive and intrinsic current drive are still open questions. We found a novel mechanism for the origin of intrinsic rotation driven by electrostatic ion temperature gradient (ITG) turbulence, which we refer to as turbulent acceleration [42, 43]. The turbulent acceleration cannot be written as a divergence of stress term, which is different from the physics of residual stress, and so acts as a local source or sink. In other words, the turbulent acceleration is an effective volume-force, while the divergence of residual stress is a kind of surface-force. We emphasize that the turbulent acceleration does not contradict momentum conservation law [44]. It is demonstrated that the conserved quantity corresponding to asymmetry of tokamak is the total canonical momentum or total momentum carried by both particles and electromagnetic fields but not the ion kinematic momentum or the ion flow velocity. The co-current turbulent acceleration driven by ITG turbulence vanishes for collisionless trapped electron mode (CTEM) turbulence [49], which may provide a possible theoretical explanation for the experimental observation of electron cyclotron heating (ECH) induced decrease of co-current core toroidal rotation in co-current neutral beam injection H-mode plasmas [50, 51]. Extension of our theory to electromagnetic (EM) ITG turbulence shows that the importance of electromagnetic effects to intrinsic parallel rotation drive [52].

Inspired by the investigation of intrinsic rotation driven by turbulence, we also present the intrinsic current (which is related to electron momentum) driven by EM ETG turbulence [45]. There exist two types of intrinsic current driving mechanisms including the divergence of residual turbulent flux and the residual turbulent source. The local intrinsic current density driven by the residual turbulent flux for mesoscale variation of turbulent flux can reach about 80% of the bootstrap current density in the core region of an ITER standard scenario, but there is no net intrinsic current on a global scale. Thus, the $q$ profile can be locally modified and the MHD could be affected. However, intrinsic current density driven by the residual turbulent source is small as compared with the bootstrap current and can be neglected.

6 SUMMARY AND OUTLOOK

Over the last two years, the J-TEXT researches has contributed to the impacts of 3D MP fields on magnetic topology, plasma disruptions, MHD instabilities, and plasma turbulence transport. The locked mode is avoided by the feedback application of RRMP and the TM can be suppressed by negatively biased electrode. A new control strategy for TM control is proposed based on modulated static RMP and proved numerically. Further experimental researches seem to be promising. The fluctuations of electron density, electron temperature, and plasma potential can be significantly modulated by the island structure. The RE generation and suppression has been studied, especially on their relationship with the magnetic perturbations. The MGI can cause MHD activities before disruptions, while the strong magnetic fluctuations during the CQ can suppress the RE generation. The RE generation can be actively suppressed by applying SMBI and RMP induced locked island. The SPI has been successfully applied to dissipate the MGI-induced runaway current for the first time on J-TEXT.
In the following two years, several diagnostics and auxiliary systems will be available on J-TEXT. The upcoming ECE-Imaging, VUV spectrometer, Doppler reflectometry can provide more information for the study of MHD activities, turbulence and transport. The divertor configuration will be tested using the high-field X-point configuration and the island divertor concept, respectively. The 105 GHz/0.5 MW/1s ECRH system will be commissioning in 2019. It will support the plasma heating, current drive and hence disruption and MHD instabilities control.

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