WENDELSTEIN 7-X TRIM COILS - COMPONENT SAFETY ASPECTS AND COMMISSIONING STRATEGY

K. Risse[1], F. Füllenbach[1], T. Rummel[1], M. Mardenfeld[2], X. Zhao[2]
[1] Max-Planck-Institut für Plasmaphysik (IPP), Greifswald, Germany
[2] Princeton Plasma Physics Laboratory, Princeton NJ USA
Corresponding author e-mail: konrad.risse@ipp.mpg.de

Abstract— **The stellarator fusion experiment Wendelstein 7-X (W7-X) is currently under construction at the Max-Planck-Institut für Plasmaphysik in Greifswald (IPP), Germany. Five normal conducting trim coils have been designed to allow for fine tuning of the main magnetic field during plasma operation. In order to limit the mechanical stresses in the coil, the proper functioning of the coil cooling system must be carefully monitored. Two independent systems will monitor the coil temperature. Additionally, flow monitors in the outlet hydraulic line of each coil will determine if the required cooling water flow is present. The trim coil system will be provided as part of a collaboration program between the Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory and the Wendelstein 7-X project, and is funded by the U.S. Department of Energy.**

Keywords-magnetic field, coils, stellarator, field correction

I. INTRODUCTION

The stellarator fusion experiment Wendelstein 7-X (W7-X) is currently under construction at the Max-Planck-Institut für Plasmaphysik (IPP) in Greifswald, Germany [1][2]. The main magnetic field will be provided by a superconducting magnet system consisting of 70 coils distributed in five identical modules. The coil system will generate a fivefold toroidal periodic magnetic field. However, unavoidable manufacturing inaccuracies can result in small deviations of the magnetic field which disturb the toroidal periodicity. In order to have a tool to influence these field errors five additional normal conducting trim coils have been designed to allow a fine tuning of the main magnetic field during plasma operation [3]. The coils will be mounted on the outer cryostat wall, one coil per each of the five W7-X modules. Due to the relatively large coil size but compact cross section, it is very sensitive to uneven cooling which could cause delamination in the winding pack during current operation. For this reason, safety measures focus on reliable component cooling with two independent fault detection systems. The trim coil system will be provided as part of a collaboration program between the Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory and the Wendelstein 7-X project, and is funded by the U.S. Department of Energy. IPP has received all coils and 3 of the 5 coils are already assembled on the outer vessel (see Fig.1).

II. TRIM COIL DESIGN

A. Trim coils

Five normal conducting trim coils have been designed to fit on the outer surface of the outer vessel of W7-X. Due to construction space restrictions two different coil types were developed: four type A coils and one coil of type B. The type A coil has a nearly rectangular shape with dimensions of 3.5 m x 3.3 m and 48 turns in 8 pancakes (see Fig.1). The 110 x 151mm² coil cross section is comparably compact. The type B coil with dimensions of 2.2 m x 2.8 m is smaller. To compensate, the B coil has a larger number of turns (72 turns) and a higher operational current. The coils were fabricated from a square hollow profile of oxygen free copper, with a side length of 16.26 mm and an inner channel diameter of 10.2mm.

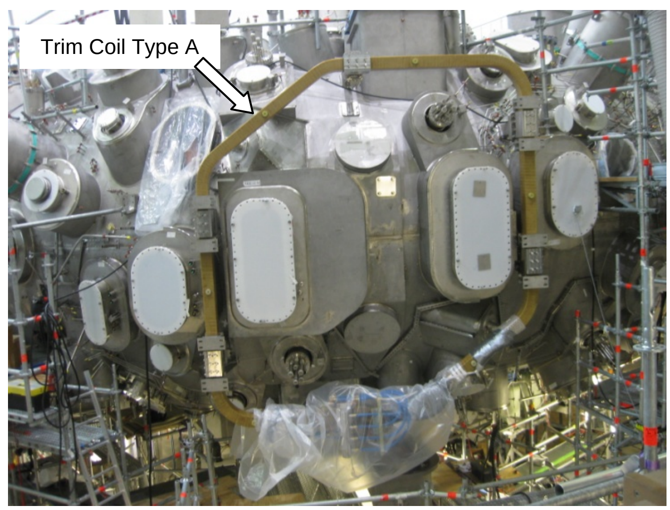

Fig. 1 Type A Trim Coil assembled on outer cryostat wall

The coils are designed to operate with a nominal current of 1.8 kA for type A and 1.95A kA for type B. The insulation system of the coils is designed to withstand the nominal voltages of < 200 V and the test voltages of 2 kV DC to ground while maintaining an insulation resistance of 1 G Ohm. To test the inter-turn insulation, a test voltage of 800 V was applied over the coil terminals. The electrical parameters of the trim coils are presented in Table 1.

