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Experimental study on the advanced methods of fault diagnosis and reliability evaluation to be applied for complex energy systems

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Summary

- Both the university researchers and the corporate engineers on diagnostic techniques and reliability evaluation of complex technical systems have started cooperative study to examine the applicability of their methods to a helical plasma experimental facility Heliotron J which is operated by Institute of Advanced Energy (IAE), Kyoto University.
- The kick-off group meeting was conducted on June 29, 2023, when the four subjects were presented: this year's cooperative research plan, plasma diagnostics at Heliotron J, data assimilation study for plasma experiment, and preliminary study on applying a dynamic reliability evaluation method GO-FLOW for Heliotron J.
- Then after the discussion, this year's three works were decided: (A)Application of the higher harmonic diagnosis system for selected electrical equipment, (B)Study of data-driven science for Helical plasma, and (C) Application of GO-FLOW for the reliability evaluation of water cooling loop of Heriotron J.

Conduction of the kick-off group meeting, June 29, 2023
—Contents of the four presentations(1)—

This year's cooperative research plan by H. Yoshikawa

- Objective: To create an advanced ICT maintenance technology platform that contributes to the construction of a zero-emission energy infrastructure
- Approach: Collaborative research by researchers with different specialties to develop analytical methods for equipment diagnosis and risk prediction using the large experimental facilities owned by the Institute of Advanced Energy.
- Plans for this fiscal year: Focus on research on degradation diagnosis, risk and reliability assessment, and AI application to plasma diagnosis for Heliotron J to realize fusion plasma with magnetic confinement.

Plasma control/diagnostic systems for Heliotron J by S. Kobayashi

- Introduced control and diagnostic systems for magnetically confined plasma experimental device Heliotron J
- Heliotron J measurement/diagnostic systems can be divided into two categories, for control of the experimental apparatus (ex: power supply, coil, water cooling systems, etc.) and for the plasma diagnostic (ex: measurements for the density, temperature and their fluctuations).
- Introduced our current work about machine-learning and data-driven analysis for the plasma diagnostic data.

Conduction of the kick-off group meeting, June 29, 2023 —Contents of the four presentations(2)—

Data assimilation study for plasma experiment by Y. Kuroe

- Data assimilation is a method of improving the accuracy of simulations of complex large-scale systems by supplementing data obtained from sensors and other sources when a complete mathematical model of the target system is not available.
- Formulation of the problem of reconstructing the equilibrium state of a magnetically confined fusion plasma based on data assimilation and its solution by (1) the sensitivity equation method and (2) the adjoint equation method
- Introduction of the results of the application of (2) above to plasma experiments using a reverse magnetic field pinch plasma device.

Preliminary study on applying a dynamic reliability evaluation method GO-FLOW for Heliotron J by T. Matsuoka

- Classification of the components of the heliotron J (coils, power supply, plasma heating, plasma injection/exhaust, cooling, etc.), configuration of the plasma measurement system, and investigation and arrangement of operation and maintenance methods
- Discussion of the concept of plasma device anomalies, troubles, experimental failures, and criteria for success.
- Analytical steps required for reliability evaluation by GO-FLOW (Success Path Dynamic Reliability Analysis Method) ((1) FMEA, (2) Schematic representation of the entire system, (3) Creation of GO-FLOW chart) and research and collection of parameters required for these steps.

Conduction of the kick-off group meeting, June 29, 2023 —Results of whole group discussions—

Comments from Heliotron side by S. Kobayashi

- It is appropriate to apply GO-FLOW reliability analysis to the cooling water system of Heliotron J as a target. However, the application of the GO-FLOW analysis to the whole Heliotron J system seems to be difficult because there are no researchers in the Heliotron J group who specialize in the fusion engineering.
- As well as in other research fields, data driven analysis have been widely used in the fusion plasmas. In our group, there are several applications based on collaboration research.

Direction of further studies this year as the result of group discussion

- Subject A (Mr. Nitta): Experiments on installation of a harmonic diagnosis system for electrical equipment in the water cooling system pumps, etc. of the Heliotron J
- Subject B (Prof. Kuroe): Participate in the joint workshop of Heliotron J and National Institute for Fusion Science, and aim to apply the method proposed by Prof. Kuroe's group to heliotron experiments.
- Subject C (Prof. Matsuoka): To study the application of GO-FLOW to the short-term and long-term reliability assessment of the Heliotron J water cooling system, based on information provided by Prof. Kobayashi.

