stellarator news
Published by Oak Ridge National Laboratory
Building CR 5600 P.O. Box 2008 Oak Ridge, TN 37831-6169, USA
Editor: James A. Rome Issue 146 December 2014
E-Mail: jamesrome@gmail.com Phone (865) 482-5643
On the Web at *http://www.ornl.gov/sci/fed/stelnews*

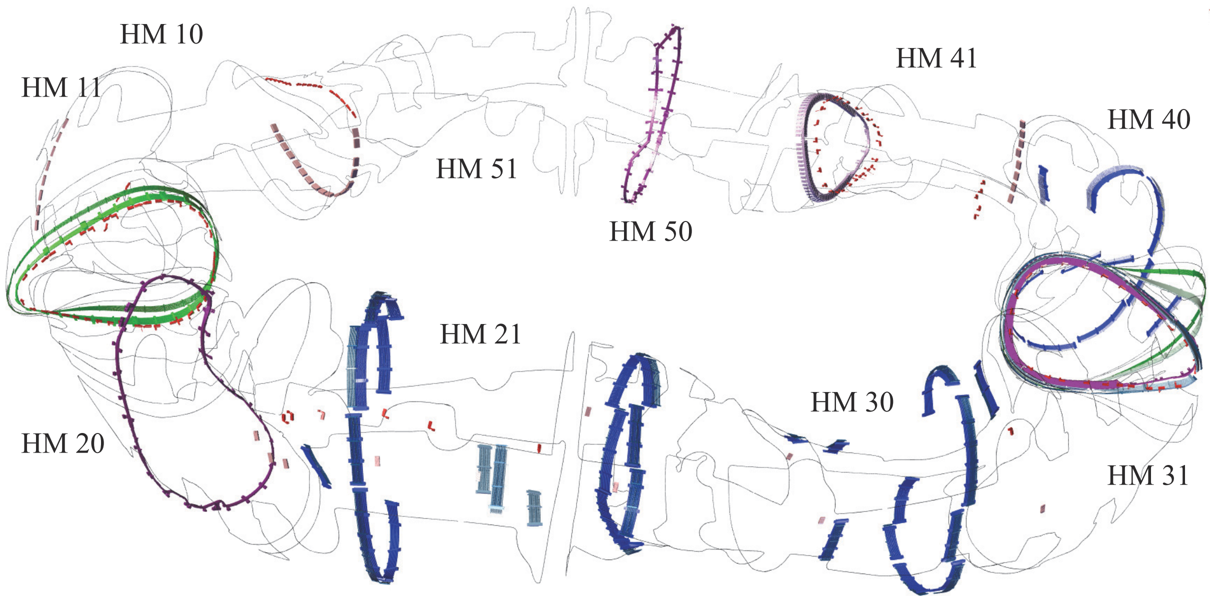

Fig. 1. Complete set of W7-X magnetic diagnostics. For color code see text. The numbering of the 10 half modules (HM) of W7-X is indicated. The pick-up coils shown in lighter shades of color are additional coils which may be installed at a later stage.

Installation of magnetic diagnostics for W7-X completed

This summer, the integration of the magnetic diagnostics for Wendelstein 7-X (W7-X) operation phase 1 (OP1) into the core device was completed. The entire set is shown in Fig. 1. The magnetic equilibrium diagnostics are

- ⇨ an almost symmetric set of 40 saddle coils on the outside of the plasma vessel (PV) (black in Fig. 1),
- ⇨ three Rogowski coils in triangular planes (two on the outside of the PV, one inside the PV, green in Fig. 1),
- ⇨ five sets of poloidal magnetic field probes (also called segmented Rogowski coils), two of which are in a triangular plane and three in near-bean-shaped planes (most sets consist of a subset on the outside of the PV and a subset inside the PV in matching positions; blue in Fig. 1), and
- ⇨ three diamagnetic loops inside the PV, two in near-bean-shaped planes and one (with compensation coils) in a triangular plane (violet in Fig. 1).

In addition, there are 125 Mirnov coils, most of them arranged to form one partial and three complete poloidal arrays in triangular planes (red in Fig. 1).

In this issue . . .

Challenges in the design of the W7-X magnetic diagnostics

Because classical pick-up coils were chosen for the magnetic equilibrium diagnostics, their signals must be integrated in time to know the magnetic flux at each moment of the discharge. Although offset voltages in the coil circuits can be determined before the start of a plasma discharge, even a small change or drift in these voltages will affect the integrated signal strongly in a long-pulse discharge (W7-X is designed for discharges of up to half an hour). It was demonstrated that the required long-pulse accuracy can be achieved in the electronics part of the coil circuits [1], by using a chopper stage at the front end, which periodically reverses the polarity of the input signal. Drifts of offset voltages in the rest of the coil circuit (e. g., thermovoltages) can not, as a matter of principle, be distinguished from "true" signals and must still be kept to a minimum. The integration is performed numerically after digitization of the signals.