B. Coil Cooling System

The coil cooling is designed to have a cooling capacity of 200 kW for the type A coil and 260 kW for type B. This will maintain a temperature difference between the inlets and outlets of 30 K. The Table I explains the main hydraulic parameters of the coils and Fig. 2 illustrates the single pancake cooling principle.

The maximum expected operational pressure of 21 bars occurs within the type B coil. This value considers the pressure drop over the coil (including a 20% safety margin), as well as 6 bars of static pressure and the hydraulic resistances of the cooling water return lines and their safety valve.

TABLE I. ELECTRICAL AND HYDRAULIC PARAMETERS

Electrical and Hydraulic Parameters		
Technical Feature	***Type A***	***Type B***
Number of turns	48	72
Nominal current [kA]	1.8	1.95
Total coil current [kA* turns]	86	140
Total coil conductor length [m]	556	617
Electrical resistance at 20°C [mOhm]	51	56
Nominal voltage [V]	140	173
Dissipated power [kW]	200	260
Temperature Difference inlet / outlet [°C]	30	
Nominal cooling flow [m³/h]	5.3	6.8
Resulting pressure drop [bar]	6.2	9.9

III. SAFETY ASPECTS AND SYSTEMS

Operational procedures must both ensure coil integrity and prevent any risk to surrounding components or people. This section concentrates on the most critical issue for coil integrity while operating with electrical current: potentially uneven cooling of the pancakes or faults in the cooling system. Near the lead region the 30 K temperature difference between the inlet and outlet of the coil occurs within the plane of the cross section. Furthermore, the winding pattern of the conductors creates locations where adjacent turns are 5°C apart, separated only by thin layers of insulation (~ 1 mm). These effects distort the cross section of the coil from a rectangle to a trapezoid, and conductors on the inner diameter of the coil tend to expand more than the outer diameter. Collectively this induces bending stresses and tension normal to the copper insulation boundary [4].

FE analysis performed by PPPL shows that interlaminar shear stress in the insulation system is much closer to the maximum allowable than any other stress quantities. Results displayed in Table II show that an uneven temperature distribution between pancakes can lead to a significant reduction of load cycles, potentially up to a static delaminating failure. The analysis was made under the assumptions of an inlet temperature of 30°C, a temperature rise of 30°C in the non faulty pancakes, and reduced cooling capacity in a single pancake which leads to an increased outlet temperature. The specified requirement is to sustain a minimum of 60,000 load cycles.

TABLE II. FAULT IN ONE PANCAKE EFFECTS LOAD CYCLE NUMBER

Outlet Temp.of faulty pancake	***Cycles to failure***
60 °C	1,390,000
65 °C	122,000
70° C	5,500
75°C	27
75,9°C	1

The results in Table II indicate that a temperature increase of only few degrees can mean the difference between thousands of survivable cycles. For this reason the coil will be equipped with different independent safety systems to monitor the pancake temperature, the cooling water temperature and the presence of the nominal cooling water flow.

In the case of a sudden flow restriction in one of the eight pancakes, the temperature of the faulty pancake will increase, while the temperature of adjacent pancakes remains constant, until the current is shut off. It is recommended that after the current is shut off the cooling circuit flow is also stopped to prevent the faulty pancake from cooling down more slowly than the adjacent turns, which will increase the temperature difference and interlaminar stress.

A. Temperature Monitoring by RTD

In order to monitor cooling water temperature a RTD (Resistance Temperature Device) system with Platinum temperature sensors will be install. The RTDs will be type Pt100 per DIN 60751 and accuracy class A.