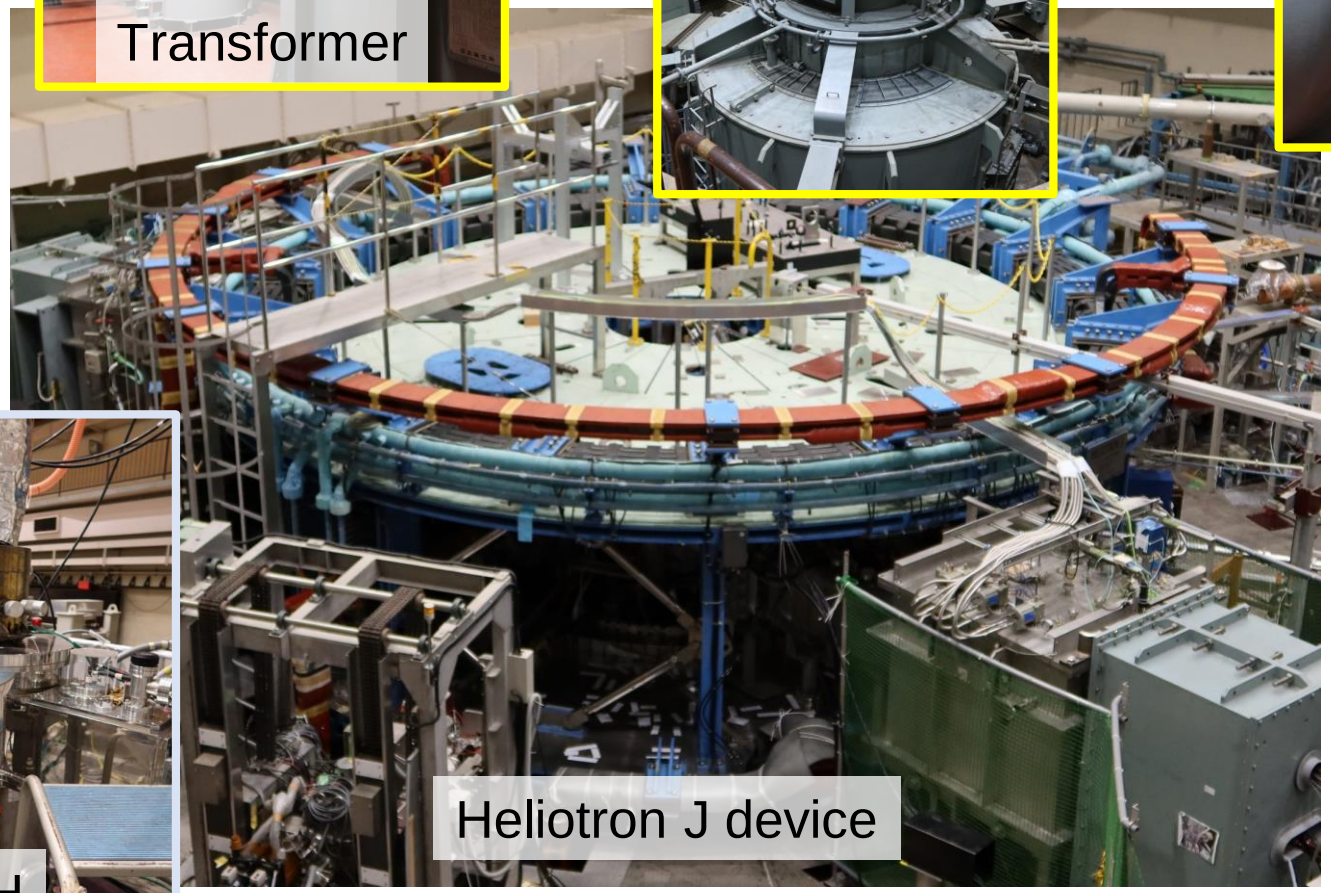
Major Components of composing Heliotron J system


