Impurity transport in tokamak plasmas, from theory to real-time control

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Impurities are an unavoidable component of a tokamak plasma. If their concentration in the plasma increases out of control, they can have very negative effects, even leading to plasma disruptions. At the same time, if their presence is kept under control, they can have positive effects, as the seed of some impurities is also observed to improve the confinement, and will certainly be required in a reactor to increase peripheral radiation and reduce the heat loads which reach the divertor plates.

The amount of impurities present in the different regions of the plasma, from the core to the edge, is the result of a combination of effects connected with the strength of their sources at the periphery (and at the centre for He ash in a burning plasma) and the transport. With respect to the main plasma components, impurities have the additional physically interesting, but more complex, property that their transport is concomitantly governed by both collisional and turbulent mechanisms, whose relative role depends not only on the plasma conditions, but also on the impurity charge and mass. The high mass and charge also open the possibility of impurity density distributions which are not poloidally homogenenous on the magnetic flux surfaces, providing additional complexity to the problem, but also increasing the number of physical parameters which can be experimentally used to modify their radial profiles. The need of metallic walls for fusion reactors and in particular the use of a highly charged element like tungsten has required the development of robust techniques to limit the concentration and avoid central accumulation of highly charged impurities, for a successful experimental operation. At the same time, the mechanisms of impurity transport have received renewed interest and a more complete theoretical treatment has been achieved, the reliability of the predictions has been increased by a detailed validation, leading to increasingly realistic modelling.

In this presentation, the main mechanisms of impurity transport are reviewed from a theoretical standpoint and the effects by which impurity density profiles can be modified in a plasma by affecting the impurity transport properties both directly and indirectly, by a modification of the bulk plasma profiles, are described. The consistency between the theoretical predictions and the experimental observations has allowed an increasingly comprehensive understanding of the physical mechanisms which are behind the operational recipes which are experimentally adopted to limit the impurity concentration and avoid central accumulation. New mechanisms impacting the radial profiles of impurities have been identified theoretically and have been later experimentally confirmed. The processes of accumulation and accumulation avoidance can now be consistently reproduced by integrated transport modelling. This successful story of combined theoretical, modelling and experimental research has paved the way to real-time control applications, and gives today increased reliability to the identification of proper sensors and to the utilization of effective actuators for the control of impurity density profiles.