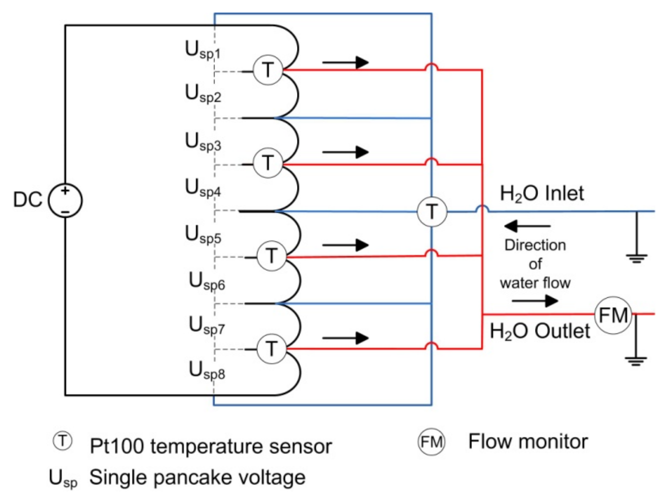

Fig. 2 Schematic cooling circuit with instrumentation

The temperature of the cooling water inlet will be monitored by placing one temperature sensor on the inlet manifold. The instrumentation of the coil outlets must ensure that any atypical water temperature can be detected. For this reason, one temperature sensor plus an additional spare sensor will be positioned onto the conductor profile at the four outlets. These so-called pancake crossovers carry the outlet water of two adjacent pancakes. At this location an average temperature of two neighbouring pancakes is measured, which reduces the sensitivity with respect to a single pancake cooling fault. The time delay of the temperature signal is estimated to be 10 to 15 seconds due to the combined effects of heat conduction through the mass of copper between the sensor and the coolant water and the time response of the Pt100 sensor itself. Due to this limitation, this system is insufficient by itself to adequately detect a cooling fault in one pancake.

B. Pancake Voltage Measurements

A second, independent temperature measurement will be made by using "voltage taps" at the inlet and outlet of every pancake. The average temperature of each individual pancake can then be computed by the central control system from the measured voltage drop across each pancake, the operating current, and the known temperature dependency of the resistivity of copper. Trip points will be set to automatically switch off the coil if temperatures exceed preprogrammed ranges for overall temperature or pancake to pancake temperature differences. Stress considerations restrict the allowed difference in mean temperatures between pancakes within a single coil to < 2.5°C.

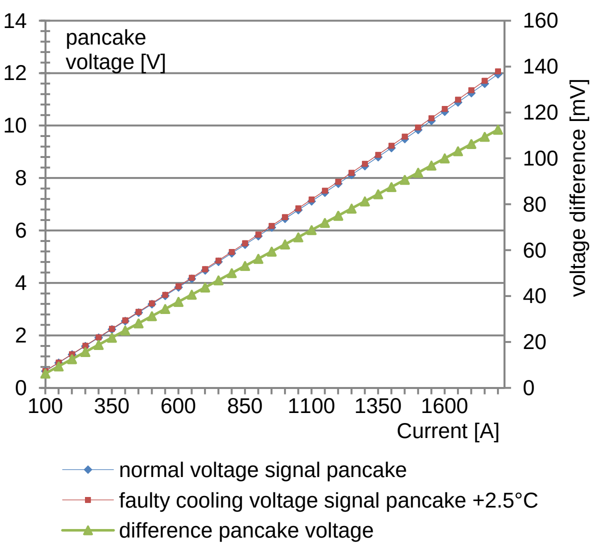

Fig. 3 Type A pancake voltage signals for normal operation and an assumed fault scenario with 2.5°C temperature increase in a single pancake. Water inlet temperature is assumed to be 20°C.

The diagram in Fig. 3 shows that the sensitivity of the voltage system must be in the order of mV to detect the 2.5°C temperature difference at lower currents.

C. Flow Monitor

In the hydraulic outlet line of each coil a flow monitor will be used to detect if the required cooling water flow is present. The trim coil cooling circuit will have a central pump and the five coils will be connected hydraulically in parallel. The pump is designed to provide a 20% margin on the nominally expected flow as given in Table I. During commissioning of the cooling circuits, they will be balanced to a value well above the nominal flow rate, ensuring that the temperature difference between inlets and outlets should be well below the limit of 30°C.

IV. Sensor Data Evaluation

A. I/ O box electronics and control scheme

PPPL has designed and manufactured an Input / Output electronic enclosure (I/O box) which will collects and preprocess the sensor data. Ten Pt100 RTDs, eight voltage signals and one flow monitor will be connected to each I/O box. The core unit is a periphery Simatic ET200M with modules for RTD control, analog data input and one digital input for the flow switch. The electronics will have redundant 24V DC power supplies, as shown in the schematic view in of the I/O box in Fig. 4.

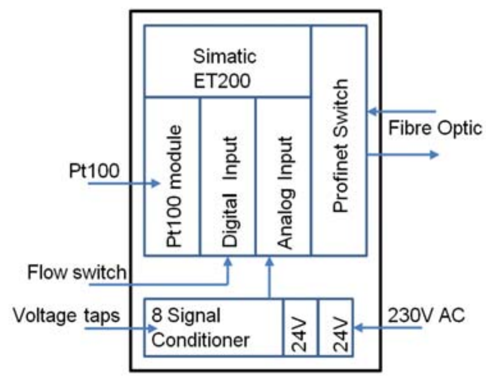

Fig. 4 Schematic view on components in I/O box

The cubicle fulfills the requirements for the electromagnetic compatibility according to class A of standards EN61000-3-2 and EN61326-1. To reduce noise in the voltage measurements cables the cables are shielded with aluminum foil and the distance between coils and I/O box is limited to 9m.

