Status and prospects of the MHD diagnostics at Wendelstein 7-X stellarator

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The Wendelstein 7-X (W7-X) stellarator in Greifswald has accomplished its first operational phase (OP1.1) starting December 2015 until March 2016. In order to protect the in-vessel components, on which the graphite tiles as well as the divertor units will be installed before the next experimental campaign, a heating energy limit of 4 MJ per discharge had been imposed. A specific magnetic configuration (“J”) was chosen for a safe operation with the installed limiters, which provides closed flux surfaces up to limiter and beyond. Flux surface measurements in this configuration have been performed prior to the start of OP1.1 and the quality of the vacuum magnetic field has been found to be in very good agreement with the predictions [1]. It should be noted, that the configuration J is insensitive against potential (n,m) = (1,1) error fields, since the rotational transform is below $\iota=0.87$ (cf. Fig 1). The plasma performance has been very good, especially after He glow discharge when the machine wall conditioning was at its optimum [2].

During OP1.1, the equilibrium conditions for the plasma profiles could be reached only partially. With energy confinement times of ~150ms [3] the plasma energy could reach equilibrium conditions depending on the heating scenario discharge length and density evolution. However, the plasma current was far from reaching steady state condition since W7-X is lacking an ohmic transformer and the total plasma current evolution is governed by the L/R-time ($\tau_{L/R} \sim T^{3/2} > 20$ s for $T_{e,0} \approx 8$keV). Also the internal current density distribution is still evolving in discharges with lengths of 1s or below, since the resistive skin time (indicative for the redistribution of the plasma shielding currents) is of the order of 1 s. Stored plasma energies of up to $W_p = 500$ kJ (measured by the compensated diamagnetic loop [4]) and a finite central beta of $\beta_0 = 2$ % at full magnetic field of 2.5 T have been achieved. The beta value were derived from the electron temperature profiles by electron cyclotron emission (ECE) and Thomson scattering (TS) diagnostics and density profiles from TS and XICS diagnostics [5,6,7]. Using the MHD equilibrium calculation code VMEC [8], a small Shafranov-shift of the central flux surfaces is expected ($\delta \approx 3.4$ cm at $\varphi = 36°$, cf. Fig 2). In a joint activity of the theory department and the experimental MHD group at W7-X, a set of

VMEC equilibria are available as reference configurations in a central repository. To make the equilibrium information available to non-specialists, access to it is provided via web-service interface which returns, for example, flux surfaces, profiles, magnetic field components and performs mappings.

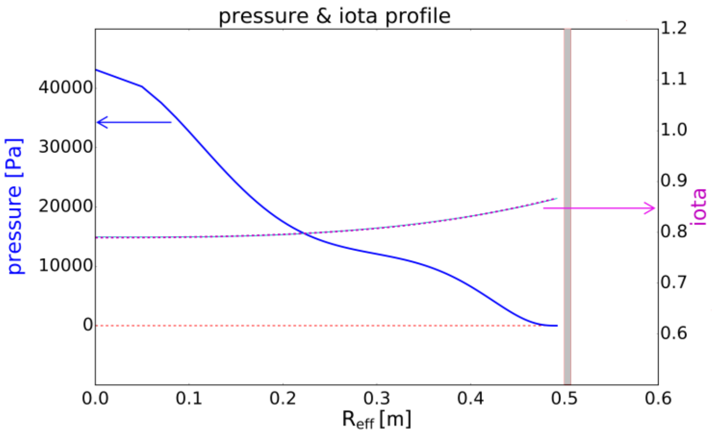

Fig. 1: Profiles of plasma pressure and iota versus effective radius. The limiter radius is at R_{eff}=0.5 m. *The pressure profile is modeled considering experimental profiles from TS and ECE.*

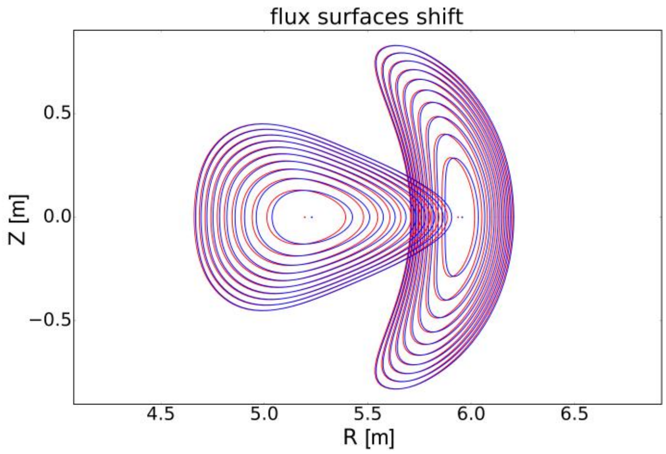

Fig. 2: Configuration J: Shafranov shift calculated by VMEC considering a pressure profile (blue, β_0=2%) *according to Fig. 1 with respect to the vacuum case (red). The plot shows the triangular* (φ= 36°) *and the bean shaped flux surfaces* (φ= 0°).

Equilibrium MHD & Stability The available magneto-hydrodynamic (MHD) diagnostic systems during the first operational phase were the magnetic pickup diagnostics, i.e. diamagnetic loops, saddle coils and Rogowski coils. During the start of OP1.1, these diagnostics and their data acquisition systems have been commissioned and the diamagnetic loops as well as a set of saddle coils have been calibrated during magnetic field ramps of the super-conducting field coils and the trim coils. The available magnetic probes and their commissioning are described in more detail in Ref. [4].