The pick-up coils located inside the PV can be exposed to a significant level of stray 140 GHz electron cyclotron resonance (ECR) radiation, since ECR heating (ECRH) is the main heating system of W7-X, and some of the heating scenarios work with low single-pass absorption. In order to achieve a high winding density, classical polyimide-insulated winding wire was used for the in-vessel equilibrium diagnostics. The microwave absorption of polyimide is high, and the windings must be shielded from the stray ECR radiation.

An additional thermal load on the in-vessel magnetic diagnostics originates from the back faces of the wall protection elements, which are located between the plasma and the PV wall and which will receive plasma radiation and convective loads from the edge plasma.

To summarize, the harsh environment inside the plasma vessel requires a design providing good microwave shielding, low microwave absorption of the shielding, and either active cooling or good thermal contact with actively cooled components, or else the capability to operate at high temperatures (of the order of several 100 C).

In the design of the ECR stray radiation shielding and the heat conductors, these structures must not strongly influence the signals recorded by the respective pick-up coils. Since Cu provides both ECR shielding at low absorption and good thermal conduction, it is the preferred material, but eddy current coupling to the windings would damp and phase-shift the recorded signals too strongly above some boundary frequency. In order to achieve a time resolution of the order of 1 ms for the diamagnetic loop and its compensation coils in the triangular plane and for the in-vessel Rogowski coils, the heat conductors are arranged perpendicular to the windings. The PV is used as the heat sink, and the pick-up coils are attached to it by adapter blocks with custom shaped surfaces designed using information obtained from local laser scans of the PV surface.

An alternative approach is chosen for the Mirnov coils: A high winding density is not desired for them, and a metallic ECR shield would be particularly harmful due to the high frequencies to be measured. Therefore, a Konstantan® wire is wound on an aluminum nitride (AlN) coil former, which is attached to the cooling pipes of the wall protection elements by a CuCrZr clamp (see Fig. 2). The coil former can tolerate heating to peak temperatures of 460° C, according to ANSYS® finite element simulations, in spite of the high heat conductivities of AlN and CuCrZr.

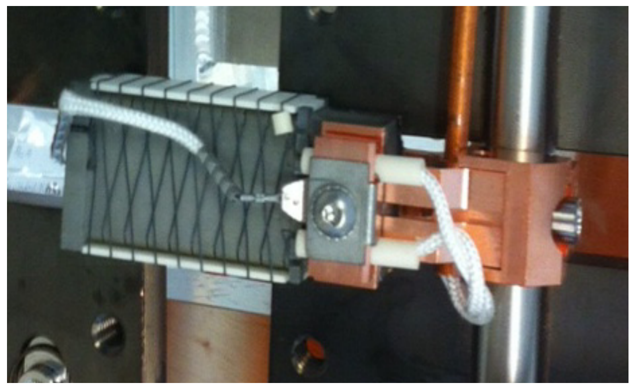

Fig. 2. Mirnov coil attached to a cooling pipe of the wall protection elements by a CuCrZr clamp (right). The Konstantan® winding wires of the two winding layers continue through a Cu pipe (toward the top right, parallel to the cooling pipe). Inside the Cu pipe, the two wires are twisted and insulated by silicate sleeves (visible in front of the CuCrZr clamp).

During the engineering design activities, mock-ups and prototypes of the different coil designs were tested in a pair of Helmholtz coils to assess their electromagnetic response, in the MISTRAL test chamber to assess their microwave resilience [2, 3], and in a vacuum chamber equipped with a special thermoelectric heater to assess their heat conductance.

In-vessel continuous and segmented Rogowski coils

In Fig. 3, an in-vessel Rogowski coil segment is depicted during assembly. It consists of 10 solenoids, each with 2 winding layers on a stainless steel tube as core. The solenoids are connected electrically in series. Each solenoid is inserted in an outer stainless steel tube with 0.25 mm wall thickness that serves as a stray ECR radiation shield. This wall thickness is chosen to preserve sub-1 ms time resolution and to allow bending the solenoid into proper shape. The shapes were individually designed for a total number of 452 in-vessel solenoids, due to the strongly three-dimensional (3D) shape of the PV. After solenoids were bent, each segment was assembled on an individual rig with the end and intermediate holders used to attach it to the PV. Between the stainless steel shielding tubes, Cu profiles are clamped; these will conduct the heat deposited on the surface of the shielding tubes to the end and intermediate holders, where it is transmitted to the PV through the Cu adapter blocks. The heat conductance of the thin stainless steel shielding tubes is entirely insufficient for this purpose, but the use of tubes with sufficiently high heat conductance in the longitudinal direction (e.g., made from Cu with a larger wall thickness) would also increase the electric conductance parallel to the winding (i.e., around the tubes) to intolerable values.

