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The prediction of tokamak plasma confinement, from scaling laws to full-radius integrated modelling

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For many decades the prediction of the global confinement of a tokamak plasma has been based on empirical scaling laws. While these regressions can be built on large databases of present observations and can identify robust dependencies on the main engineering parameters, they do not have any theoretical basis and, for the prediction of a reactor plasma, they need to be applied largely outside the parameter domain on which they have been derived. Moreover, they do not allow the prediction of the plasma kinetic profiles. In this topical plenary presentation, a new approach is described, which, by combining the achieved and increasing understanding of turbulent transport in the core and the edge of the confined plasma, of the MHD limits determining the pedestal and of the properties of the scrape-off layer, predicts the plasma thermal energy as well as the complete profiles [1-3]. Following the same strategy as the scaling laws, this new approach only uses engineering parameters as inputs, such as plasma current, magnetic field, heating power, the gas puff levels or, similarly to scaling laws, the averaged plasma density. Differently from scaling laws, which are based on an empirical 0D approach, this new approach tackles the problem of the prediction of tokamak plasma confinement, in both low (L-) and high (H-) confinement modes, from the standpoint of the integrated modelling over the full cross-section of the confined plasma. Thereby, predictions from empirical 0D scaling laws of the confinement time can be compared and replaced with results of full-radius simulations. The input parameters are the same as the regression variables of the scaling laws and can be directly taken from the pulse program. No input parameter is taken from measurements. The transport models, and in particular the TGLF [4] and QuaLiKiz [5] turbulent transport models, are completely theory-based in the case of L-mode plasmas [3]. Empirical transport elements are used in the pedestal model for H-mode plasmas [1,2], which however is also robustly constrained by the MHD limits for pedestal stability. The boundary conditions are defined at the separatrix by a reduced analytical model for the scrape-off layer. This modelling approach, based on the ASTRA transport code, is applied to ASDEX Upgrade plasmas and is demonstrated to provide results which are in better agreement with observations than any available empirical scaling law for confinement. Dependencies on main engineering parameters are individually analyzed and related to the properties of turbulent transport, particularly at the edge [6], and/or to the MHD stability. Moreover, and beyond the possibilities of the scaling laws, this new modelling approach is also able to identify dependencies on hidden variables and to provide a physical understanding of the origin of these parametric dependencies, The relative computational lightness of this modelling framework allows its application to extended databases of existing experimental data. This is required for an appropriate qualification of its reliability in view of the prediction of future devices. Hence, the full-radius integrated modelling framework is also extended to Alcator C-Mod and JET-ILW plasmas [7], demonstrating the general potentialities of this approach, which leads to a complete change of paradigm in the prediction of tokamak plasma confinement.

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