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Feature extraction and prediction of radiative collapse in Large Helical Device using sparse modeling

The features of radiative collapse have been extracted from high-density plasma experiments in the Large Helical Device (LHD Toki, Japan) with a sparse modeling technique. The extracted features have been used to explore the underlying physics of radiative collapse and to develop a machine learning predictor of the collapse.

In stellarator-heliotron plasmas, radiative collapse is one of the most critical issues that limit the operational density. The well-known Sudo scaling law for the density limit suggests that the balance between heating power and radiative power loss is a key, together with robust confinement capability such as plasma volume and magnetic field [1]. However, contributions of other operational conditions (e.g., impurity contamination, wall conditions) to the occurrence of radiative collapse are not expressed in the Sudo scaling law.

In the present study, a machine-learning classifier that distinguishes plasmas in the close-to-collapse state (in which radiative collapse is likely to occur) and in the stable state has been constructed based on experimental data from LHD. In the experiment, a hydrogen and deuterium gas-puff was used as fueling, and the magnetic configuration was fixed at the magnetic axis position R_{ax} of 3.6 m, with B = 1.375 T or 2.75 T. The surveyed line-averaged density and heating power range up to 1.5×10^{20} m^{-3} and 15 MW, respectively. The data was classified into stable and close-to-collapse states according to the density exponent

$$x = \frac{\dot{P}_{\rm rad}/P_{\rm rad}}{\dot{\bar{n}}_e/\bar{n}_e},$$

which is a criterion of thermal instability [2]. Here, the dots indicate time derivatives.

Using the constructed classifier, features of radiative collapse have been extracted using exhaustive search (ES), a sparse modeling technique. Sparse modeling is one of the frameworks of data-driven science; it exploits the inherent sparseness in all high-dimensional data to extract the maximum amount of information from the data [3]. In ES, all possible combinations of input parameters are compared with each other to find the optimal set.

As a result of feature extraction, line-averaged electron density $\bar{n}_e$, line emissions of C IV and O V, and electron temperature at the plasma edge $T_{e,\,\rm edge}$ have been identified as key parameters of radiative collapse. Using those parameters, collapse likelihood has been calculated, corresponding to distance from the boundary between stable and close-to-collapse states obtained by machine learning. Figure 1 shows a typical discharge with radiative collapse in LHD. In this discharge, the collapse likelihood increased and reached 1.0 (100%) before the plasma collapsed.

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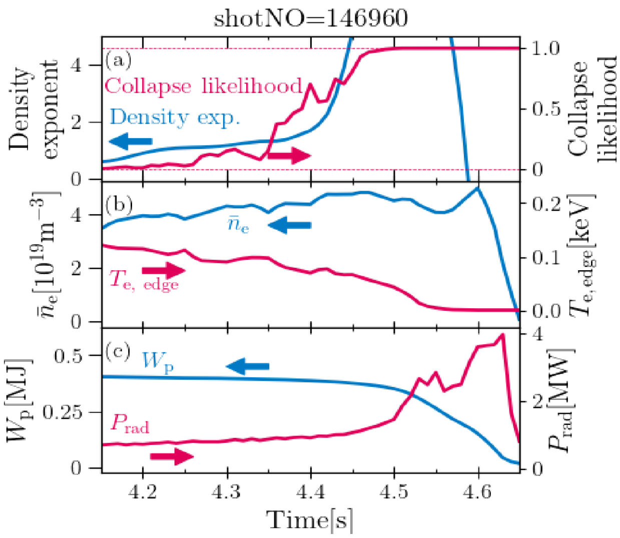

Fig. 1 An example of a collapsed discharge in LHD: (a) density exponent and collapse likelihood, (b) line-averaged electron density and electron temperature at plasma edge, (c) diamagnetic energy and radiated power.

