Contributed Paper

Dynamics of Plasma during the Formation of a Weak Negative Central Magnetic Shear Configuration Using Counter Neutral Beam Injection in the JFT-2M Tokamak

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Abstract

In the JFT-2M tokamak, discharges exhibiting good performance have been produced by counter-NBI after boronization. An improved core confinement mode under an H-mode edge condition is sustained for ~5τE with \( H_{\text{tep}} \sim 1.5 \) and \( \beta_p \sim 2.0 \) at a line-averaged electron density of around 70\%–80\% of the Greenwald density limit. It is found that the \( q \)-profile changes from a monotonic one having \( q_0 \sim 1 \) to a zero or weak negative central magnetic shear configuration having \( 1 < q_{\text{min}} \leq q_0 < 3 \) during improved core confinement mode using counter-NBI under an H-mode edge condition. The central electron temperature very clearly increases when the sawtooth activity disappears, while the previous result without boronization exhibited a significant degradation of the energy confinement due to the accumulation of impurities. The mechanism governing the improved core confinement mode including the density peaking and/or ITB formation due to negative shear is presently unclear.

Keywords:
tokamak, ctr-NBI, sawtooth, \( q \)-profile, negative shear, MSE, boronization

1. Introduction

Recent tokamak experiments have concentrated on advanced scenarios. Of these, internal transport barrier (ITB) discharge under an H-mode edge condition has especially achieved a high performance level in a quasi-steady state [1-5]. Results from recent tokamak experiments, including ASDEX Upgrade, DIII-D, JET, and JT-60U, have shown that the product \( \beta_p H_{\text{tep}} \) reaches up to ~6 (or greater values, corresponding to the requirements for a steady state tokamak reactor, SSTR) in plasma when approaching a stationary conditions. Here \( \beta_p = B_p/(p a B_T) \) is the normalized beta in \% m T/MA, \( p \) the plasma current, \( a \) the minor radius, \( B_T \) the toroidal magnetic field, and \( H_{\text{tep}} \) the confinement enhancement factor relative to the ITER89P scaling. In addition, a steady-state tokamak reactor will need a high bootstrap fraction and operation at a high density, 80–90\% of the Greenwald density limit [6-8]. This requires that the poloidal beta \( (\beta_p) \) be significantly greater than unity in order to achieve effective energy confinement at moderated plasma current. Furthermore such plasmas would achieve \( \beta_p > 3 \) if very high toroidal fields are to be avoided.

Since the multichannel motional Stark effect (MSE) diagnostic has been newly applied to measure the \( q \)-profile on JFT-2M [9], the study of advanced scenarios...
has been performed using counter neutral beam injection (ctr-NBI). In recent experiments after boronization of the JFT-2M vacuum vessel, the improved core confinement mode under an H-mode edge condition has been sustained for ~ 5 energy confinement time ($\tau_E \sim 20$ ms) with $H_{95} \sim 1.5$ and $\beta_N \sim 2.0$ at the line-averaged electron density around 70%–80% of the Greenwald density limit. It should be noted that the plasma in the previous experiments without boronization exhibited a significant degradation in $\tau_E$ and/or disruption due to a sudden high-Z impurity accumulation during the improved confinement phase [10].

This paper is organized as follows. In sec. 2, the major diagnostics used in this study are explained. In sec. 3, the $q$-profile evolution and plasma dynamics during the formation of a weak negative shear configuration using ctr-NBI are presented. A comparison between co- and ctr-NBI discharges in terms of the effect of NBCD is also described. In Sec. 4, we discuss these results and summarize the work.

