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W7-X magnetic diagnostics: Rogowski coil performance for very long pulses[a)]

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Stellerators can be operated without the need of significant plasma current for generation of poloidal magnetic field components. Wendelstein 7-X (W7-X) is optimized for stiff magnetic configurations by minimizing pressure driven currents, such as bootstrap and Pfirsch–Schlüter currents. In Addition to the largely reduced plasma currents, the HELIAS-type device is a low magnetic shear configuration required for magnetic boundary islands. However, the diverting magnetic field structure is already influenced by small net plasma currents. In particular, the W7-AS divertor results revealed a significant sensitivity of the *X*-point location with respect to favorable edge plasma states. Thus, a precise *X*-point control for W7-X is envisaged and, although expected net plasma currents range in the order of 10–100 kA only, stabilization by adaptive controllers is foreseen to an accuracy of about 1 kA. This stabilization should be reliable even after 2000 s of plasma operation. A precondition for achieving this is a reliable current detection. For this purpose, W7-X will be equipped with Rogowski of which the first has now been assembled onto one of the plasma vessel sectors. The integral performance and sensitivity inhomogeneities have been tested by employing the digital integrator of W7-X [A. Werner, Rev. Sci. Instrum. **77**, 10E307 (2006)] and a cable energized with 200 A, representing the plasma current. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2957933]

INTRODUCTION

The basic concept of the Wendelstein 7-X (W7-X) magnetic configuration is to minimize all plasma driven internal currents, i.e., the Pfirsch–Schlüter currents for a stiff magnetic configuration with respect to the plasma pressure and the bootstrap currents for reduced changes in the edge rotational transform. In this way, W7-X is expected to have a reduced Shafranov shift and a robust island divertor configuration, respectively.[1] However, W7-X is a low magnetic shear device, meaning that slight changes in the total plasma current may lead to measurable changes in the distance between the *X* point and the target plate distance. Calculations of the magnetic configuration with an on-axis current revealed a change of 2.5 cm in the *X*-point position at a plasma current of 10 kA, which is approximately half the envisaged distance from the *X* point to the target (Figs. 1 and 2). Island divertor experiments at W7-AS revealed that this distance is crucial for achieving favorable edge plasma conditions, in particular, for the partially detached edge plasma state needed for reduced power loads onto the target tiles.[2]

The operation of W7-X will be even more demanding, since steady state operation not only depends on the plasma edge control for physics reason as mentioned above but also on the avoidance of overloading plasma facing components. W7-X is not equipped with an Ohmic transformer, thus allowing only two means for the compensation of bootstrap currents. Either the vacuum magnetic field is adjusted to compensate for the net current contribution to the edge rotational transform or the net current is compensated by electron cyclotron or neutral beam injection current drive. Both variants require precise knowledge of the plasma current with an accuracy better than 1 kA. A further challenge is the requirement to achieve this accuracy even after 30 min of plasma operation.

W7-X relies on the use of well proven diagnostic techniques. The plasma current measurement employs Rogowski coils poloidally enclosing the plasma column in order to be sensitive enough for small current changes and to have a robust and reliable sensor, despite the drawback that inductive methods are not inherently steady state capable. Steady state current sensors such as birefringent optical fibers for plasma current measurements by means of Faraday rotation or arrays of Hall probes are not well proven for the highly three dimensional (3D) shaped stellarator configuration. However, such techniques will be investigated in a later stage of the W7-X operation.

REQUIREMENTS AND BOUNDARY CONDITIONS ON THE ROGOWSKI COIL

The basic concept of making inductive sensors capable for very long pulses is to maximize the raw signal by a large winding area and to reduce the long term drift of the subsequent signal integrator. The latter has been already achieved as discussed in Ref. 3. Nevertheless, error voltages caused by

