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Intelligent control for predicting and mitigating major disruptions in magnetic confinement fusion

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ABSTRACT

Magnetic confinement fusion is believed to be one of the promising paths that provides us with an infinite supply of an environment-friendly energy source, naturally contributing to a green economy and low-carbon development. Nevertheless, the major disruption of high temperature plasmas, a big threat to fusion devices, is still in the way of mankind accessing to fusion energy. Although a bunch of individual techniques have been proved to be feasible for the control, mitigation, and prediction of disruptions, complicated experimental environments make it hard to decide on specific control strategies. The traditional control approach, designing a series of independent controllers in a nested structure, cannot meet the needs of real-time complicated plasma control, which requires extended engineering expertise and complicated evaluation of system states referring to multiple plasma parameters. Fortunately, artificial intelligence (AI) offers potential solutions towards entirely resolving this troublesome issue. To simplify the control system, a radically novel idea for designing controllers via AI is brought forward in this work. Envisioned intelligent controllers should be developed to replace the traditional nested structure. The successful development of intelligent control is expected to effectively predict and mitigate major disruptions, which would definitely enhance fusion performance, and thus offers inspiring odds to improve the accessibility of sustainable fusion energy.

KEYWORDS

Magnetic confinement fusion, intelligent control, major disruption.

Amid the rapid development of modern society, science, and high-technology continuously improve our living standards. Nevertheless, the development comes at a price, which is the explosively growing consumption of fossil energy. The combustion of traditional fossil fuels releases large amounts of carbon dioxide and other noxious gases, which leads to severe issues of environmental pollution and global warming. Nowadays, green economy and low-carbon development are increasingly becoming international consensuses. As a leading gesture, China has been committed to accomplishing the goals of carbon-emission peak by 2030 and carbon neutrality by 2060. Thus, new resources of clean energy must be developed immediately to reduce carbon emission. Undoubtedly, nuclear fusion provides us with a potentially infinite supply of an environment-friendly and inherently safe source. Particularly, magnetic confinement fusion occupies a decisive position. However, a major disruption of high temperature plasmas is still challenging to be dealt with during discharges in fusion devices. Decades of extensive efforts, both theoretically and experimentally, have been devoted to the prediction and the mitigation of major disruptions, yet the issue has not been completely solved. Fortunately, the recent development of artificial intelligence offers potential solutions towards entirely resolving this frontier issue. The following sections briefly introduce the study history of major disruption in magnetic fusion and highlight the significant change brought by intelligent control.

1 A vexing challenge in magnetic fusion

Nuclear fusion energy is commonly believed to be the ultimate energy source for us, human beings, to solve energy issues once and for all. With the aim to confine hundreds of millions of degrees high temperature plasmas during fusion reactions, magnetic confinement fusion, also widely known as an "artificial sun", is regarded as the most promising way to bring fusion energy into our life. After construction of many large toroidal magnetic fusion facilities and decades of worldwide efforts on experimental research, remarkable progress has been made in the field of magnetic fusion, providing a sound base for the construction of an economically viable fusion reactor. Nevertheless, technical difficulties in plasma performance still exist. So far, one of the most pressing challenges is to avoid major disruptions caused by macroscale plasma instabilities in fusion reactors. The release of massive free energy in magnetic fusion devices is responsible for driving plasma instabilities. The resulting disruptions can instantaneously break the well magnetic confinement, thus halting the process of power production. Consequently, great amounts of heat deposit onto the confining vessel in a very short time and destroy core components. Usually, the activities that result in disruptions are combinations of different destabilizing instabilities due to density-limit, beta-limit, and so on. Therefore, there is no easy way to classify disruptions. In particular, major disruptions are extremely detrimental for large-scale high-performance systems, such as the international thermonuclear experimental reactor (ITER)[1]. The ITER costs billions of dollars to be built and is still under construction at present. The target of ITER is to generate more power via fusion than the power consumption for the first time, approaching real reactor conditions. Any major disruption would be a large threat to ITER, and thus it is highly essential to prevent

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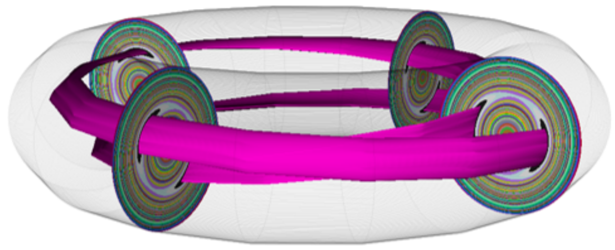

Fig. 1 Illustration of 3D helical magnetic islands in a toroidal fusion device simulated via MHD@Dalian Code.

major disruptions from damaging core components of ITER, ensuring high-performance continuous operation in ITER. Otherwise, huge economic loss would be inflicted.