Thyristor system

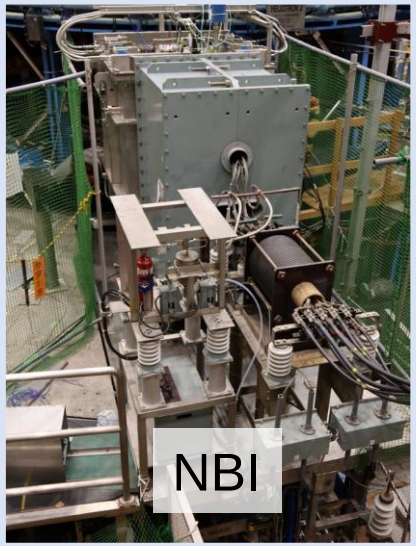

Transformer

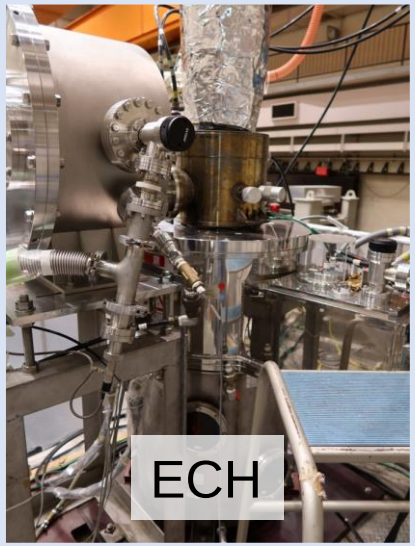

Motor generator

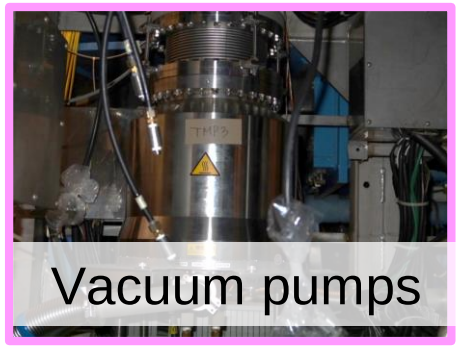

Power distributor


Heliotron J device

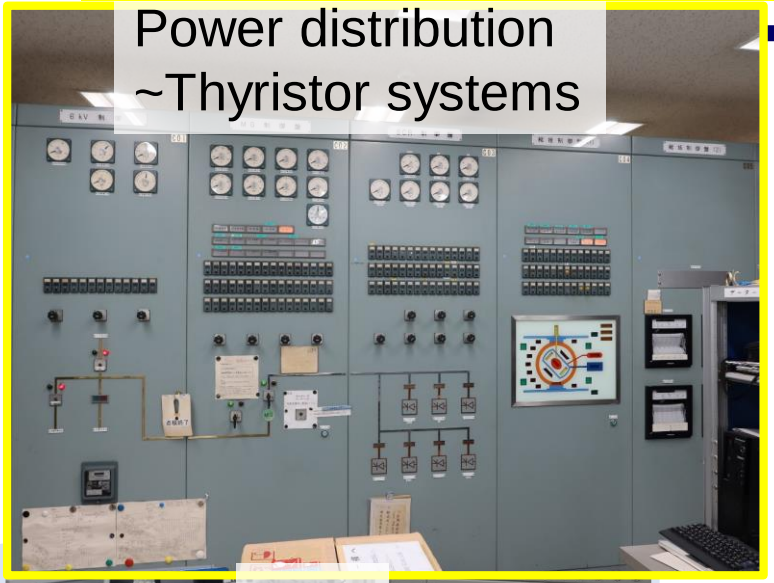

Water-cooling


NBI


ECH


Vacuum pumps

These devices have individual measurement equipment (temp, press, flow, volt, cur) and independently controlled → used as interlock signals to main control systems