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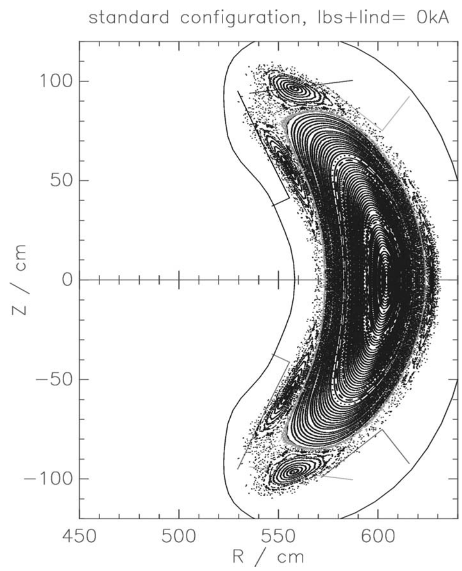

FIG. 1. Poincare plot of the W7-X standard magnetic configuration at $\langle\beta\rangle = 3\%$, calculated using VMEC and the w7 version of the EXTENDER code (Ref. 5). The vessel shape and divertor structure are indicated by solid lines.

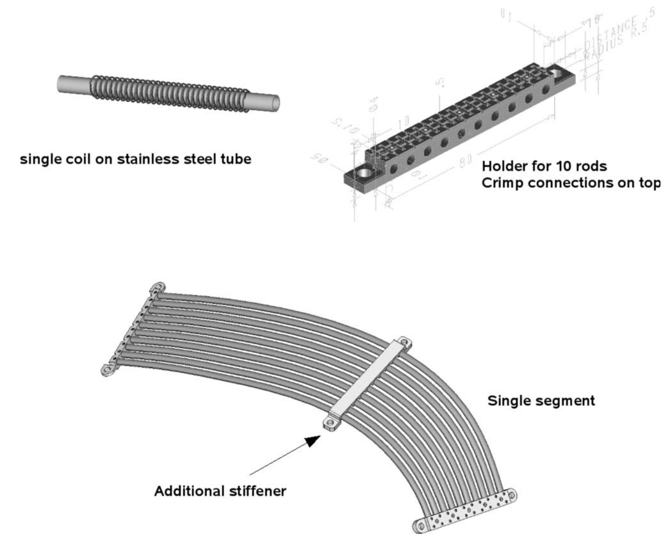

FIG. 3. Components of the flat Rogowski coil.

thermovoltages, creeping currents, and other effects will lead to some finite drift of the integrated signal. Even integrators themselves introduce such drifts. All these effects and integrator types have been discussed in Ref. 4. An overall accuracy of 1% is envisaged with respect to the nominal plasma current value. This accuracy should not only apply to the temporal evolution of the error but also to the variation with the spatial plasma current distribution.

Maximization of the raw signal is a challenge even in the case of the large stellarator W7-X since space is restricted in both the region outside the plasma vessel beneath the multilayer insulation of the cryostat and inside the plasma vessel beneath the first wall elements. Typical dimensions in height are of the order of 10 mm. In the lateral extension, that is, approximately the toroidal direction, space of up to 100 mm has been made available, which is challenging to the Rogowski coil design, since the poloidal circumference changes significantly on both edges due to the 3D shape of the plasma vessel. Nevertheless, taking the expression for the induced signal of the Rogowski coil:

$$U_{\mathrm{Rogo}} = \oint U dl = -An_l \oint \dot{\vec{B}} d\vec{l} = -\mu_0 A n_l \dot{I}_{pl},$$

only the winding density n_l and the coil cross section A can be maximized, the latter with the restrictions mentioned before. The increase in the winding density can be achieved by a tightly wound coil and by the reduction in the wire diameter. The limit in lowering the wire thickness is given by the overall Ohmic resistance. A low inner resistance of the voltage source reduces the integration errors by creeping and radiation induced currents and improves the common mode rejection ratio (see Refs. 3 and 4).

