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Plasma physics for fusion reactor system codes: Framework and model code

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ABSTRACT

Design of a fusion reactor power plant requires putting together physics elements (plasma physics) and engineering elements (plant characteristics). System codes are tools that perform integrated plant design taking into account those two aspects. Design optimization can also be carried out, to produce the "best" reactor design, according to some pre-defined figures of merit. However, presently used system codes often lack a plasma model with sufficient level of realism in terms of description of plasma processes and non-linearities. In this work, for the first time, a framework in which the plasma model should interact with the engineering elements is detailed, giving the attention on the logic of how the plasma physics should be represented inside the system codes. Ultimately, no ambiguity is left on how the problem should be addressed and solved. Concrete details on how the plasma model should be written are also presented. A novel code PLASMOD has been written which incorporates these elements and can be used in a generic engineering system code.

1. Introduction

Fusion reactors are foreseen as the main source to replace coal, fission-based power plants for the future needs of mankind. Comprehensive designs of such a reactor have already been undertaken worldwide. In Europe particular focus is now devoted to the Tokamak DEMO design [1,2]. To design such a complex machine, many elements have to be put together including, in particular: the plasma, the magnets, the blanket, the coils. Each element has its own characteristics, constraints, limits, and requirements. The available engineering knowledge that goes into those sub-systems is put together into system codes (SC), comprehensive software tools that aim at providing a complete design of the machine, including costs. The SC is often equipped with an optimization routine that also looks for the best design, in terms of some predefined figure of merit. One of the most used SC in EUROFusion is PROCESS [3], which contains all such elements defined above. Example of other codes which are in development or are used elsewhere are SYCOMORE [4], NOVA/Blueprint [5], MIRA [6].

SC usually focus on the engineering aspects, materials, magnets, force limits, irradiation limits, etc., and the plasma itself which provides the fusion power is simply described as a 0D entity via some widely used scaling laws (e.g. the ITER Physics Basis 1998 (IPB98) scaling law for the confinement time [7]) and prescribed profiles. Such a plasma description provides already a rough estimate of the fusion power produced by the plasma, and its dependence on some global parameters. However, many drawbacks render this approach practically useless to define what would be the best design and its actual performance, for the following reasons:

(1) Profile effects are very important in determining the actual fusion power produced at constant H factor [8]. Parametrized profiles are already in used in system codes, however it is known from experimental observations that profile shapes are not self-similar (i.e. the coefficients of the parametrization are actually parameter-dependent), in particular the relation between density and temperature is complex and cannot be captured by a simple parametrization.
(2) The physics of core and pedestal in an H-mode plasma are completely different and cannot be "independently" captured by a single global scaling.
(3) Divertor protection requirements cannot be easily computed in a 0D setting.
(4) Prediction of the bootstrap current (as well as of the plasma equilibrium) requires knowledge of realistic plasma profiles.
(5) Many non-linear processes happening in the plasma are local in radius, and thus cannot be included in a 0D framework.

Since including, at least, a 1D description of the plasma would not dramatically require more computational time for the SC, it is then preferrable to describe the plasma with profile effects and with relevant physics so that the inter-dependencies and non-linearities that dominate the plasma behavior, as both described theoretically and observed experimentally, are retained.

The paper is organized as follows: Section 2 describes the physics

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interfaces between plasma and technology. Section 3 discusses the relevant plasma processes that should go into the plasma model. Section 4 describes in detail the coupling scheme taking into account the previous sections results. Section 5 describes the new code PLASMOD and shows a few examples of results obtained with the code. Section 6 discusses some technical issues. Section 7 draws the conclusions.

2. Plasma-technology interfaces

The first realization of how a plasma model should couple to the engineering modules, comes directly from the natural way of interaction between the plasma and the outside materials.