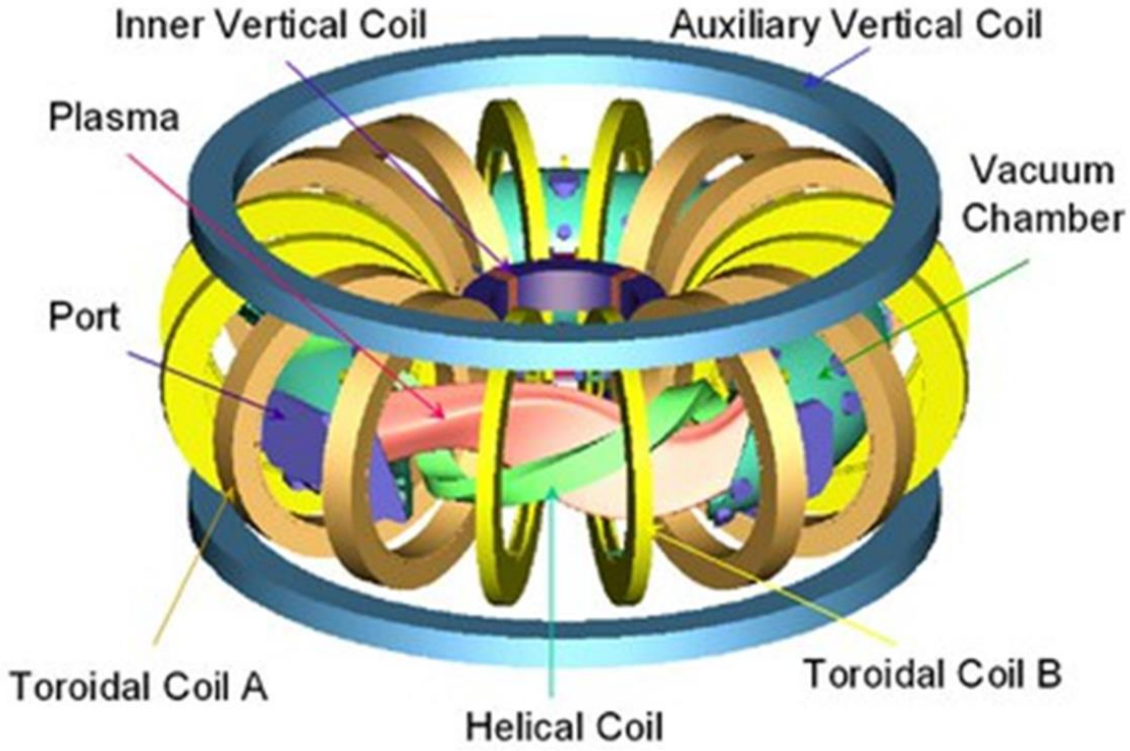

Power distribution
~Thyristor systems


ECH


NBI

External control parameters

- Coil currents → Configuration (a, R, V, B, ε_h, ε_b, ε_t …)
- Heating (P_{ECH}, P_{NBI}, P_{ICRF}) x (Pulse width, timing…)
- Fueling (Gas species, fueling rate, timing, etc.)

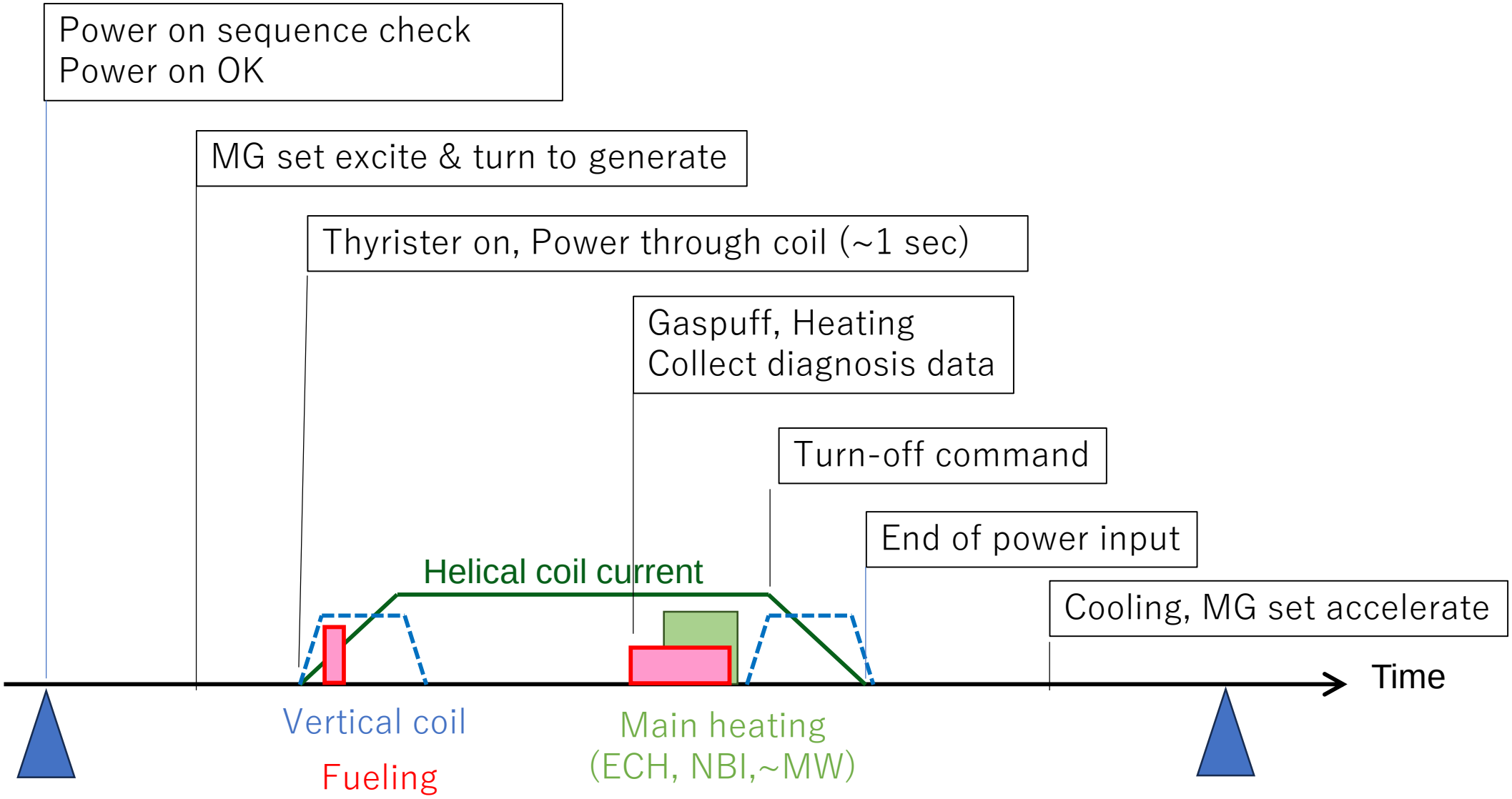



Water-cooling


Vacuum system

Distributed control boards for Heliotron J system

Timing chart of one plasma shot (ca. 3 second)