2. Apparatus

JFT-2M is a medium sized tokamak (major radius $R = 1.31$ m, minor radius $a = 0.35$ m, elongation $\kappa < 1.7$), which has two tangential hydrogen neutral beams at a beam energy of 32 keV (0.8 MW each); one is co-parallel and the other is counter-parallel to the plasma current as shown in Fig. 1. The multichannel motional Stark effect (MSE) diagnostic has been implemented on JFT-2M in order to measure the profile of the internal magnetic field pitch angle [$\gamma_p = \tan^{-1}(B_p/B_T)$, where $B_p$ is the poloidal magnetic field and $B_T$ is the toroidal magnetic field]. The $q$-profile is reconstructed by the MHD equilibrium calculation using the measured MSE data in conjunction with external magnetic measurements including magnetic probes, flux loops, and Rogowski coils. It should be noted that the effect of the radial electric field ($E_r$) on the MSE measurement is neglected in this paper. As recently demonstrated on DIII-D and TFTR tokamaks [11 and 12], simultaneous viewing of both co- and counter-NBI lines allows resolution of $E_r$ and $\gamma_p$ with MSE on JFT-2M [9]. But it is not available in the discharge with a high-power NBI of up to 0.8 MW using two injector sources per each NB line. Since these have slightly different poloidal injection angles of $\pm 4.8^\circ$, both Doppler shifted H$_\alpha$ emissions indicate slightly different polarization angles ($\sim \gamma_p$) with nearly the same Doppler shifted wavelength at the intersection of the beam-sightline. This causes a large error due to the change in the offset polarization.
angle during high-power NBI heating using two injector sources. Thus, MSE measurement was performed using an opposite directional NBI line employing a single injector source as described in Sec. 3. In this case, the $E_r$ in the plasma, which is due mainly to toroidal rotation ($V_{\phi}$), can pollute the MSE measurement. The magnitude of this effect is estimated to be about $\pm (0.1 \sim 0.2)^{\circ}$ by using the value of $E_r$ (typically, $10 \sim 20$ kV/m) obtained from previous analysis of both MSE and charge exchange recombination spectroscopy (CXRS) measurements. The uncertainty in reconstructed $q_0$ is estimated to be less than 0.2 in the case of the monotonic $q$-profile having $q_0 \sim 1$. The line-averaged electron density is measured by means of a far-infrared laser interferometer (FIR) and 2 mm wave interferometer. The central electron and ion temperatures are measured using a soft X-ray pulse-height analyzer (PHA) and CXRS, respectively. The profile of the soft X-ray (SXR) emission is measured by means of an array of 24 PIN photodiodes. In all the discharges shown in this paper, the plasma fuel used was deuterium in an upper single-null divertor configuration at a toroidal field of 1.0 T. In these experiments, boronization was carried out using DC glow-discharge in gas mixture of 1% B(CH$_3$)$_3$ (trimethyl-boron) + 99% He. After boronization with glow-discharge cleaning using He gas, it was observed that the total radiation power loss and oxygen ion line intensities were reduced to 1/3 and 1/20, respectively, for several discharge conditions, including Ohmic and L-mode [13].

3. Experimental Results

3.1. Formation of weak negative shear configuration using ctr-NBI

Waveforms of a typical weak negative shear discharge (#94849) are shown in Fig. 2. The plasma current ($I_p$) was ramped up at 1.0 MA/s in the limiter configuration until the desired $I_p$ value of 0.15 MA was reached at 400 ms, which corresponds to a $q_{95}$ of 3.5, where $q_{95}$ is the safety factor at the 95% flux surface. During $I_p$ ramp-up, the “pre-heating” phase with co-NBI of 0.35 MW using a single injector source, which also acted as the diagnostic beam for MSE, was started at 350 ms. The divertor configuration was also formed during the early pre-heating phase. The $q_0$ and minimum values in the $q$-profile ($q_{\text{min}}$) decreased to about unity at

