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Development of long pulse scenarios at the stellarator Wendelstein 7-X

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Stellarators offer a relatively straightforward route to steady state fusion power operation. Future reactors, such as DEMO, are expected to operate quasi-continuously with divertor heat fluxes as low as 5 MW/m^2 [1]. This requires that most of the power leaving the plasma has to be radiated away by the plasma impurities in the so-called detached regime, in which the divertor target plates are protected from the hotter plasma by a dense layer of cold (T_e < 5 eV) plasma. One of the objectives of the Wendelstein 7-X research is to achieve and optimise the long pulse scenarios. The recently installed high heat flux divertor, consisting of water-cooled CFC target elements, can handle power loads of up to 10 MW/m^2 in continuous operation, which for W7-X plasmas means up to 30 minutes.

During the W7-X operational phase OP1.2 (2017-2018), discharge lengths of 100 s with attached [2] and 30 s with detached plasma [3] were achieved. In the latter case, the detachment was successfully stabilised by keeping the plasma density at a relatively high level (~1.2×10^{20} m^{-2}) necessary to set the radiation fraction to approximately 90% of the input electron cyclotron resonance heating (ECRH) power. The scenario was developed using feedback-controlled gas fuelling with the line-integrated electron density and total plasma radiation as control parameters [4]. The experiments showed that a robust detachment scenario allows to reduce the peak heat flux by almost one order of magnitude, and no significant increase in impurity concentration was observed.

In the recent campaign OP2.1, we significantly extended these scenarios reaching in attached conditions plasma durations of up to 8 min in the attached state (ECRH input power of 3.5 MW; line-integrated electron density was set to approximately 5×10^{19} m^{-2} and kept constant throughout the discharge with a density feedback system; the diamagnetic energy was kept at a level of about 430 kJ, and the ion and electron temperatures were 1.5 keV and 2 keV, respectively). Such a scenario did not lead to any overloading of the surface of the components facing the plasma.

In detached case, a more sophisticated scenario had to be developed which resulted in up to 2 min. discharge lengths with almost completely detached divertor (surface temperatures of 150-160℃). ECRH input power of 5 MW was applied, both intrinsic (mostly carbon) and seeded (neon) impurities were used to increase the plasma radiation fraction up to ~80%). The line-integrated electron density was set at 1.3×10^{20} m^{-2}, resulting in both ion and electron temperatures at the level of 1.5 keV and a diamagnetic energy of about 600 kJ. No increase of impurity concentration was observed with line-averaged Z_{eff} values below 1.5 and stable line emission of e.g. carbon and oxygen in the X-ray spectra of the Pulse-Height Analysis diagnostic.

[1] N. Asakura et al., Nuclear Fusion 57, 126050 (2017).
[2] T. Klinger et al., Nuclear Fusion 59, 112004 (2019).
[3] M. Jakubowski et al., Nuclear Fusion 61, 106003 (2021).
[4] M. Krychowiak et al., Nuclear Materials and Energy 34 101363 (2023).

Primary author: KRYCHOWIAK, Maciej (Max-Planck-Institute for Plasma Physics)

Co-authors: DINKLAGE, Andreas (Max-Planck-Institut für Plasmaphysik); ZHANG, Daihong; NAUJOKS, Dirk (IPP Greifswald); JAKUBOWSKI, Marcin (Max-Planck-Institut für Plasmaphysik); KUBKOWSKA, Monika (IPPLM); Dr LAZERSON, Samuel (Max-Planck-Institut für Plasmaphysik); STANGE, Torsten (Max Planck Institute for Plasma Physics, 17491 Greifswald, Greifswald, Germany); Dr GAO, Yu (Max-Planck-Institute for Plasma Physics, Greifswald, Germany)

Presenter: KRYCHOWIAK, Maciej (Max-Planck-Institute for Plasma Physics)

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