2 Trying to know more about instabilities

In light of the fact that plasma instabilities are responsible for major disruptions, the immediate idea is to make clear the properties of plasma instabilities for their better control. Spontaneously, topics associated with plasma instabilities continually attract heated interests in the field of magnetic fusion.

In theory, the strongest instabilities in toroidal fusion devices can be described through magnetohydrodynamic (MHD) equations[2,3]. The fundamental destabilizing forces include current gradients and pressure gradients. Moreover, the MHD instabilities are generally divided into two categories: ideal modes and resistive modes. Ideal instabilities can happen even though the plasma is perfectly conducting. While the resistive instabilities rely on the finite plasma resistivity. In the earliest experiments, magnetic fusion devices encounter different kinds of macro-scale instabilities. At that time, these instabilities were not totally understood but could be ascribed to the MHD scope. As diagnostic techniques develop, observed instabilities can be identified via a variety of diagnostic methods. It is found that the tearing mode (TM)[4,5], a deleterious resistive MHD instability, plays an important role in the excitation of major disruptions[2]. During the nonlinear phase of TM, the equilibrium magnetic topology inside the plasma is dramatically broken. Well-nested axisymmetric magnetic surfaces are reconnected into so-called helical magnetic islands. Sufficiently large magnetic islands often lead to major disruptions. In addition to the most dangerous TM, macro-scale pressure-driven ideal modes also can induce major disruptions. By means of large-scale high-performance numerical simulation, the properties of these MHD modes can be systematically investigated under all kinds of situations. Figure 1 shows the three-dimensional (3D) spatial structure of macroscopic helical magnetic islands simulated via large-scale massively parallel MHD code[6,7].

After decades of extensive investigations, the basic mechanisms behind plasma instabilities are well understood. Therefore, the research focus gradually moves to the control of plasma instabilities.

3 Manifold control techniques are still not enough

In order to better control plasma instabilities, different kinds of techniques have been developed. For the purpose of suppressing instabilities, control techniques include differential plasma rotation[8], externally applied resonant magnetic perturbation[9,10], electron cyclotron current drive[11,12], radio frequency wave heating[13], etc. For disruption mitigation, massive gas injection, and shattered pellet injection are widely implemented. Apparently, the most effective approach is the predicting technique that can help us take action in advance to prevent disruptions. Recently, a new type of predicting technique, called real-time multi-mode 3D MHD spectroscopy (RTMM3DMSP)[14,15], has been developed. The method has been successfully applied to present-day advanced magnetic fusion devices including DIII-D in USA, KSTAR in South Korea, and EAST in China to monitor the stability of fusion plasmas. The method requires active detection of plasma response to externally applied 3D current fields. To apply a broad range of 3D current fields, the device should be equipped with multiple rows of internal non-axisymmetric coils. Figure 2 displays the cross-section of EAST device with corresponding upper and lower rows of coils and multiple arrays of magnetic sensors. By fitting applied current signals and corresponding magnetic perturbation signals, the predicting index (growth rates of MHD modes) can be obtained. As shown in Figure 3, once the predicting index reaches the warning line, corresponding control strategy will be triggered.

Our new approach could be implemented to predict major disruptions caused by instability with long warning times, which opens up the opportunity of moving from passive mitigation to active prevention of major disruptions. The merits of the RTMM3DMSP include the capability of quantifying eigenvalues of multiple stable MHD modes, the high efficiency to enable real-

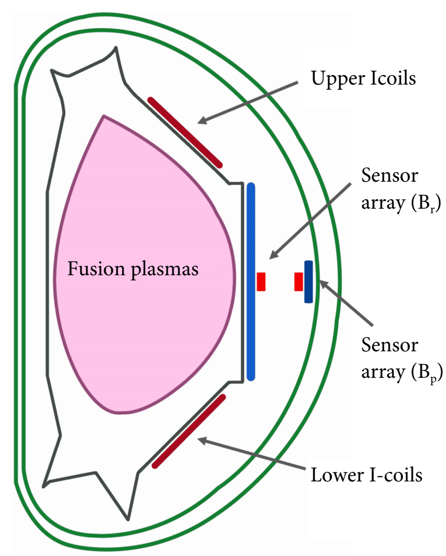

Fig. 2 Schematic diagram of current field coils (dark red blocks) and sensor arrays (combination of blue and red blocks) arranged in the cross-section of EAST.