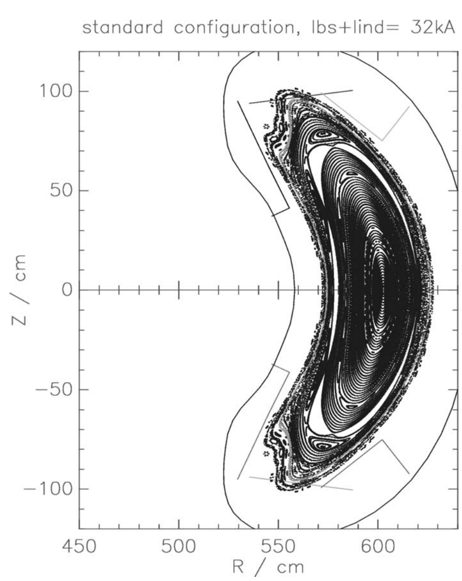

FIG. 2. Same as Fig. 1 but with 32 kA net plasma (bootstrap) current.

COIL DESIGN AND CONSTRUCTION

The W7-X Rogowski coil has to adapt its shape to the 3D shape of the plasma vessel, has to be flat, and must ensure a well defined cross sectional area. Furthermore, considerations in how to manufacture a 3D shaped coil have considerably influenced the final design which is based on an array of single stainless steel tubes serving as the coil bobbin. These tubes of 5 mm diameter and 1 mm wall thickness can be bent by hand. This has the major advantage that the double winding layer can be wound on the straight rod, allowing to use a winding machine for achieving a high degree in homogeneity. The wire itself is a polyimide (Kapton) insulated copper wire of AWG 24 with 1% tolerance in diameter. The single coils can be bent afterwards manually to shape them as given by a template that has been manufactured according to the computer aided design data. ten single coils form a poloidal segment of the Rogowski coil with an appropriate shape and are fixed in holders at the end. These holders are used to mount each segment onto the plasma vessel and fix a very flat connector box (Fig. 3).

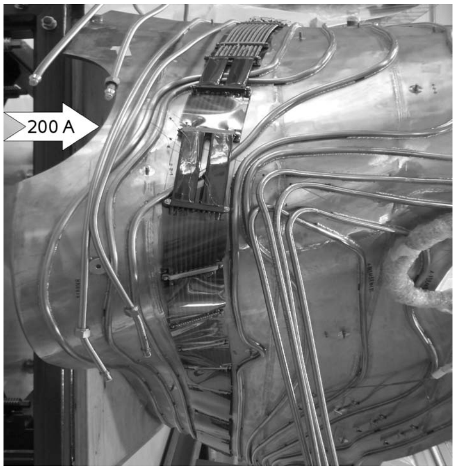

FIG. 4. Assembled Rogowski coil with indicated fed of the 200 A cable.

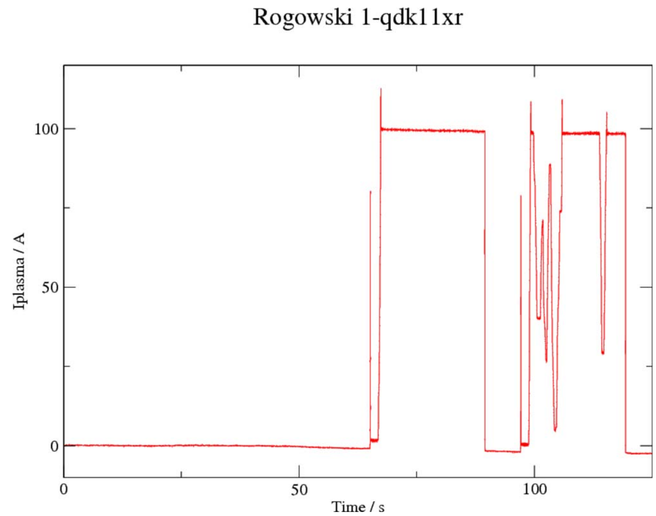

FIG. 5. (Color online) Induction test of the Rogowski coil using a 200 A cable representing the plasma current (the current has been varied randomly for the time integration test). The coil itself is split into two parts; thus the full current level belongs to a 100 A plasma current. The time until 55 s is used for a drift correction of thermovoltages. After further 70 s operation, the baseline is approximately 3 A off zero.

After each segment has been mounted onto the plasma vessel, all the single coils are connected in series by means of crimp connectors. This type of connection has been considered to be the most reliable one compared to soldering, screwing, clamping, and cold pressure welding.

