CHIN. PHYS. LETT. Vol. 37, No. 4 (2020) 045202 **Express Letter**

A New Path to Improve High β_p Plasma Performance on EAST for Steady-State Tokamak Fusion Reactor *

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(Received 6 March 2020)

High β_p scenario is foreseen to be a promising candidate operational mode for steady-state tokamak fusion reactors. Dedicated experiments on EAST and data analysis find that density gradient ∇n is a control knob to improve energy confinement in high β_p plasmas at low toroidal rotation as projected for a fusion reactor. Different from previously known turbulent stabilization mechanisms such as $\boldsymbol{E}\times\boldsymbol{B}$ shear and Shafranov shift, high density gradient can enhance the Shafranov shift stabilizing effect significantly in high β_p regime, giving that a higher density gradient is readily accessible in future fusion reactors with lower collisionality. This new finding is of great importance for the next-step fusion development because it may open a new path towards even higher energy confinement in the high β_p scenario. It has been demonstrated in the recent EAST experiments, i.e., a fully non-inductive high β_p (∼2) H-mode plasma ($H_{98y2} \geq 1.3$) has been obtained for a duration over 100 current diffusion times, which sets another new world record of long-pulse high-performance tokamak plasma operation with the normalized performance approaching the ITER and CFETR regimes.

PACS: 52.75.−d, 52.77.Fv DOI: 10.1088/0256-307X/37/4/045202

The plasma β's are important measures to characterize many aspects of plasma performance. It is well known that the poloidal β_p is positively correlated with the bootstrap current I_{BS}, where $\beta_p = \langle P\rangle/[B_p^2/2\mu_0]$ is the ratio of the plasma pressure to the poloidal magnetic field pressure, I_{BS} is self-generated plasma current due to existing of trapped particles in the toroidal magnetic configuration. The high bootstrap current fraction $f_{BS} = I_{BS}/I_p \sim \varepsilon^{1/2}\beta_p \sim \beta_N q_{95}$ desires high β_p at the lower aspect ratio $\varepsilon^{-1} = R/a$, where a and R are the minor and major radii of a tokamak. The normalized $\beta_N = 100\beta(aB_T/I_p)$ is often used to characterize the plasma performance against stability boundary. The high β_p scenario is an attractive candidate operational scenario for steady-state tokamak fusion reactor,[1,2,3] as it addresses high bootstrap current fraction f_{BS}, which can reduce the requirement for external current driving and lower the risk of disruptivity with higher edge safety factor q_{95}. However, it is a key challenge to achieve and maintain good energy confinement in the high β_p scenario, especially at low plasma rotation as projected for a tokamak fusion reactor.[4] Scenario development of the high β_p plasma to improve energy confinement accompanied with increase of bootstrap current fraction has thus been conducted on EAST, largely motivated by developing and testing candidate steady-state scenarios for ITER[1,2] and CFETR.[5] Recently, a new approach to achieve high energy confinement in this scenario has been discovered on EAST, for the first time. This progress leads to increasing confidence in applying the high β_p scenario to a steady-state tokamak fusion reactor.[6]

EAST, as a superconducting tokamak, aims to address key physical and technical issues relevant to steady-state advanced H-mode plasmas[6,7] in supporting future fusion reactors.[5,8] To achieve this goal, EAST is equipped with high-power heating and current drive systems, including Lower Hybrid Current Drive (LHCD),[9] Electron Cyclotron Heating (ECH), Ion Cyclotron Resonant Heating (ICRH) and two Neutral Beams (NB) which can be operated at balanced injection. To facilitate long pulse operations with high heating power, EAST has installed a water-cooled tungsten divertor with power handling capability of ∼10 MW/m^2.[7]

So far, significant progress has been made in exploring steady-state long-pulse H-mode operation[8,10,11] on EAST with the operational parameter space extended toward those of ITER and CFETR as shown in Fig. 1. After demonstration of long-pulse H-mode discharge over 100 s[12] on EAST in 2017, high β_p scenario sustained over 60 s with high f_{BS} has been recently achieved, under ITER-like conditions, i.e., tungsten divertor, dominant electron heating and zero torque injection with pure radio-frequency (rf) power, which is relevant for burning fusion plasmas since α particles predominately heating electrons. This long-pulsed high β_p plasma exhibits good energy confinement with $H_{98y2} > 1.3$ and approaching the normalized plasma pulse length of ITER and CFETR,[12] see the red star in Fig. 1.