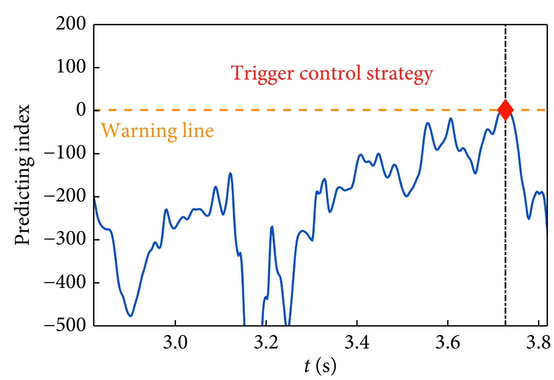

Fig. 3 Operating pattern of the real-time multi-mode 3D MHD spectroscopy.

time implementation, the great convergence for better noise proof, the feasible deployment in multiple devices equipped with 3D coils and magnetic sensors. The main demerit is the possibility of false positives, which could be continually ameliorated by improving the quality of diagnostic signals. It is noted that the new approach should be able to detect all the low frequency instabilities within the MHD frame. The stable kink and probable stable tearing mode have been detected in experiments. Considering the vertical displacement events (VDEs), one of the most challenging threats to the ITER, could also be described by MHD models, the application of the RTMM3DMSP on VDE prediction could be expected and will be attempted in future experiments.

Abundant techniques have been developed for the control, mitigation, and prediction of MHD instabilities and of resulting disruptions. The feasibility and effectiveness of each individual technique are widely corroborated. Nonetheless, complicated real experimental situations and complex nonlinear physics processes lead to the myriads of changes of specific control strategies. Although the massive large-scale simulations can help optimize the control strategy on some level, the computation requirements are tremendously huge, which would cost big money and almost infinite time based on today's computing resources. Does this mean fusion energy is a dream that never comes true?

4 The rise of artificial intelligent (AI) trends

On the occasion when the progress of disruption related research moves slowly, the fast developing of a new technique, namely AI, injects fresh vitality into the plasma control in magnetic fusion.

In the mid-20th century, the concept of AI had already been brought forward. The development of AI went through several ups and downs. Recently in 2016, AlphaGo (an AI developed by DeepMind) beating Sedol Lee (world champion in the game of go), serving as an iconic event, rekindled the zeal of AI research and surely accelerated the developing progress in the field of AI. In the following years, the enthusiasm for AI swept around the world. Tech giants, including Google, Baidu, Microsoft, and IBM, all invested huge sums to establish AI subsidiaries one after another. After years of high-speed development, AI has now been applied to many different kinds of fields such as data science, computer vision, automatic drive, etc. Actually, several applications of AI have already been initially implemented in the field of magnetic fusion. In experiments, Julian et al. have attempted to predict disruptive instabilities in DIII-D and JET devices and obtain some inspiring preliminary results[16]. Jonas et al. successfully apply AI to automatically control a variety of plasma boundary shapes on the TCV device[17]. In numerical simulations, Zhao et al. accomplished quick prediction of beta limits in HL-2M device via AI, with an accuracy rate being as high as 95%[18]. Li et al. build a surrogate model through AI to predict the transition of micro-instability in fusion devices[19]. Figure 4 shows a good agreement between the simulation output and the surrogate model prediction. Inspiringly, the surrogate model will dramatically improve the computing efficiency in comparison with the large-scale simulation.

Previous applications show that AI is good at dealing with mass data and highly nonlinear system issues. What could happen if the plasma control issue encounters AI technology?

5 Intelligent control will be the path to the ultimate goal

The core difficulty of plasma control in magnetic fusion devices is the complicated high-dimensional process resulting from complex nonlinear multi-modal physics. The countless combinations of control techniques and disruption causes determine that simple rules and concise criteria cannot be found. The traditional control method is to design a series of independent controllers based on linearized system dynamics with single-input and single-output. Each controller is individually separated from one another. Although the controllers are generally feasible in handling individual control needs, real-time complicated control of plasma instability requires extensive engineering expertise and design effort, together with the complex estimation of plasma states across a broad range of plasma parameters. Thus, a powerful tool that can deal with the complex system without setting specific constraint conditions is imperatively required. Fortunately, AI just can meet this need, bringing possibilities to completely solve this plasma control issue.