The collapse likelihood has been verified with about 500 discharges in LHD, and more than 85% of radiative collapses have been predicted successfully at least 30 ms before occurrence. Also, using the extracted parameters, mechanisms of occurrence of radiation collapse have been explored focusing on radiation loss of light impurities at the plasma edge, especially outside the last closed flux surface.

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NIFS-SWJTU Joint Project (NSJP) for CFQS

The National Institute for Fusion Science (Japan) and Southwest Jiaotong University (China) signed a Memorandum of Understanding (MoU) on 3 July, 2017, to begin an international joint project to design, build, and operate a stellarator with the quasi-axisymmetry. The name of the device was decided to be the Chinese First Quasi-axisymmetric Stellarator (CFQS). We have published several papers describing the physics design elements and the engineering design results. The web site for this project is open:

https://reso.nifs.ac.jp/eng/international/

The purpose of this article is not to describe the device design or the experimental program. Readers may visit the web site, and succeeding articles will appear in *Stellarator News* and in other places. Instead we discuss the origin of this joint project between NIFS and SWJTU, and the reasons for adopting the quasi-axisymmetric stellarator as the device in the program. Because we do not intend to give a complete record of the research histories of the stellarator community, some important stellarator programs may not be mentioned. We hope to receive comments and requests for amendments to any unintentional inaccuracies in the descriptions.

We believe that the NSJP is very important in the long and unbroken stream of stellarator research. The stellarator concept, developed by the famous Lyman Spitzer, was pursued in a series of magnetic confinement programs at the Princeton Plasma Physics Laboratory (PPPL) in the 1950s and the 1960s. Stellarator of all types produce rotational transform by means of external coils with little or no toroidal plasma current. The stellarator family includes several unique devices called Asperators at Tohoku University in Japan, which had a very strong three-dimensional shaping of the magnetic axis to contribute to the creation of the rotational transform. [It should be noted that without the aid of computers, early stellarators probably had no closed flux surfaces.] At the University of Wisconsin, Madison (UW), an Interchangeable Module Stellarator (IMS) was constructed using a pioneering design with modular coils rather than using a continuous helical conductor winding.

When the experimental results of the T-3 tokamak at the Kurchatov Institute in the Union of Soviet Socialist Republics (USSR) were reported with a record high electron temperature, many fusion laboratories in the world made a decision to employ this idea in their research on magnetic confinement. In an impressive effort, PPPL converted its Model C stellarator into the ST tokamak. During the 1970s and 1980s, the major line of development of magnetic confinement research was led by tokamak devices. In this phase of magnetic confinement research, tokamaks had a great advantage of being able to heat the plasma using the confining toroidal current for ohmic-heating (OH). OH has a very good heating efficiency and requires a relatively simple and cheap hardware structure.

In parallel with this big tokamak world, there were two continuous streams of stellarator research at Kyoto university in Japan (Heliotron experiments) and IPP in Germany (Wendelstein experiments). They continued fundamental fusion experiments with a series of stellarator devices. However, they had to wait until the technology for external plasma heating was developed before stellarators could be competitive with tokamaks using OH. Positive experimental results with electron cyclotron heating (ECH) on these devices were followed by many new stellarator experiment proposals all over the world. ATF (Advanced Toroidal Facility) in Oak Ridge, U.S.A., the Compact Helical System (CHS) at NIFS, Japan, and Wendelstein 7-AS (W7-AS) at IPP, Germany were all started around 1988. The H-1 heliac and TJ-II heliac joined the community as well. The first stellarator with a complete configuration optimization, the Helically Symmetric Experiment (HSX) at UW also started configuration design in 1990. Construction of two major devices, LHD and W7-X was started at this time.