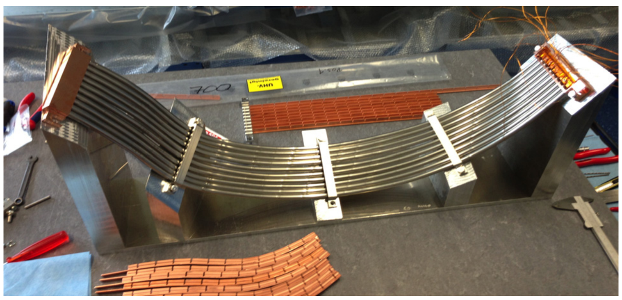

Fig. 3. Assembly of an in-vessel Rogowski coil segment on a purpose-built rig. The surfaces of the supports at the end and intermediate holders correspond to the surfaces of the Cu adapter blocks to which the segment will be mounted in the plasma vessel. The Cu heat conduction rails (lower left) are ready for insertion between the individual solenoids.

In one of the end holders, which is later closed by a Cu cover for microwave screening, the winding wires are crimped to signal cables, which run in Cu tubes and Cu cable ducts to the vacuum feedthroughs at the ports, such that continuous microwave screening for the polyimide-insulated cables and wires is established.

Inside some of the core tubes, Pt1000 sensors are placed for temperature surveillance in locations where the most critical thermal loads are expected. For the continuous Rogowski coils, segments of this type are lined up poloidally in a closed circle with the poloidal gaps between adjacent segments minimized. The individual segments in this case are electrically connected in series. In the segmented Rogowski coils, each segment is contacted individually by its own signal cable. Whereas the continuous Rogowski coils are optimized for measuring the total plasma current through their openings, the segmented Rogowski coils provide additional information on the poloidal and also the radial distribution of the plasma current density.

Diamagnetic loop with compensation coils

As a second example, the triangular plane diamagnetic loop is shown in Fig. 4 in a folded state and after installation inside the PV. The articulated design was chosen to make it possible to complete the winding of the main loop outside the PV and to transport the coil to its positions inside the PV through a narrow port. The introduction of multi-pin connectors between different sections had been discussed as an alternative, but the thermovoltages at these connectors were found to introduce intolerably large uncertainties in long-pulse integration of the signals.

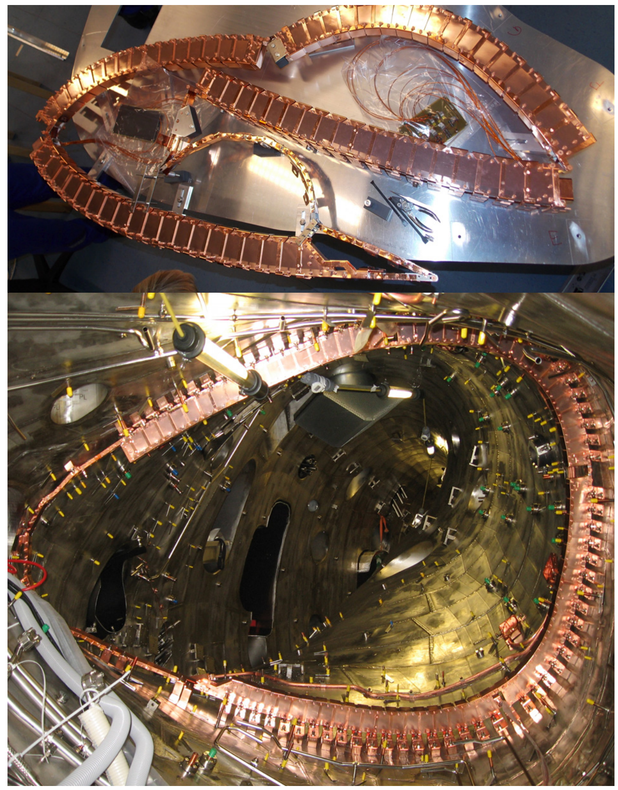

Fig. 4. Diamagnetic loop in fully folded state (top) and after integration into the W7-X plasma vessel in a triangular plane (bottom). This loop consists of four sections with compensation coils and a short flat section with the main loop only (to the left in the bottom view), where the available space between plasma vessel and wall protection elements was insufficient for a further compensation coil. In the bottom view, the wall protection elements are not yet installed.