![Fig. 2 Waveforms in the ctr-imbalance NBI heating case #94849. (a) Plasma current and NBI power. (b) Safety factor on axis ($q_0$, solid), minimum value in $q$-profile ($q_{\text{min}}$, dashed) and normalized radius at $q_{\text{min}}$ (chain). (c) Soft X-ray emission for the vertical sight lines from the chord passing through $\rho = 0.0$ to 0.7. (d) Line averaged electron density from the chord passing through $\rho = 0.0$ (solid) and 0.7 (dashed), and $D_\alpha$ emission (chain). (e) Central electron and ion temperature. (f) Normalized beta value and total radiation loss.](image-url)
400 ms, and then ST oscillations appeared simultaneously, indicating that the plasma is near the resistive equilibrium. The “main-heating” phase was started at 450 ms with additional ctr-NBI of 0.65 MW, where a total NBI power, $P_{NB}$ of 1.0 MW with a co-fraction, $(P_{co}/P_{ctr})/P_{NB} = -0.3$ (ctr-imbalance-NBI discharge). When additional ctr-NBI was applied at 450 ms, the plasma made a transition into the H-mode as seen by the sharp drop of $D_a$ intensity and the increase in the edge electron density. Soon after the transition, the edge density and radiation power reached a new plateau level with a rapid increase in $D_a$ intensity (so-called EDA-like H-mode edge condition observed in the Alcator C-Mod tokamak [14]). On the other hand, the central electron density continued to increase gradually. The observed density peaking was not inconsistent with the inward pinch effect due to the toroidal momentum injection in the ctr-parallel-direction through the formation of the negative $E_r$ and/or $dE_r/dr$ as discussed in Refs. 15–17. The central ion temperature also increased with the increase in the central density (i.e., density peaking), indicating an improvement in the energy confinement in the plasma core region. It should be noted that the density peaking and improved core confinement using ctr-NBI is compatible with the H-mode edge condition. The $q$-profile was monotonic during the early main-heating phase until the last ST crash at 540 ms. During the ST-avoidance phase, the location of ST’s inversion radius moved to the magnetic axis as shown in Fig. 3 (b), keeping the $q_0$ constant within the range of experimental error. Note that the fast change in $q_0$ due to the magnetic reconnection ($m = 1$) must be averaged with a time resolution of 10 ms. Somewhat later after starting the main-heating, i.e., at ~ 500 ms, the central electron temperature ($T_{e0}$) started to increase from 0.5 to 1.0 keV. After complete avoidance of ST, the $q_0$ and $q_{min}$ were beginning to evolve toward the formation of the zero central magnetic shear configurations. And at ~ 600 ms, the weak negative shear configuration with normalized radius at $q_{min}$, $\rho_{qmin} \sim 0.5$ was formed. During shear-reversal phase ($q_0 > q_{min}$), until collapse at ~ 648 ms just before the $q_{min}$ passing through the $q = 2$ surface accompanied by MHD precursor ($m/n = 2/1$) in the magnetic probe signals, the $\rho_{qmin}$ continued to expand for the larger minor radius. It is noted that an observed long time scale of about 150 ms ($\gg \tau_C$, where $\tau_C$ is the global energy confinement time) is required to modify the $q$-profile. This is an order comparable to the characteristic core current diffusion time ($\tau_R = \mu_0 r^2 / \eta$), where $\mu_0$ is the vacuum permeability ($4\pi \times 10^{-7}$ H/m), $r$ the scale length, and $\eta$ the resistivity. It is also found that an improved confinement mode using ctr-NBI, which is compatible with the H-mode edge condition, is sustained for ~ 5$\tau_C$ with $H_{gyp} \sim 1.5$ avoiding the accumulation of impurities with the boronization of the first wall.
3.2. Comparison between co- and ctr-NBI discharges

A typical example for the co-imbalance-NBI discharge (shot #94855) is shown in Fig. 4. The experimental conditions of this case are nearly identical to the ctr-imbalance case (#94849), including such factors as the current ramp rate, the equilibrium configuration, and sufficient wall condition with boronization, but not the direction of both pre- and main-heating using NBI. The pre-heating using a ctr-NBI of 0.35 MW was started at 350 ms, which also acted as the diagnostic beam for MSE using single injector source. Compared with the ctr-imbalance-NBI case, it was found that the ST-free condition having \( q_0 > 1 \) sustained during the pre-heating using ctr-NBI, indicating slower relaxation in both \( q_0 \) and \( q_{\text{min}} \) as shown in Fig. 4 (b) and Fig. 5 (a). The main-heating phase was started at 450 ms using additional co-NBI of 0.65 MW, where the \( P_{\text{co-NBI}} \) of 1.0 MW with a co-fraction \( +0.3 \) (co-imbalance-NBI discharge). As the co-NBI of 0.65 MW was added at 450 ms, the plasma made a transition into H-mode, indicating an evolution in the edge density, \( D_{\alpha} \) emission, and radiation power similar to those in the ctr-imbalance-NBI case. However, different dynamics compared with the ctr-imbalance-NBI case were observed, especially in regard to \( q \)-profile evolution and core confinement. As shown in Fig. 4 (e), significant increases in the central electron and ion temperatures were observed just after the further addition of co-NBI. In this case, the co-NBI affected the central heating, because its central deposition was enhanced by a peaked target density profile at the ST-free condition using pre-ctr-NBI. However it was sustained only for \( \sim \tau_{\text{E}} \), since the \( q_0 \) was reduced to about less than unity, and then the improved core confinement was lost at the onset of ST instability. As well, the toroidal momentum injection in the co-parallel-direction led to cancellation of the negative \( E_i \) and/or \( dE_i/dr \) in the plasma core region as discussed in Ref. 10. This resulted in a broader density profile and further degradation of the global energy confinement.