(A) Applying higher harmonic diagnosis system of electrical equipment failure for Heliotron J

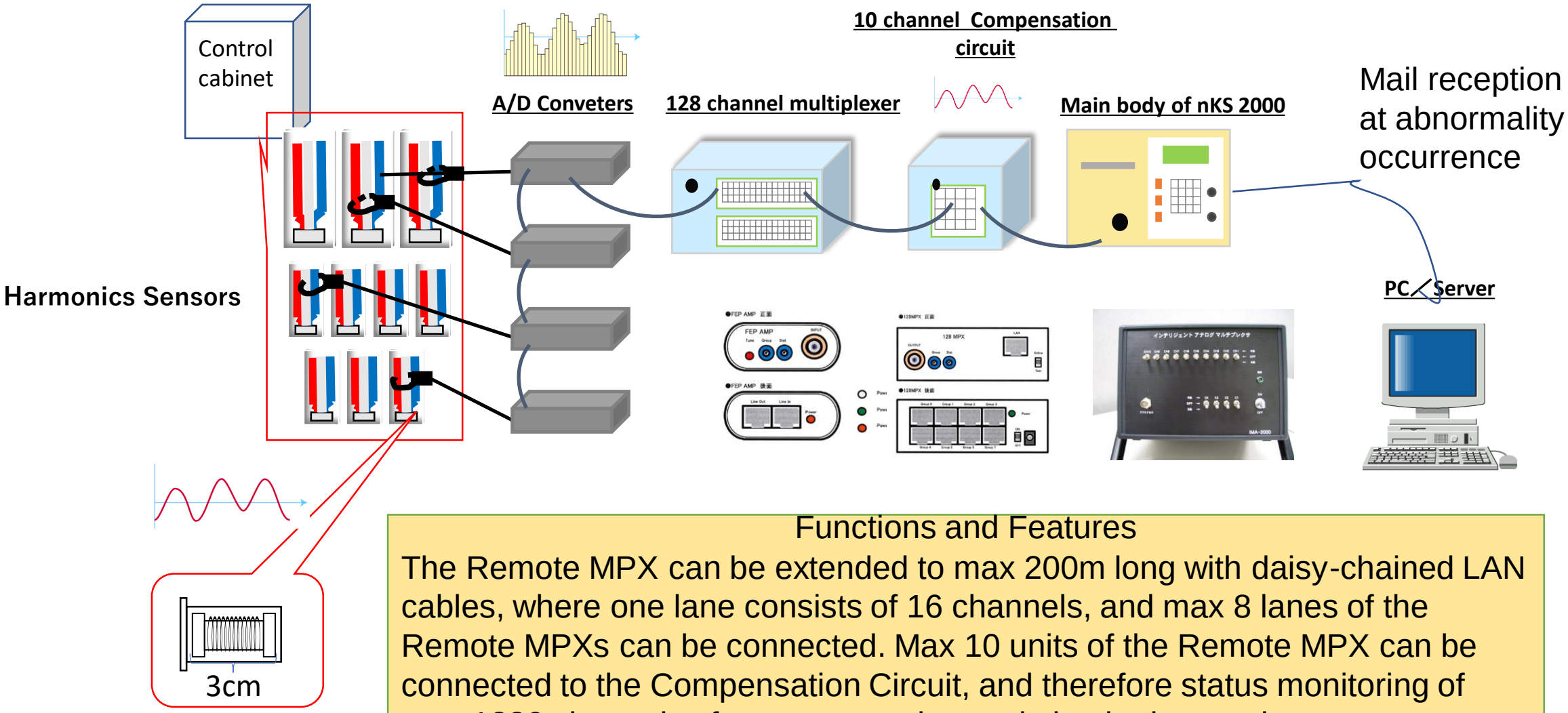
What is higher harmonics diagnostic method?

- The electric current flows through the electric equipment basically as the form of distorted wave which is the composite of basic wave and many higher harmonic waves.
- If the equipment is working normally, higher harmonic components are not so large in the electric current. But when some problem occurs somewhere in parts and modules, specific orders of higher harmonics will appear and exhibit higher percentage in the distorted wave.
- Higher harmonics diagnosis method will diagnose the state of electric equipment by examining what kinds of higher harmonics with their percentage are contained in the distorted wave.

