stellarator news

An international journal of news from the stellarator community

Editor: James A. Rome Issue 164 February 2019

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On the Web at https://stelnews.info

Second divertor operation campaign: High-density, long-pulse operation

The most recent operation campaign, which was finished in fall 2018, marked the completion of the initial divertor campaign of Wendelstein 7-X (W7-X) at Max Planck Institut für Plasma Physics, Greifswald, Germany. During the 14 weeks of operation, W7-X operated for 35 days, and a total of 1500 scientific plasma discharges were accomplished. As in the previous campaign in 2017, operation was done in full island divertor geometry with 10 inertially cooled divertor targets. Thus, heat loads to the plasma-facing components needed to be monitored closely and led to an initial limit on the allowed heating energy input of 80 MJ, which could be increased to 200 MJ later in the campaign. In addition to enhanced diagnostics capabilities, two major new components were implemented: improved wall conditioning via boronization, and neutral beam injection heating. Primary goals of the campaign were to develop stationary high-density hydrogen discharges and to operate the divertor in a safe and controlled way. More than 300 proposals were selected by the topical task forces and the proposals were executed to address these goals.

Boronization has a tremendous effect on the plasma performance. The associated reduction in the impurity content leads to much lower plasma radiation losses and allows W7-X to operate at considerably higher plasma densities in hydrogen.

Figure 1 displays a comparison of stationary hydrogen plasma densities achieved before and after boronization. It is evident that the impurity radiation fraction is strongly reduced after boronization and stationary line-averaged plasma densities exceeding $1 \cdot 10^{20}\ \mathrm{m}^{-3}$ could be routinely achieved. The maximum density was only limited by the available ECRH power of $P_{ECRH} \leq 6$ MW. At these high plasma densities, a transition in the divertor heat load is observed. This is shown in Fig 2. In the right-hand plot, the longest discharge so far achieved at W7-X with a duration of 100 s is shown. At an ECRH power of 2 MW and relatively small plasma density, the divertor surface temperature t_{div} steadily increases. The length of this stationary discharge is limited by the maximum allowed divertor temperature of only 1800° C.

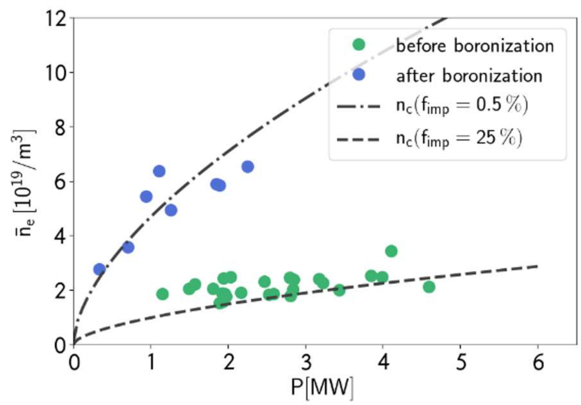

Fig. 1. Comparison of achieved mean plasma densities before and after boronization with an estimate of the expected density for a certain concentration of impurities f_{imp}.

Second divertor operation campaign: High-density, long-pulse operation
In the second divertor campaign, Wendelstein 7-X operated for the first time with high-density hydrogen discharges exceeding $1 \cdot 10^{20}\ \mathrm{m}^{-3}$. At these high densities, divertor detachment is achieved; this allowed for stationary discharges of up to 30 s with 5 MW of heating power. The key for these operational achievements was to apply boronization, which reduced the plasma impurity content considerably. Neutral beam injection heating was operated for the first time at Wendelstein 7-X and could sustain the plasma for 5 s.

If, however, the plasma density is increased (left-hand side of Fig. 2), the divertor temperature drops to well below 500°C, which is an indication of divertor detachment. Without the definition of a general heating energy limit, this scenario can be extended to discharge times much longer than 30 s, even without water-cooled divertor elements. In this context, it was important to achieve control over the position of the heat load onto the divertor target, particularly if, e.g., the bootstrap current is evolving in time. Additionally, 2 separate target elements (the so-called scraper elements) were qualified. These elements are designed to protect the divertor edges from large heat loads. Neutral beam injection heating was applied at W7-X for the first time. Up to 3.5 MW of heating power could be coupled for 5 s into the plasma. The heating efficiency was best demonstrated by the fact that the plasma discharge could be sustained by neutral beam injection heating only, without any additional ECRH. Due to beam-beam fueling, the highest plasma density of up to $2 \cdot 10^{20} m^{-3}$ with centrally peaked density profiles was achieved in this case.

In summary, the most recent campaign was very successful, and the major physics goal were accomplished. We achieved a lot of experimental results and the detailed data analysis and physics exploitation is ongoing. Over the next few years, W7-X will be completed by installing the high-heat-flux divertor and water cooling. This technical prerequisite and the experience obtained in the last two divertor campaigns will form the basis for the development of long-pulse, high-performance operation in the next campaigns.

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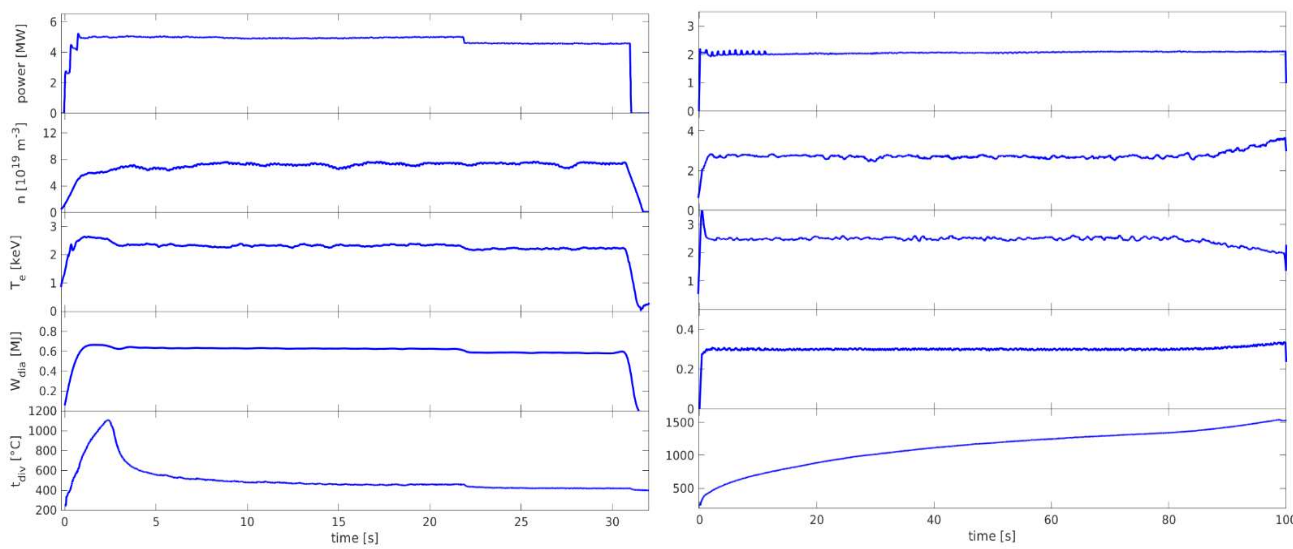

Fig. 2. Discharge overview of two stationary hydrogen discharges displaying, from top to bottom; the time evolution of the ECRH power, the central plasma density, the electron temperature, the diamagnetic plasma energy, and the divertor surface temperature.