In the high β_p scenario development, we have found that the energy confinement enhancement factor (H_{98y2}) increases with β_p[13,14] as evidenced by two typical rf-heated H-mode discharges with different β_p values shown in Fig. 2. The discharge with higher β_p and higher normalized density n_e/n_{GW} exhibits a higher H_{98y2}. These discharges are charac-

*Supported by the National Magnetic Confinement Fusion Science Program of China under Grant No. 2015GB103000.
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terized by the existence of an Internal Transport Barrier (ITB) in the electron temperature profile,[15] similar to the previous DIII-D/EAST high-β_p joint experiments with an ITB in the ion temperature profile under dominant ion heating.[16] The ITB and higher energy confinement was sustained with either high or low toroidal rotation.[16] Transport analyses have shown that the $\boldsymbol{E}\times\boldsymbol{B}$ shear is not the key effect behind the ITB formation.[14,17] Further experiments and TGLF modeling[17] confirm that the Shafranov shift has a key stabilizing effect on plasma turbulence, which is responsible for the ITB formation and higher energy confinement.[18]

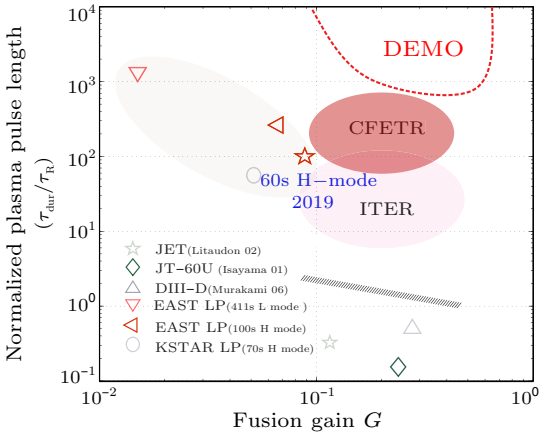

Fig. 1. Overview of the parameter space of obtained and prospective long pulse high β_p H-mode plasmas in EAST. Normalized plasma pulse length as a function of the fusion gain G. Here τ_R is the resistive diffusion time and $G=\beta_N H_{89P}/q_{95}^2$ is a parameter quantifying plasma performance. Note that the red star represents the 60 s H-mode achieved in 2019. The red star represents the 60 s H-mode achieved in 2019.

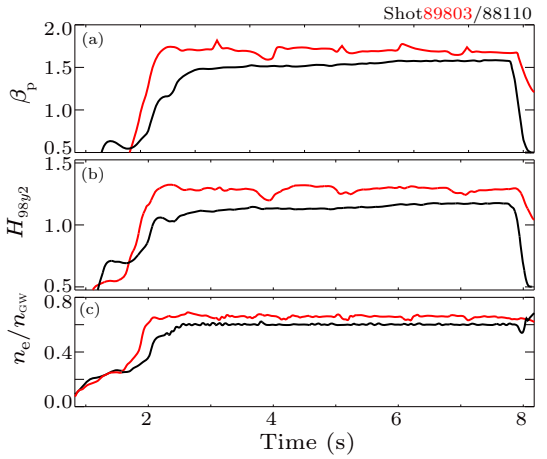

Fig. 2. Time traces of two high β_p discharges in EAST. From top to bottom, normalized poloidal beta, energy confinement improvement factor H_{98y2} and line-averaged density over the Greenwald density limit.

Further data analysis exhibits a clear positive dependence of energy confinement on the density peaking factor. Dedicated experiments have been performed to identify the role of density peaking in improving plasma confinement. Figure 3 shows a scatter plot of the confinement improvement factor H_{98y2} against the density peaking factor n_e from four categories of discharges with different heating combination in EAST, i.e., LH only, LH + EC, LH + NB and LH + EC + NB. Here the density peaking factor is calculated as the ratio of the central line integrated density to the line integrated density at $\rho\sim 0.6$ measured by a POlarimeter-INTerferometer (POINT) system.[19] Here ρ is the normalized plasma minor radius. Each category of discharges has the same β_p value and heating/current drive scheme, thus similar Shafranov shift stabilizing effect and plasma rotation effect on the energy confinement. A clear dependence of H_{98y2} on the density peaking factor was observed in all four categories of discharges as shown in Fig. 3, implying a new universal mechanism for confinement improvement independent of Shafranov shift and external torque injection. Increase of H_{98y2} is significant in all cases, generally by 20%–30% within the range of achievable density peaking factor in present experiments. Particularly, for the category of LH + EC discharges, a remarkable increase of H_{98y2} from 1.0 to >1.3 has been observed, denoted by red solid squares in Fig. 3, with the density peaking factor increasing from ∼1.4 to ∼1.7 at a fixed β_p. This category of discharges is more reactor relevant as they are heated by pure rf power which predominantly heats electrons with nearly zero external torque injection as projected for a fusion burning plasma. In addition, as the rf power systems are capable of continuous operation, this scenario is currently the main candidate for achieving long-pulse H-mode discharges on EAST.