Harmonics Diagnosis and Its Benefit

- Contactless and Live State measurement by search coil at the Control Panel of the local machine.
- Enables overall system diagnosis of Abnormality and/or Deterioration for various parts of Motor, Load, and Inverter
- Electric Power Balance is diagnosed to see how the Loading Mode between motor and load.
- Optimum Motor Efficiency to Minimize Motor Loss can be observed.

HAMOS System Configuration for continuous remote monitoring



Functions and Features

The Remote MPX can be extended to max 200m long with daisy-chained LAN cables, where one lane consists of 16 channels, and max 8 lanes of the Remote MPXs can be connected. Max 10 units of the Remote MPX can be connected to the Compensation Circuit, and therefore status monitoring of max 1280 channels of systems can be made by the harmonics measurement tool.

Application of Condition Monitoring System (HAMOS) to the water cooling system of Heliotron J

Plan of HAMOS application for water cooling system

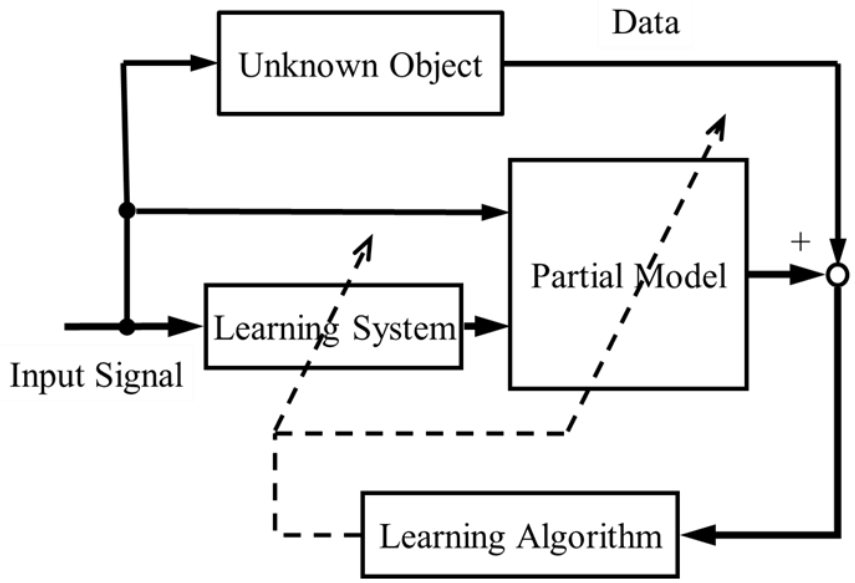
- There are many peripheral facilities that ensure the safe operation of the Heliotron J. In particular, we will focus on the diagnosis of the deteriorated state of the "electrical facilities related to the water cooling system".
- Conduct condition monitoring of cooling water pumps and accumulate long-term deterioration diagnosis data to conduct cooling water-related reliability analysis.
- Specifically, a harmonic sensor is attached to the power cable of the cooling water pump and the harmonic content is measured periodically (every two hours).
- Observation of time-series changes in each harmonic component will reveal which part of the cooling water pump is under stress and to what degree. Detailed analysis enables predictive diagnosis

Cooling tower of Heliotron J

(B) Study of data-driven science for Helical plasma

Development of Model Inclusive Learning and Data Assimilation

- A priori knowledge and inherent property on a target object or system (partial model) are included in the learning loop of learning system.
- A priori knowledge on a target system can be embedded in learning result.



Features of Model Inclusive Learning

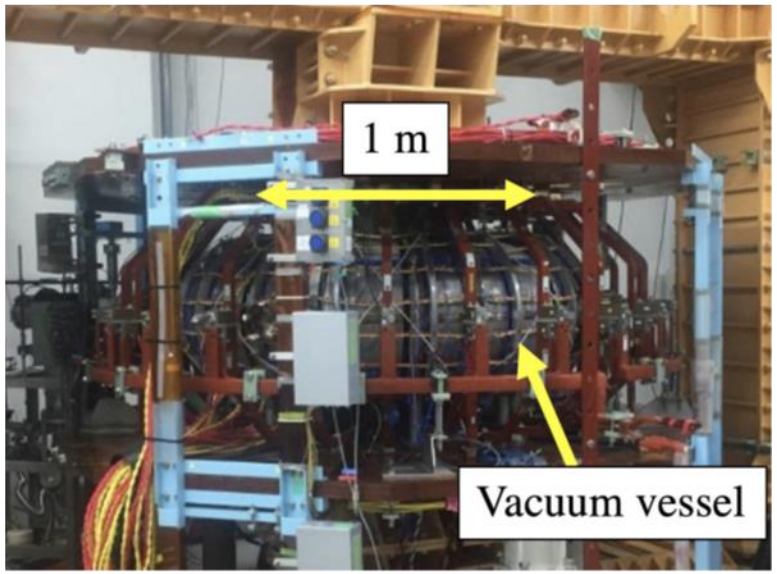
- utilize a priori knowledge on a target object.
- make it possible to treat a problem in which teacher's signals are not available.
- easy to realize data assimilation (both assimilate data and assimilate to data).
- regularize an ill-posed problem and improve generalization ability.