All five I/O boxes and the Superordinated Control Unit (SCU) of the trim coil system will be connected via Profinet fibre optic cables. The I/O boxes and the power supply controls will each be connected in separate circles (see Fig. 5).

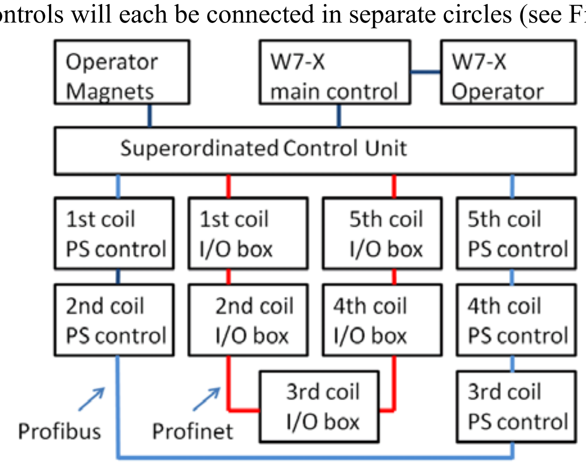

Fig. 5 Control scheme for trim coil system

The Superordinated Control Unit (SCU) is based on Siemens S7© technology, and will handle the remote control of the power supply system and communication with all of W7-X primary control systems. In addition the SCU evaluates the sensor data on the coils and creates a “permit status” for operation of electrical current for each coil. The permit status is continuously reviewed and a visualization system based on WinCC will display it on the operator terminal.

B. Sensor Data Evaluation

The coolant flow, the voltage tap data and the RTD data sets will be evaluated in the SCU to control the permit for operation of electrical current.

The following sensor data must be continuously checked and met to allow operation of current:

I. Flow monitor signal within nominal range

II. T inlet <30°C and T outlet <70°C

III. Δ T between Inlet and Outlet <30°C

IV. Δ T between outlets of individual pancakes <2.5°C

Before the evaluation of the RTD Pt100 sensor data in the SCU starts, the following pre-check has to be made to determine if signals are reasonable: the primary and redundant RTD at the same location shall read temperature signals within 0.3°C of each other, and all the outlet RTDs shall be within a 0.3°C of each other. If the test is successful the following data shall be evaluated to allow an operation permit:

I. Cooling circuit is working, flow monitor signals indicate nominal flow

II. The inlet temperature is <30°C and the outlets are <70°C

III. The difference between inlet and outlet temperatures is <30°C

a) If the temperature at each outlet is within 1.5°C of each other then issue a green or OK permit.

b) If the temperature difference of between any outlets of a single coil is greater than 1.5°C, but they are all within 2.5°C of each other, then issue a yellow or warning permit.

The SCU can evaluate voltage signals by direct comparison of the single pancake voltage drops. A 2.5°C difference in pancake temperature will result in a 1% voltage difference. Differential voltage signals with sufficient magnitude for reliable data evaluation require electrical currents above 600A. For currents below 600 A, the permit for current operation created by the RTD is sufficient by itself. Above 600A the voltage evaluation in the SCU shall follow the following procedure:

I. Flow monitor signal within nominal range

II. Calculate the pancake temperatures via single pancake voltage drops. The pancake temperature must be less than 70°C.

III. Compare the pancake temperatures with the inlet temperature provided by the RTD. The difference must be less than 15°C.

IV. The min and the max values of each pancake’s voltage drop must differ less than 1% from each other.

All listed conditions must be fulfilled to allow current operation above 600A by combining the “partial” permits from the RTD and the voltage system. .

V. Commissioning

During the commissioning phase of the trim coil system, the startup order must be first the trim coil cooling circuits, then the coils with I/O box functionality, then followed by the power supply and its control system, and finally the superordinated control unit with the local magnet operator terminal. During the testing phase the coil current shall be limited. It is expected that the RTD system can be commissioned immediately, while the voltage tap system will need fine tuning to achieve reliable functioning.

VI. Summary

The W7-X stellarator will be equipped with five additional trim coils to be mounted on the outer cryostat wall. The trim coils are normal conducting water cooled copper coils and will be individually controlled by separate power supplies. Two independent safety systems will permanently evaluate RTD readings and voltage signals in real time to guarantee the thermal stress in the coil is within acceptable limits. Additional flow monitors in the outlet of each coil will guarantee the presence of nominal cooling water flow during current operation. The trim coils and the related power supplies will be contributed within the framework of a collaboration program between PPPL, Oak Ridge National Laboratory and the Wendelstein 7-X project and are funded by the U.S. Department of Energy. The company Everson Tesla Inc. has manufactured and delivered the five trim coils. The first three type A coils are already assembled on the outer vessel. The I/O boxes are at IPP and the control logic for the superordinated control unit will be developed by IPP.

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