In the sections with compensation coils, the structural elements are side walls laser-cut from a ceramic fiber-reinforced ceramic (Keramikblech®) with 3 mm thickness (see Fig. 5). The winding area of the compensation coils is perpendicular to the toroidal direction. Therefore, eddy currents in highly conductive side walls would reduce the time resolution of these coils. The stray ECR radiation shielding is therefore manufactured from 0.1 mm stainless steel sheets that are plated on the outside with 3 μm Cu to reduce the microwave absorption. Nevertheless, the heat conductance of the thin stainless steel sheets is still insufficient. Therefore, there is a 10 mm × 4 mm cross-section Cu heat conductor on each side, every 50 mm poloidally along the loop that directly connects to a Cu adapter block bolted to the PV. The high electric conductance in radial direction does not affect the time resolution of the compensation coil, since its winding runs in poloidal direction for most of its length. Additional 1 mm Cu heat shields are located toward the back faces of the wall protection elements, such that thermal radiation from these elements does not hit the 0.1 mm stainless steel ECR shielding. Each of the Cu heat shields is directly attached to two of the heat conductors on the two sides of the loop, and poloidal gaps between the individual heat shields prevent their high electrical conductance from jeopardizing the time resolution of the compensation coils.

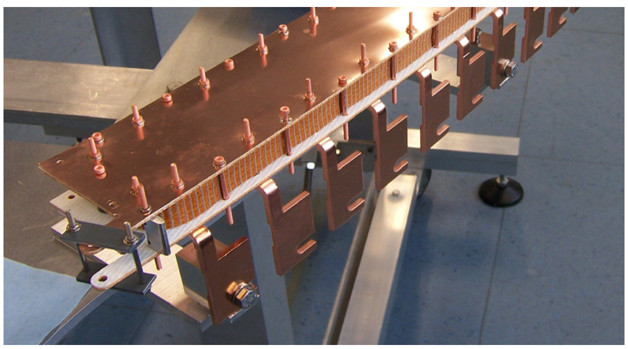

Fig. 5. Assembly of a compensation coil section of a diamagnetic loop. The side walls of 3 mm ceramic fiber-reinforced ceramic (white) are covered on the outside by 0.1 mm stainless steel sheets with a 3 μm Cu layer. The windings are formed by 25-wire ribbon cable with the individual wires connected in series. The pivot connecting to the next section is visible at bottom left. The winding of the compensation coil is already installed; the winding of the main loop (one further layer of ribbon cable) is installed once the sections of the loop are connected. Finally, the opening between the side walls is closed by further 0.1 mm stainless steel sheets with a Cu layer. At the bottom of the section, the heat conduction rails/brackets of 4 mm Cu are visible They provide for attachment of the entire structure to the PV via Cu adapter blocks. The heat conduction rails/brackets on the top are not yet installed.

Outlook

Presently, the signal cables from the vacuum feedthroughs to the positions of the electronic and data acquisition cubicles are laid, and the electronics and data acquisition equipment are prepared. As soon as these are functional, the integration of the magnetic signals into the W7-X machine control system will start.

Two calibration phases are foreseen: First, the signals generated by changes in the field coil currents will be recorded in order to be able to distinguish them from signals generated by plasma currents during discharges. In addition, it is planned to introduce specially designed exciter coils into the plasma vessel, in particular to explore the influence of eddy currents in in-vessel components on the signals recorded by the magnetic diagnostics.

Acknowledgement

From the first drafts of the W7-X magnetics in 1999 to this date, some 60–70 colleagues at the IPP Garching and Greifswald sites contributed significantly to the realization of these diagnostics, with the support of many staff at external suppliers. Most of the time, the core team consisted of 2–3 physicists, 1–3 engineers, 3–5 designers, and 2–5 technicians. Without the accurate work of all these people it would not have been possible to build these complex diagnostics and to integrate them into the W7-X device.

References

[1] A. Werner, Rev. Sci. Instrum. **77**, 10E307 (2006), [Proc. 16th Topical Conf. on High-Temperature Plasma Diagnostics, Williamsburg, VA, USA, 7–11 May 2006].

[2] M. Hirsch et al., The impact of microwave stray radiation to in-vessel diagnostic components, in Proc. of the Int. Conf. on Fusion Reactor Diagnostics (9–13 September, 2013, Varenna), 2013.

[3] D. Hathiramani et al., Fusion Eng. Design **88**, 1232 (2013), [Proc. 27th Symp. Fusion Technology (SOFT-27), Liege, Belgium, 24–28 September 2012].

Michael Endler for the W7-X Magnetics Team
E-mail: michael.endler@ipp.mpg.de
Max Planck Institute for Plasma Physics,
Wendelsteinstr. 1,
17491 Greifswald, Germany