EFFECT OF BORON POWDER INJECTION ON THE DENSITY LIMIT IN THE LARGE HELICAL DEVICE

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In this contribution, we report on recent experiments in the Large Helical Device, where the injection of boron powder into the plasma increased the maximum attainable density by up to 30%, reaching $n_e{\sim}1.1n_{sudo}$. Possible mechanisms responsible for the improvement are the reduction of intrinsic impurities, as well as reduction of edge turbulence, both driven by powder injection.

In a fusion reactor, the produced fusion power scales with the density as $P_{fus} \propto n^2$, therefore operating at high density is attractive for energy-producing future fusion devices. While the density limit in tokamaks is determined largely by the plasma current, this is not true in stellarators, where the external magnetic field is provided almost entirely by external coils. The density limit in stellarators is described in first approximation by the empirical Sudo limit [1], $n_{Sudo}[10^{19}m^{-3}] = 2.5\sqrt{(P_{in}B)/(r^2R)}$, believed to be determined by the balance between the input power and the power radiated by the plasma. Densities above the Sudo density limit are sometimes observed in stellarators, e.g. in LHD [2]. In particular, further studies in LHD and W7-X indicated that the density limit in stellarators might be determined by the power radiated in the edge of the plasma by impurities [2,3]. On the other hand, recent theory development showed that the density limit in tokamaks might be determined by a transition in edge turbulence [4]. The same mechanism could be at play in stellarators as well.

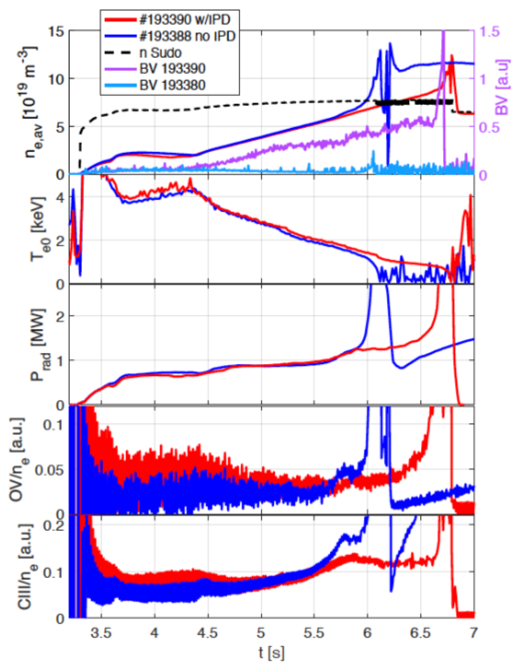

Figure 1: From top to bottom: time traces of electron density and BV spectroscopic measurement, electron temperature, total radiated power, OV and CIII spectroscopic lines normalized to density, for a shot with (red) and without (blue) B powder injection.

In recent experiments in LHD, boron (B) powder was injected using the Impurity Powder Dropper (IPD) [5], designed and built by Princeton Plasma Physics Laboratory, for wall conditioning purposes. During B powder injection, a reduction in intrinsic impurities such as C, O, Fe is generally observed [6], which can result in an overall decrease of the radiated power [7]. Furthermore, during powder injection, a reduction of turbulence and an increase in confinement is sometimes observed [8]. Therefore, B powder injection might result in an increase of the density limit, either in the case it is determined by edge radiation, or edge turbulence, or both.
To test this hypothesis, a first set of experiments has been performed in LHD. Here, the density limit is first determined by density ramps. Secondly, the same plasma discharge is repeated, while injecting B powder in the plasma at the same time. Two heating scenarios are considered, a low power one where the plasma is heated by neutral beams $P_{in} = P_{NB} = 3.5\ MW$, and a high power one with the addition of electron cyclotron heating $P_{EC} = 1.5\ MW$ for a total of $P_{in} = P_{NB} + P_{EC} = 5\ MW$.

In the high power case, without B injection a rapid density increase is observed starting at $n_e{\sim}0.85n_{sudo}$, quickly leading to a radiative collapse. B powder is injected into the plasma starting at t = 4.3 s, in increasing amounts on a shot-to-shot basis. As a result, the maximum attainable density is increased up to $n_e \sim 1.1 n_{sudo}$. The intrinsic impurity concentration of O and C, measured by the spectroscopic lines OV and CIII respectively, remains below the reference level during B injection. This might be due to a change in neoclassical transport of the impurities. No remarkable change in total radiated power is observed in the phase leading to the collapse of the reference discharge. No substantial change in the density profile is observed as well, while the density fluctuation level measured by phase contrast imaging (PCI) is decreased of ~25% in the edge of the plasma $r_{eff}/a_{99} > 0.75$. The turbulence level, for which we consider the line integrated PCI spectrum normalized by the average electron density as a proxy, shows a decrease in the lower frequency part, F < 30 kHz, in the phase before the collapse of the reference discharge, 5.5 < t [s] < 6. The turbulence level for higher frequencies, 30 < F [kHz] < 150, is lower during the first second into powder injection, recovering the reference level in the phase 5.5 < t [s] < 6. From here to plasma collapse, the turbulence level in this frequency range is further decreased. The electron temperature is also slightly increased of about 8% as a result of B powder injection, consistently with previous observations of simultaneous turbulence reduction and confinement improvement [8].

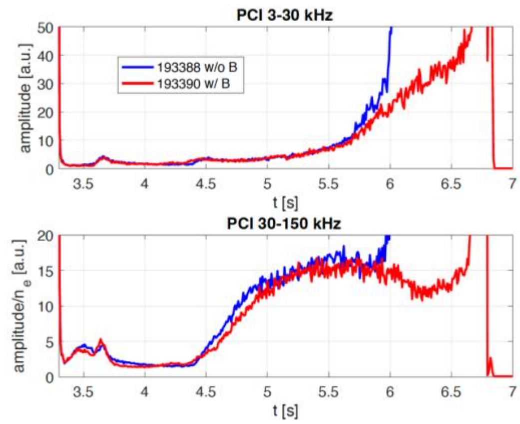

Figure 2: Turbulent density fluctuation amplitude measured by PCI(line integrated) normalized by electron density, for a shot with (red) and withut(B) B powder injection.

In the lower power case, the reference discharge (without B powder) already reaches a density of $n_e \sim 1.6\, n_{sudo}$. Densities about double the Sudo limit were previously observed in LHD [2]. In this case, the addition of B powder does not result in an increase of the density limit, causing the plasma to collapse slightly earlier instead. The effects of the powder injection observed on the concentration of the intrinsic impurities is mixed, as C concentration is decreased, while O is increased. The total radiated power is increased by ~25%. No substantial change in plasma density and temperature profile is observed during B injection, and the amplitude of the turbulent density fluctuations measured by PCI in the edge of the plasma is increased by ~15% in the phase before the radiative collapse.

This first set of experiments shows encouraging results for improving the density limit via powder injection. Nevertheless, the difference in response between the low and high power scenario needs to be understood. The smaller effect of B powder for the low power scenario might be in part explained with a shallower penetration of the powder and subsequently of the evaporated B ions into the plasma, as the plasma density is higher in this scenario, and the penetration of the powder has been shown to decrease with increased density in LHD due to stronger deflection via ion drag force in the divertor leg, that the powder has to cross to reach the main plasma [9].

The present experiments do not allow to disentangle the effect of reduced impurity radiation and reduced edge turbulence on the density limit, since both effects occur when B powder injection improves the density limit (high power scenario). Further experiments comparing different powder materials are foreseen for the next LHD campaign to shed light on this matter.

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