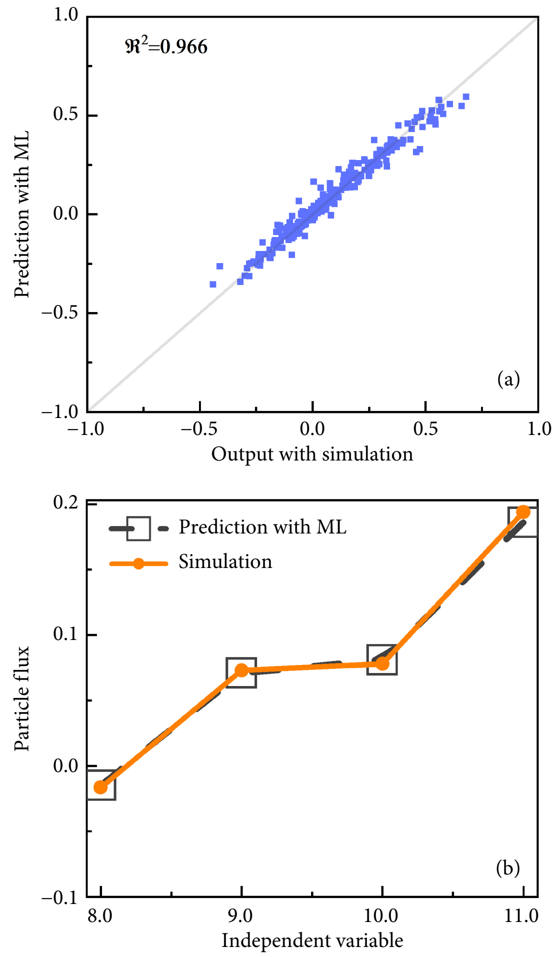

Fig. 4 Multi-variable comparison between large-scale simulation results and machine learning predictions. (a) Regression analysis. **(b)** Key variable comparison.

With the aim to simplify the control system, a radically novel way of designing controller is made possible by AI to generate a relatively low-resource nonlinear intelligent controller, replacing the nested control structure. The introduction of AI could reduce the development cycle, and consequently speed up the development progress. If we make an aggressive and positive expectation, intelligent control via AI might help us automatically finish the control decision in the future. Figure 5 shows the envisioned simplest structure of intelligent controller. In this pattern, the only input is a variety of diagnostic signals. The diagnostic methods can be soft X-ray, electron cyclotron emission imaging, Thomson scattering, etc. The overall process of optimizing the control strategy will be automatically handled by the intelligent controller. Finally, the only output, optimal strategy, will be given by the controller. Here, the intelligent controller contains three layers. The first layer is a bunch of predicting algorithms, such as RTMM3DMSP, which receive input signals directly from corresponding diagnostic equipment and provide predicting information including when and how major disruptions would happen. The second layer refers to the corresponding disruption causes calling the pre-existing control techniques which are included in the last layer. After being trained using large amounts of diagnostic data from training reactors and large-scale simulations, the intelligent controller could be capable of automatically dealing with plasma control issues under diverse situations. The corresponding control process will be optimized to minimize the disruptive rate and accordingly the optimal strategy will be given. Red arrows in Figure 5 indicate a possible route while the intelligent controller working. It is noted that the above elucidation is only a preliminary outlook, and the corresponding control techniques involve more complicated operations which should also be set in extra sublayers in the real design of an intelligent controller.

In summary, a confluence of AI, large-scale simulation, and massive experimental data show good prospects for achieving intelligent control in the future. Eventually, the ultimate target is to totally prevent major disruptions but not just to mitigate their influences. Using a variety of diagnostic data from training reactors and large-scale simulations, the intelligent controller could be trained to automatically control the plasma instability via optimizing control strategy to minimize disruptive rate. We could make good use of high-dimensional data for training models to enhance control effectiveness, as well as large-scale supercomputing resources to promote accuracy and efficiency. The aforementioned example of optimizing control strategy via an intelligent controller highlights the potential for synergistic application between AI and traditional theoretical modeling in the control of extremely complex physics systems. As the technology of control further develops, the feasibility and availability of intelligent control in fusion science will be recognized. The development of intelligent controllers has the potential to shape future fusion research. Underspecified targets would lead to optimal control strategies that maximize the performance of steady state and eventually maximize power production. In comparison with present controllers, the developed intelligent controller should be easily deployed on a new fusion device without complex design and evaluation. After successfully developing intelligent control, together with further real-time experimental testing, large-scale simulation and theoretical modeling, a more substantial foundation will be built for the steady operation of future fusion reactors. The successful prevention of major disruptions would absolutely enhance fusion performance, therefore offering inspiring chances to accelerate research progress, moving sustainable fusion energy a major step towards our real life. Hopefully, we are finally able to build an "artificial sun" on the earth in the not-too-distant future.

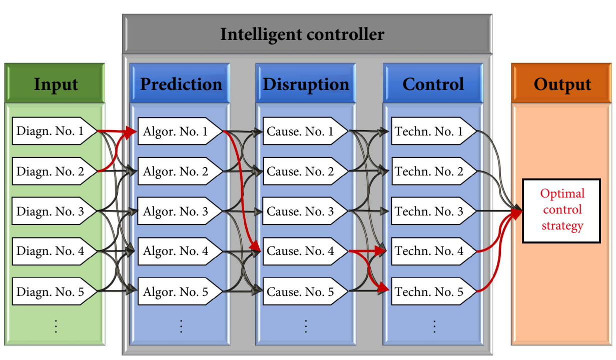

Fig. 5 Envisioned workflow of intelligent control for preventing major disruptions in magnetic fusion devices.

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Additional information

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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