Our works on Model Inclusive Learning Methods

(1) Problem of shape from shading, (2) The vector fields approximation problem, (3)The estimation problem of motion and diffusion fields.

A Data-Assimilation Based Method for Equilibrium Reconstruction of Magnetic Fusion Plasma[(1),(2)]

- We propose a new method of equilibrium reconstruction for fusion plasma based on the data assimilation.
- Aiming at applying not only to axisymmetric toroidal plasmas but also to more general toroidal plasmas, we formulate the problems of equilibrium reconstruction in generalized forms and derive methods to solve them.
- The reconstruction is formulated as an optimization problem to determine a set of unknown adjustable parameters which minimizes the cost function.
- Two methods to solve the optimization problem are proposed:
  - method based on the sensitivity equation, and
  - method based on the adjoint equation.
- We also propose a method for applying the proposed reconstruction method to the RFP whose equilibrium is described by the Grad-Shafranov (GS) equation.
- The method based on the adjoint equation can reduce the computational time drastically compared to the method based on the sensitivity equation



RFP Machine at KIT

(1)IEEE Access, vol. 9, pp. 74739–74751, 2021 (2) IEEE Access, vol. 11, pp. 62639-62651, 2023.

Applying Model Inclusive Learning and Data Assimilation for Heliotron J

Data-Assimilation Based Method for Equilibrium Reconstruction

- Since equilibrium of Heliotron J is non-axisymmetric, it is necessary to develop a model and a method which can treat three-dimensional equilibrium.
- There are two possible models: one is the generalized Grad-Shafranov equation and the other is the inverse solver model which the code VMEC uses.
- It is conceivable that, with these two models, equilibrium reconstruction method based on data assimilation is developed in the following manner.
  - Parameterize the models with appropriate parameters.
  - Develop models of measurement processes.
  - Formulate equilibrium reconstruction method as an optimization problem.
  - Develop a method to solve the optimization problem.

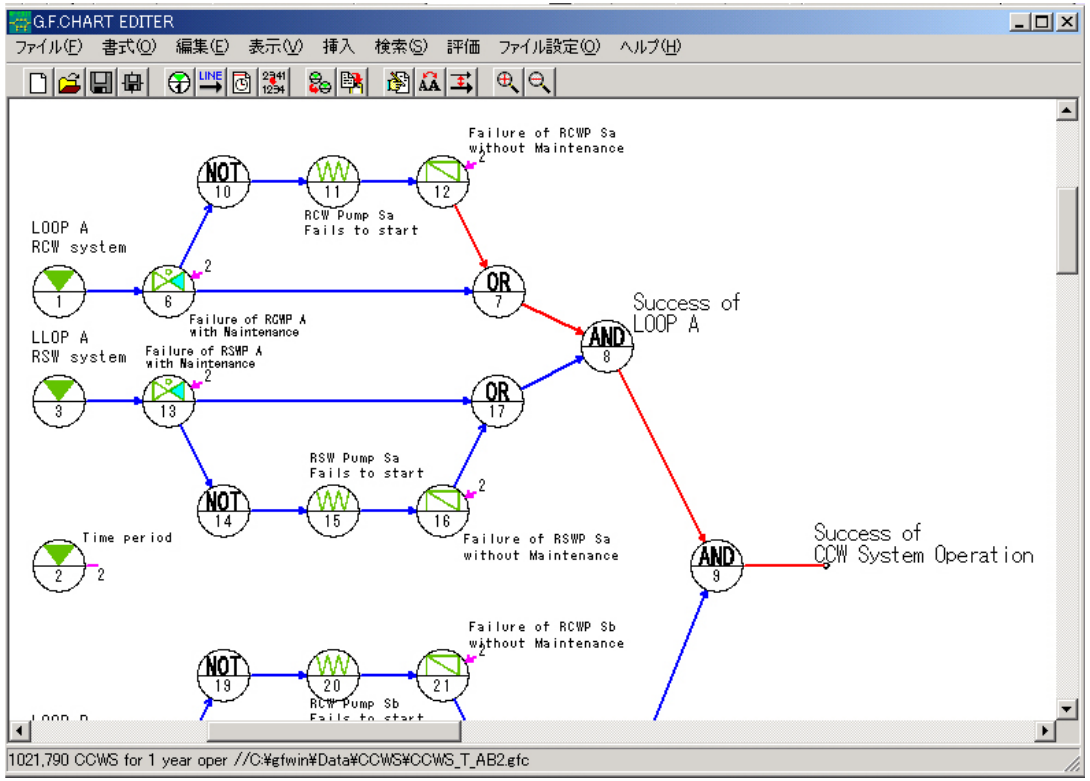
Application of Model Inclusive Learning to Modeling, Analysis and Control Problems in Heliotron J