In Japan, the major role of CHS was to understand stellarator confinement physics in the Heliotron type magnetic configuration developed in a series of experiments at Kyoto. In addition, a new type of magnetic configuration study with poloidal field control, which was introduced from the ATF program, was an important subject. This poloidal field control scheme has become the most powerful tool to control the position of the magnetic axis in LHD and other stellarators. Such pioneering works are necessary before starting much larger size experiments such as LHD. When the LHD experiment started in 1998, the main experimental research activities at NIFS were handed over to LHD from CHS. The next role of the CHS team was to find out the next step of the compact stellarator experiment. At that time, the standard computational configuration optimization technique was widely adopted in stellarator magnetic configuration design; one example was the pioneering design work for HSX. Because one of research targets of the CHS program is to study the confinement physics in a low-aspect-ratio stellarator, we chose an optimization with quasi-axisymmetry. In this stellarator optimization work, we had a happy opportunity of collaborating with Prof. J. Nührenberg and Prof. P. Merkel who pioneered stellarator optimization. After completing the physics and engineering design, an experimental program of CHS-qa was proposed in 2000, but unfortunately this plan was not accepted by NIFS as a next step of the CHS experiment.

PPPL began designing a National Compact Stellarator Experiment (NCSX) with quasi-axisymmetry in 1998 and succeeded in initiating device construction in 2003. However, after working for 5 years to manufacture the device, the program was canceled. These two programs would have been major experimental activities in the stellarator world because quasi-axisymmetry is one of very new and challenging topics in stellarator research in the 2000s. Although the LHD experiments and the tireless construction of W7-X continued during this decade, we lost one step of a new generation of stellarator concept development.

In 2015, NIFS received an inquiry from a university in China about the possibility of the transfer of the CHS device for learning and doing research on a stellarator experiment. Because the main line of the fusion development in China is tokamak research, there was no stellarator experiment running in China at this time. However, discussions of the strategy of fusion development in China are very similar to those of other countries; namely, it is important to study stellarator physics now, even though the present main line is tokamak research. Such a comprehensive understanding is supported especially by top-level fusion scientists in China. University experimentation is an appropriate venue for starting a new but important program in fusion research in China. The university is Southwest Jiaotong Universtiy (SWJTU), located in Chengdu city of Sichuan province. Jiaotong in Chinese means "transportation," and this word is given to the top-level technical university in China because the technology of transportation (railway) used to be the university's most important role. NIFS leaders decided that it was a good idea to assist stellarator research in China and work together in order to establish strong stellarator research activities in Asia. The name of the device was at that time, the Chinese First Stellarator (CFS).

After further discussions about the cost of transferring CHS and preparing the experimental environments as well as the experimental programs, a different idea emerged; construction of a new device with an advanced stellarator design would be more appropriate for a new project at the university. NIFS agreed to modify the program and created an MoU for starting a new international joint project, the NIFS-SWJTU Joint Project (NSJP). The device name was modified to Chinese First Quasi-axisymmetric Stellarator (CFQS). In the MoU, the role of NIFS is to lead the design work for the device and the research program, as well as to contribute to the heating and diagnostic systems of the experiments. The role of SWJTU is jointly design the device, to construct the device and experimental facilities, and conduct the experiments in collaboration with

NIFS and other international researchers. The magnetic configuration design, data, and physics and engineering experience and design work from the CHS-qa design programs were fully utilized. For more than 15 years a host of calculations and discussions have been conducted for stellarator optimization in general, and for the quasi-axisymmetric stellarator in particular, but in theory only! It is time to validate these theoretical efforts against real quasi-axisymmetric plasmas in real experiments. The first priority of the program was to start the experiment as soon as possible without spending more time on discussions. We wanted to restore the lost 15 years. We thought that the important tasks to complete before starting the experiment are reliable (robust) engineering designs and the adequate estimation of the necessary accuracy of the device.

The construction of the mockup coil for the MC4 modular coil, which has the highest complexity of the three-dimensional shape, was started in 2018, and we are now entering the manufacturing phase for the four different types of modular coils. The manufacturing of the vacuum chamber is just starting. Future articles in *Stellarator News* will include an introduction of the research environment in the University and the city of Chengdu, as well as a more detailed report on the CFQS device design and manufacturing.

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