Electron-cyclotron-resonance heating in Wendelstein 7-X: A versatile heating and current-drive method and a tool for in-depth physics studies

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Important criteria for the optimum heating mix of magnetic confinement fusion experiments are heating efficiency, power deposition profiles or the ability to also drive plasma currents. In particular, for stellarators, which need no or only small amounts of current drive, ECRH is a promising heating method even for the envisaged application in a fusion power plant.

Wendelstein 7-X (W7-X) is equipped with a steady-state ECRH system consisting of ten gyrotrons which operate at 140 GHz corresponding to the 2^{nd} cyclotron harmonic at a magnetic field of 2.5 T. The heating power available ranges from 7 to 9 MW which today is the largest ECRH facility in operation. W7-X uses ECRH for plasma start-up, heating and current drive and also plasma vessel conditioning. All ten gyrotrons are operational and already have delivered 7 MW to W7-X plasmas. With the heating power available in the first campaign, energy confinement times were achieved which were lying on the international scaling for stellarator confinement (ISS04). First studies indicate the existence of a radiative density limit with a Sudo-like power scaling.

The power of the ten gyrotrons is transmitted through air to the W7-X plasma vessel using a quasi-optical mirror system. The overall transmission efficiency was experimentally estimated to be 94%, which is close to the theoretical value. Front steering launchers direct the gyrotron beams individually to the plasma. First current drive experiments revealed periodic internal plasma-crash events, which can be explained by the appearance of low order rationals of the rotational transform, i, due to current drive close to the plasma center leading to an i-change, $Di \sim I/r^2$. In the current operation campaign of W7-X remote steering launchers (RSLs) were tested for the first time. Without movable parts near the plasma, the remote steering technology may be a possible solution for a power plant. Since the RSLs are located near the minimum of the magnetic field, they also allow probing of the electron distribution function by changing the amount of trapped and passing electrons.

The paper addresses plasma confinement properties specific to the application of strong electron heating by ECRH, the heating of plasmas at high densities which requires a change from 2^{nd} harmonic X-mode to 2^{nd} harmonic O-mode, the possibility to test our understanding of electron-cyclotron current drive, and heat-wave experiments delivering insight into the characteristics of plasma transport.