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Divertor detachment and re-attachment studies with mixed impurity seeding on ASDEX Upgrade

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In GW-scale fusion power plants, most of the alpha heating power must be radiated from the edge plasma on closed field lines and the remaining fraction radiated in the scrape-off layer to reduce the surface heat flux and material erosion rate in the divertor below tolerable values. A mixture of impurities with radiation efficiencies tailored to the distinctly different regions of plasma within the tokamak will likely be injected to achieve this level of radiation. Here we overview a set of experiments on ASDEX Upgrade (AUG) that focus on divertor detachment in ELMy H-mode plasmas with different mixtures of seeded N, Ne, and Ar gas. The scenarios have a plasma current of 1 MA, powers crossing the separatrix up to 10 MW, and divertor neutral pressures ranging up to ˜4 Pa. The experiments explore both the transient divertor response to power modulations and temporary impurity gas cuts and the steady state conditions required for partial and pronounced detachment with mixtures of N and Ne and N and Ar, including comparison to equivalent scenarios with single impurity injection. Contrary to previous experience on AUG, a stable detached scenario with good core plasma performance was achieved with Ne seeding when combined with a low level of N seeding.

To understand the physics that determines the timescale for divertor re-attachment, power perturbations of ˜4 MW introduced by additional NBI heating were applied during steady-state phases with different degrees of divertor detachment. In phases of partial detachment and detachment onset the divertor re-attached within ˜80 ms, similar to the energy confinement time. However, the divertor took ˜250 ms to re-attach in the phase with pronounced detachment and strong radiation near the X-point. A simple model to predict the re-attachment time has been developed considering timescales of atomic processes and geometry. Similar experiments were run replacing the power modulation with cuts in impurity seeding gas. In these experiments, the timescale for re-attachment appears to be set by the impurity residence time; however, work is ongoing to disentangle the different physics mechanisms at play. These results should open discussion regarding the minimum timescales that real-time control systems in future reactors must be able to actuate on to react to transients.

In the steady-state phases, an analytical formula for the impurity seeded partially detached divertor operational point developed by Kallenbach et al. is extended to include impurity mixtures and compared to experimental values derived from divertor spectroscopy and neutral pressure measurements. Focus is given to the radiation efficiency fractions used for each impurity, which were previously only estimated for Ne and Ar. The formula gives satisfactory agreement to the measurements across the range of impurity mixtures and divertor conditions. While the formula is valid only for partial detachment, threshold conditions for pronounced detached are again found not far beyond the partial detachment threshold limit. Understanding how to account for impurity mixtures provides an opportunity for combining impurity concentration measurements from both W- and C- wall machines to assess the machine size scaling of the detachment threshold.

Speaker's Affiliation

UKAEA, CCFE, Culham Science Centre, Abingdon

Member State or IGO

United Kingdom

Primary author: HENDERSON, Stuart (UKAEA)

Co-authors: BERNERT, Matthias (Max-Planck-Institut für Plasmaphysik); BRIDA, Dominik (Max-Planck--Institut für Plasmaphysik); CAVEDON, Marco (Dipartimento di Fisica 'G. Occhialini', Università di Milano-Bicocca, Milano, Italy); Dr DAVID, Pierre (Max Plank Institute for Plasma Physics, Boltzmannstr. 2, 85748, Germany); DUX, Ralph (Max-Planck-Institut für Plasmaphysik, Garching, Germany); FÉVRIER, Olivier (Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland); JÄRVINEN, Aaro (VTT); KALLENBACH, Arne (Max-Planck-Institut f. Plasmaphysik); MCDERMOTT, Rachael (Max Planck Institut für Plasmaphysik)

Presenter: HENDERSON, Stuart (UKAEA)

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