Possible Research Projects:

- Applications of multiple-pinhole soft X-ray camera for monitoring three-dimensional plasma shape
- Reconstruction of edge magnetic fluctuation spectrum in fusion plasma

(C) Applying a dynamic reliability evaluation method GO FLOW for Heliotron J

- GO-FLOW methodology is a success-oriented reliability analysis technique that is capable to evaluate reliability and/or availability of the systems with complex time-sequence and phased-mission problems.
- The first step of the analysis is to construct a GO-FLOW chart which consists of signal lines and operators to represent the engineering function of the components/subsystems/system composes the engineering system under consideration
- GO-FLOW chart is constructed by using the Chart Editor as shown in the righthand side. During the construction of a chart, component failure data and analysis conditions are necessary to prepare.



Many engineering systems have been analyzed by the GO-FLOW methodology.

Nuclear applications

- A BWR plant system at startup stage with consideration of loop structures and phased mission problem
- Common cause failure analysis of PWR containment spray system
- Estimation of dynamic behavior of nuclear power plant system state under severe accident conditions
- Reliability Analyses of a Self-Holding Type Relay System by a Dynamical Event Tree and the GO-FLOW Methodology

Non nuclear applications

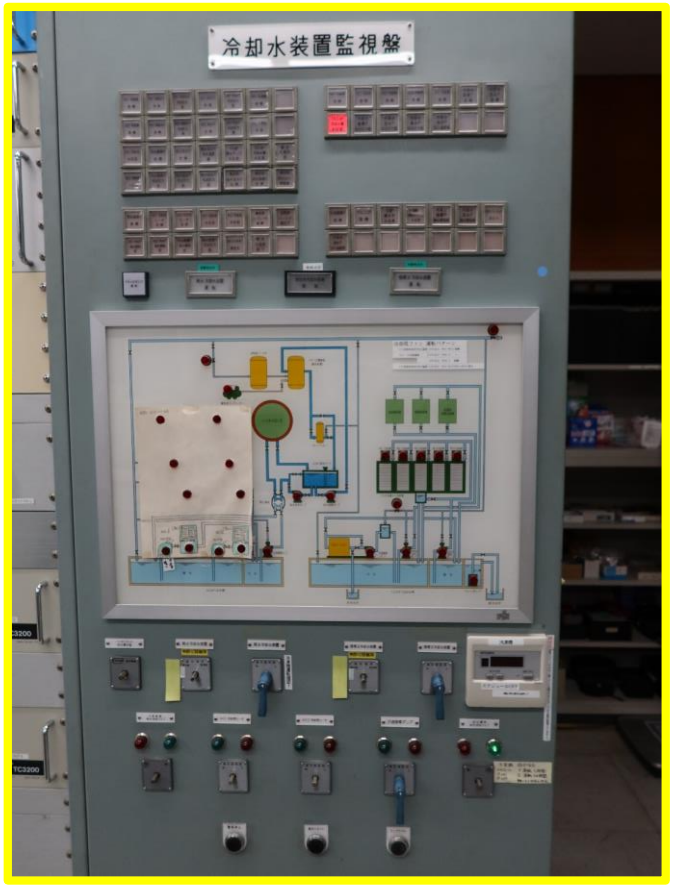
- A distributed energy system consisting of a solar panel, a rechargeable battery and a fuel cell
- Analysis of a Continuously Maintained System
- A Reliability Analysis of Automatic Train Control System of Shinkansen in Japan
- Safety Analysis of Fuel Cell Propulsion System for a 1,500 DWT Cargo Vessel
- Reliability Analysis of Man-Machine System(Holdup Tank System)

Application of the GO-FLOW to Heliotron J

Research plan

- A reliability analysis of water cooling system of Heliotron J, which has important role of the operation of the system.
- Availability of the water cooling system is evaluated for various maintenance schedules for pumps and other essential components. (long range time duration)
- Evaluate the success probabilities of Heliotron J experiments, along with the) n operational sequences. (short range time duration)
- Collects data for the analyses such as Heliotron J's system configuration, Operational condition, Success criteria, Component failure, Demand probability, Human error rates, Occurrence probabilities of external factors, and so on.

Control Board of Water Cooling System for Heliotron J



Further activity plan in 2023

- Conduct on the second group meeting to review the results of the three studies of A, B, C by J. Nitta, Y. Kuroe and T. Matsuoka, respectively.
- Plan to conduct on open workshop to report this year's activity by inviting outside experts.
- Prepare for the next year's cooperative research plan to extend this team's activity.