In order to ensure the quality of the coil, each single coil is tested several times during the manufacturing process. After the single straight coils have been wound, the winding density homogeneity is tested using an induction method. An exciter coil is used as a primary winding and moved along the single long coil. The whole setup acts as a transformer without an iron core. Although the transformer ratio deviates strongly at the ends due to the primary magnetic flux not intersecting the secondary coil, for most of the inner coil section, it yields the homogeneity and the calibration factor of the single coil, in particular, compared to neighboring single coils. Furthermore, the insulation is tested by applying a voltage of 2 kV in order to find defects of the wire insulation. However, the maximum voltage expected during operation does not exceed 60 V in the worst case, that is, the quench and fast discharge of the superconducting magnets. The tests are repeated for the bent single coils and the insulations tests are performed again after the final assembly.

PERFORMANCE OF THE ASSEMBLED COIL

In the meantime, the first Rogowski coil has been mounted on the outside of the W7-X plasma vessel. Overall performance tests have been made using a cable that has been energized with a current of 200 A. This cable was fed through the open vessel sector in the assembly stand of the so-called half-modules (W7-X consists of five vessel modules, Fig. 4). The Rogowski coil has been connected to the digital integrator prototype with a data acquisition and analysis application running on a Linux computer (as described in Ref. 3). The signal cable, however, has been connected simply by some electrical clips that cause some thermovoltages and, thus require some thermal equilibration time of about 5 min after making the connection. Figure 5 shows a time trace of such a performance test. The first 55 s are needed for the digital thermovoltage correction. After this calibration phase, the current has been fed approximately for 70 s. During this time, the drift of the current signal is less than 3 A, which is a promising value for the envisaged plasma operation for about half an hour. A linear extrapolation would lead to a deviation of around 70 A, which is by far better than the required accuracy of 1 kA for magnetic configuration control. However, if at some stage the conductor materials do not have exactly the same material properties, temporally changing thermovoltages might cause a nonlinear evolution of the drift, in particular, due to the temperature increase in the vessel by plasma heat loads. This effect cannot be quantified yet.

A further performance test has been made by spatial variation in the exciter cable position. In particular, at positions close to the segment connectors, a gap of around 20 mm in the winding causes a drop in the induced signal. The strongest variation has been detected in regions where many connector voids are closer due to short coil segments. Nevertheless, such deviations have been predicted by simulations for an absolutely localized current. Of course, such localized currents will never occur, in particular, if the plasma current is distant to the coil segments and spread over a wider area. The situation is less clear for currents flowing in the plasma vessel, e.g., due to divertor misalignment. Such currents might reach a level of a few kiloamperes and could become poloidally localized by port holes in the vessel structure. In order to estimate this level, a corresponding Rogowski coil mounted inside the plasma vessel allows for correction of such errors.

Finally, an absolute signal level of 120 μV s has been predicted for the half-coil at a current value of 200 A according to the expression

$$-\int U dt = \mu_0 A n_l I_{pl} = (4\pi \times 10^{-7})(3.08 \times 10^{-4}\ \mathrm{m}^2) \times (1560\ \mathrm{m}^{-1})(200\ \mathrm{A}) = 120\ \mu\mathrm{V\ s},$$

with A the double layer averaged winding area and n_l the maximum achievable winding density (inverse of the wire thickness). The performance tests with the cable being positioned at the plasma vessel center reveals a measured value of 112 μV s with a variation of +1.7%/−6.8% when the current carrying cable is moved close to the plasma vessel wall. The maximum value of 117 μV s is achieved close to the middle section of a long segment, whereas the minimum of 109 μV s is observed in the region with a higher cumulation of the 20 mm voids in the winding due to connector boxes. The difference in the maximum value to the predicted one can be easily explained by an additional average interwire spacing of 20 μm. Taking the maximum value as the best achievable winding density, the voids between segments already explain the measured average value simply by reducing the effective winding length by the length of voids [117 μV s(1−0.24 m/6 m)=112 μV s].

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