Without fast particle sources by neutral beam or ion cyclotron resonance heating during OP1.1 and due to the small current amplitudes in the Wendelstein 7-X stellarator (minimization of Pfirsch-Schlüter (PS) & bootstrap current [9]), the main source of free energy is the pressure gradient. Current and particle driven instabilities are not expected to play a significant role. Thus, a significant part of instabilities usually observed in fusion devices is not expected to be present in OP1.1. Nevertheless, significant internal current densities can be driven by the ECRH when performing EC-current drive (ECCD) experiments [10]. In Fig. 3 time traces of a W7-X experimental program with ECRH current drive (ECCD) are shown. The current is driven in the co-direction with respect to the bootstrap current. The plasma energy reaches saturation after approx. 700 ms ($\tau_E \approx$ 100ms), whereas the toroidal current increases during the phase of plasma heating (and constant EC current drive). After the end of the heating, an apparent overshoot of the total current occurs, caused by the dynamic of the shielding currents in the plasma. Those currents are redistributed and decay on different time scales (resistive skin time is not constant over the plasma). These signals show a splitting into two groups (upper and lower curves) which indicates the dipole structure of the fields generated by the PS-currents. The obvious drift towards positive values of all signals is due to the increasing net-current. A more detailed analysis might be able to reveal some parts of the dynamic of the internal current density distribution.

A prominent MHD feature has been detected by a range of diagnostics, including ECE, reflectometry, fast cameras and Mirnov coils, which all consistently observe a mode frequency in the range below 10 kHz. Combining the radial information from ECE [11], which finds the location of the maximum at a radius of around R_{eff} = 0.25 m and the poloidal information from the available Mirnov coils, indicate a poloidal mode number of m=5, which would be consistent with a value of iota of 4/5 expected to be present in the iota-profile (cf. Fig. 1). However, since only 4 Mirnov coils could be put into operation during OP1.1, these mode analysis results have accuracy limitations.

Prospects of the W7-X MHD diagnostics Experimentally, the expected Shafranov shift could not be detected in OP 1.1 due to the lack of spatial resolution of the presently installed diagnostics. The XMCTS (soft X-ray Multi Camera Tomography System) diagnostic (to be assembled before the start of the next campaign OP1.2 in 2017) should be capable of resolving shifts of that order by means of tomographic reconstruction of the radiation pattern in the soft-X ray spectral region recorded by a set of 20 cameras [12]. Furthermore, the data acquisition of the already installed magnetic probes will be completed. Especially the set of 125 Mirnov coils is expected to provide detailed information to characterize mode activity (in conjunction with the XMCTS diagnostic) and make the exploration of the MHD stability in the available configuration space of W7-X feasible. For the following operational phase OP2 (aiming at quasi steady state plasmas), a further extension of the number of Mirnov coils is planned. The assigned locations for a diagnostic upgrade - which is needed to improve the assessment of the toroidal mode number - won't be covered by the water cooled plasma facing components. Therefore, these additional coils require a new design to protect them against the plasma.

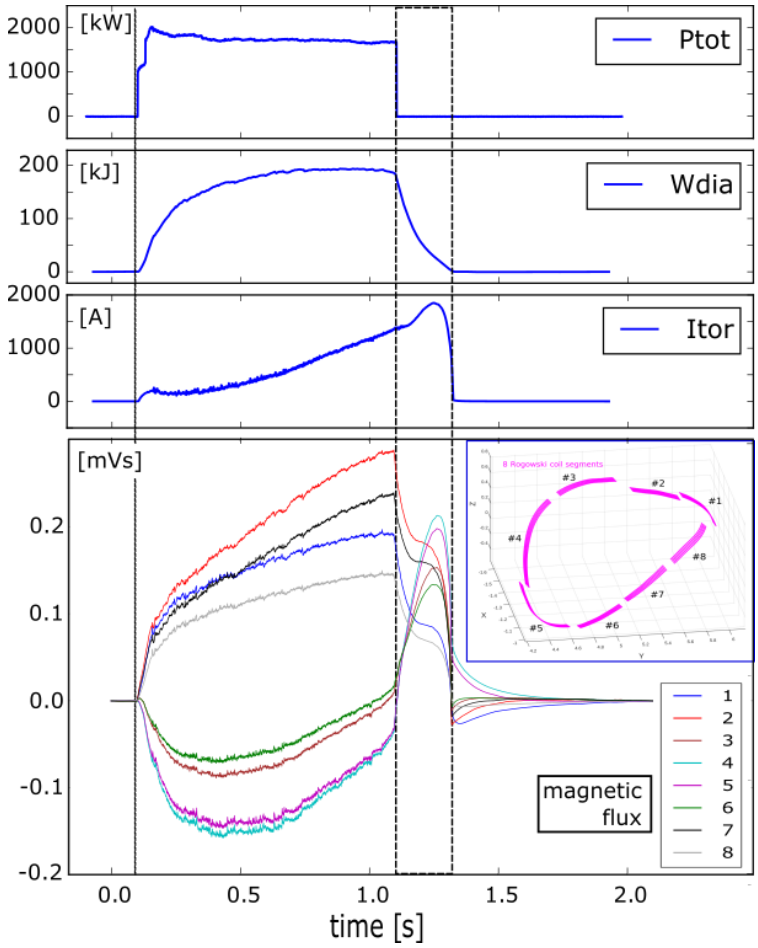

Fig.3: Total heating power, plasma stored energy, integral toroidal current from Rogowski and magnetic fluxes from segmented Rogowski coils, which are located in the triangular shaped poloidal cross-section (cf. inset figure). Data from W7-X program 20160308.012 with ECCD co-current drive in the same direction as the bootstrap current. Co-currents are associated with positive magnetic fluxes in the segmented Rogowski signals

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