In contrast to the ctr-imbalance-NBI (#94849), the modification of the \( q \)-profile leading to the ST-avoidance and shear-reversal in the plasma core was not found in the case of co-imbalance-NBI discharge (#94855), where the \( q_0 \) was maintained at less than 1.

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**Fig. 4** Waveform in the co-imbalance NBI heating case #94855. (a) Plasma current and NBI power. (b) Safety factor on axis (\( q_0 \), solid), minimum value in \( q \)-profile (\( q_{\text{min}} \), dashed) and normalized radius at \( q_{\text{min}} \) (chain). (c) Soft X-ray emission for the vertical sight lines from the chord passing through \( \rho \sim 0.0 \) to 0.7. (d) Line averaged electron density from the chord passing through \( \rho \sim 0.0 \) (solid) and 0.7 (dashed), and \( D_{\alpha} \) emission (chain). (e) Central electron and ion temperature. (f) Normalized beta value and total radiation loss.
Fig. 5 (a) Evolution of the q-profiles of #94855 at 370 ms (thin and solid), 400 ms (dashed), 450 ms (chain), and 550 ms (bold and solid).

Fig. 5 (b) SXR contour plot of #94855 for the vertical sight lines.

It is considered that the ctr-NBCD plays a key role in the avoidance of ST, and the following formation of the weak negative shear configuration. As shown in Fig. 6, during pre-heating phase the measured surface loop voltage \(V_L\) using a ctr-NBI of 0.35 MW was higher than about 0.1 Volt compared with a co-NBI of 0.35 MW at ~ 450 ms, indicating NB current drive. The difference in NBCD is estimated approximately as \(\delta I_{NBCD} = I_f (V_{L,ctr} - V_{L,co})/2V_{L,\text{ave}} \approx 15\, \text{kA}\), assuming a fully penetrated toroidal electric field and excluding bootstrap current. The estimated current drive efficiency of \(\eta_{NBCD} \approx 0.1 \times 10^9\) \((= I_{NBCD}n_e R/P_{NB}\) in A/m\(^2\)W, with the \(I_{NBCD}\) indicating the current driven by neutral beam, 

\(n_e\) the line-averaged electron density, \(R\) the major radius, and the \(P_{NB}\) NBI power) is not inconsistent with predicted order [18]. However, it may not be adequate to enhance and sustain the negative shear region in the plasma core. Returning to Fig. 4 (b) and Fig. 5 (a), though it was observed that the occurrence of ST was delayed during pre-ctr-NBI heating compared with pre-co-NBI of the same low input-power; the plasma in the L-mode state must be relaxed until reaching the resistive equilibrium with STs. During main-heating phase using ctr-imbalance-NBI of 1.0 MW, the shear-reversal effect as well as a significant increase in \(T_{e0}\) was seen, while the \(V_L\) continued to increase gradually. It is suggested that the increase in the electron temperature due to the improved confinement mode in the core and edge regions does not only impede inductive current
penetration, but also increases in the non-inductive driven current. Both of them may contribute to enhancing and sustaining the negative shear region in the plasma core.

4. Conclusion
In this paper, we revisited the study of the improved mode using ctr-NBI by means of newly equipped diagnostic (MSE) and an impurity controlling system (boronization) on JFT-2M. An improved core confinement mode under an H-mode edge condition is sustained for $-5 \tau_0$ with $H_{\text{pop}} \sim 1.5$ and $\beta_0 \sim 2.0$ at a line-averaged electron density of around 70\%--80\% of the Greenwald density limit. It is found that the $q$-profile changes from a monotonic having $q_0 \sim 1$ to a zero or weak negative central magnetic shear configuration with $1 < q_{\text{min}} \leq q_0 < 3$ during the improved core confinement mode using a counter-NBI under an H-mode edge condition. Increase in the central electron temperature is very clear when the sawtooth activity disappears. The mechanism governing the improved core confinement mode including the density peaking and/or ITB formation due to negative shear is presently unclear. Though the experimental results presented here are not inconsistent with previous observations (i.e., density peaking), the relation between the roles of the radial electric field and the magnetic shear in energy confinement has not yet been clarified. Further investigations are being planned for the next campaign of the JFT-2M by means of MSE, CXRS, and heavy ion beam probe (HIBP) measurements. Further understanding of the relation between the roles of the radial electric field and the magnetic shear in the energy confinement, including the ITB formation, is one of our future goals.

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