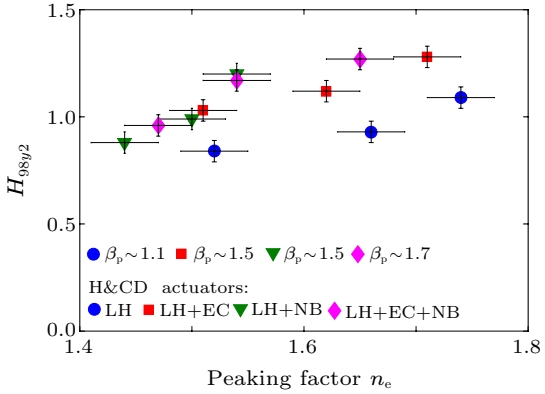

Fig. 3. Energy confinement improvement factor H_{98y2} versus density peaking factor n_e for four categories of discharges in EAST, where the error bars are uncertainties of H_{98y2} and n_e.

Figure 4 compares the profiles of electron temperature T_e and density n_e of two discharges with similar β_p value but different energy confinement performance. The T_e profile (red curve) with stronger ITB centered at $\rho\sim 0.2$ corresponds to a lower pedestal-top density and a higher density gradient, which has higher energy confinement. Recent simulation shows

that the density gradient is a control knob in improving energy confinement[20] with the enhanced stabilization effect from reduced effective trapped electron fraction and increased averaged-parallel wave number ($k_{||}$) in the Trapped Electron Mode (TEM) regime. The high β_p with large Shafranov shift makes unstable eigenfunction narrower in the bad curvature region, resulting in the reduced effective trapped electron fraction and increase of $k_{||}$ (eigenfunction averaged parallel wave number). Feeding of free energy of instability to the density gradient becomes poorer since reduced trapped electron fraction and leads to stronger Shafranov shift stabilizing effect on instability, which will also allow higher temperature gradient and results in better confinement as seen in Fig. 4. The simulation results are qualitatively consistent with the observations in EAST, indicating that this mechanism may play a role. On the other hand, analysis of extensive databases of ASDEX Upgrade and JET H-mode plasma density profiles showed that the density peaking factor increases as the plasma collisionality decreases,[21,22] suggesting that future fusion reactors are likely to have a more peaking density profile with a much lower collisionality than nowadays tokamaks.

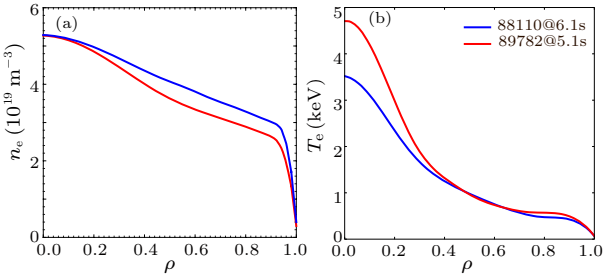

Fig. 4. Comparison of plasma profiles for two EAST high-β_p discharges with different density gradients.

This finding may open a new path towards higher energy confinement regimes to achieve high β_p and thus higher f_{BS}, which provides a readily way to access steady-state H-mode plasma operation. In the recent EAST campaign, dedicated experiments were carried out at higher density gradient to achieve higher energy confinement and f_{BS} based on this approach. Plasmas with density peaking factor up to 1.8 have been achieved mainly via central fueling with supersonic molecular beam injection (SMBI) and edge particle recycling control with lithium coating of the wall. A high performance fully non-inductive long-pulse discharge with $H_{98y2} \geq 1.3$, $\beta_p \sim 2.0$, $f_{BS} \geq 45\%$, normalized beta $\beta_N \sim 1.6$ and an ITB in the electron temperature profile has been successfully obtained with the combination of LH and EC powers for a duration over 60 s, about 100 current diffusion times. It sets another new world record of long-pulse high-performance H-mode plasma operation with its normalized performance mostly close to the ITER and CFETR regimes as shown by the red star in Fig. 1. The plasma confinement performance of this discharge is much better than the previous world record, i.e., 100-s-long-pulsed H-mode plasma, in which $H_{98y2} \sim 1.1$, $\beta_p \sim 1.2$, $f_{BS} < 27\%$ and $\beta_N \sim 1.0$.[6] The other key normalized plasma parameters are close to or even exceed those expected for ITER and CFETR steady-state regime,[23] demonstrating the feasibility of high β_p scenario with dominant electron heating and low torque injection for applications in future steady-state tokamak burning plasmas with lower collisionality.

In summary, for the first time, EAST experiments have shown a clear dependence of improved energy confinement on density gradient in the high β_p scenario. The density gradient has been found to be a control knob in enhancing the Shafranov shift stabilizing effect as suggested by simulations. This new finding is of great importance for the next-step fusion development towards a steady-state fusion reactor, as it has opened a new path towards H-mode regimes with even higher confinement and thus higher bootstrap current fraction, as demonstrated in the recent long-pulse high-performance H-mode experiments on EAST. In the near future, further dedicated experiments with higher heating power and transport analysis will be carried out to uncover the underlying stabilization effects and their synergy on the confinement.

The author would like to thank X. Z. Gong, J. P. Qian and G. S. Xu for the support of dedicated experimental operation and helpful discussions.

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