Assuming that the plasma is confined inside the first-wall (plasma includes both core and the scrape-offlayer/divertor region), than the plasma interacts in the following ways:

(1) The burning plasma core produces neutrons and line/synchrotron/bremsstrahlung radiation (both volumetric reactions), these impact the first wall elements (blanket, limiters, shielding elements, central solenoid column, etc.).
(2) The heat and particle fluxes outside of the plasma separatrix through the scrape-off-layer (SOL) are convected/conducted directly to the first wall (e.g. perpendicular transport) and to the divertor tiles (parallel transport).
(3) Plasma particle content (i.e. inventory) is provided by fueling/pumping and wall recycling. E.g. since the density peaking impacts the choice of the pedestal top density (if one wants to have a specific line average density), profile effects are important to estimate the actual amount of required fueling.
(4) The plasma is controlled both magnetically (external coils) and kinetically (auxiliary heating). As an example, tailoring of the safety factor, which could both increase the bootstrap current, enhance confinement, and lead to a steady-state inductiveless scenario, can only be obtained when profiles are computed, as the position where current drive is applied impacts all these elements.

After having identified these interfaces, it will be then straightforward to write down the exchange parameters in I/O from plasma to technology and vice versa.

3. Plasma processes and plasma model

The plasma could be divided in 4 main regions: the plasma core (up to pedestal top), the pedestal up to the separatrix, the SOL, and the divertor region. In Fig. 1 these regions are displayed, where core (1) energy is transport through the pedestal to the SOL (2), and then particle end energy flows to the divertor (3). In each region, physics processes develop which are characterized by specific parameters (that can also be cast in dimensionless form) and non-linear phenomena (that is, they do not follow simple linear monotonic behavior with respect to control parameters).

3.1. Core plasma

The core plasma is heated by auxiliary heating, and by the fusion reactions themselves. Since relevant fueling is mostly done in the edge region, the core density profile is basically determined by a balance of diffusion and convection. Once the sources are defined, together with the plasma geometrical parameters (shaping, field, current), plasma confinement can be computed assuming for example turbulence, neoclassical and some form of MHD transport. The pedestal top would act here as a boundary condition for the core plasma model.

The core confinement is determined by multi-scale processes: Larmor-scale turbulence, collisional (neoclassical) transport, and MHD (sawteeth, NTMs, etc.). Each process can in principle be modeled given the local inputs in terms of profiles (geometry, temperatures, particle densities, current density). Just to make an example, referring to typical diffusion rates, collisional transport would scale as $D_{\rm coll} \sim A^2 q^2 \rho_L^2 \nu$ m^2/s, where A, q are respectively the aspect ratio and the safety factor, while turbulent transport as $D_{\rm turb} \sim (\rho_L/R)^2 c_s R$, where ρ_L, c_s, R are respectively the Larmor radius, the sound speed, and the major radius. These basic diffusion rates already show the non-linear dependencies with respect to the local temperature.

Impurities coming from the edge would also be present in the core, producing radiation, dilution and effecting plasma confinement.

3.2. Pedestal

Plasma regimes are often divided in low-confinement, or "L-mode", and high-confinement, or "H-mode", with addition of "improved" regimes that can also be part of the core, but often are edge phenomena (improved L-modes, I-modes). In any case, physics of the edge layer (few cms inside the separatrix) is very different from core physics. That is why the pedestal region is treated on a different footing.

The plasma model should recognize in which regime it is given the local or the global parameters (e.g. $P_{\rm sep}/P_{\rm LH}$) and consequently decide what to do with the pedestal.

Let one suppose that it is an H-mode regime. In this case, the pedestal height and width could be modeled assuming type 1 ELMy regime, and employing computational tools that combine pedestal MHD and kinetic stability like EPED [9]. Notice that, in reality, the plasma regime could also be different, for example type 3 ELMy, or ELM-mitigated or suppressed via application of RMPs [10,11]. However, for the latter regimes a systematic study to extract parametric dependencies in a robust way is still ongoing and no definite scalings can be used in the presented code.

In L-mode, the pedestal would not exist as such but the core would be continued up to the separatrix.

3.3. SOL/divertor

The SOL and divertor regions can be described as both determining parallel transport to the plates, and perpendicular transport to the first wall. Many codes are available that solve this problem in a rather complete way, up to including neutrals for example [12]. However, in this context one cannot afford to routinely run such codes as the computational costs are too high. In practice, 0D recipes could be used (e.g. the two-point model), or one could use routines computing 1D radiation profiles and the consequent heating at the divertor from upstream.

4. System codes coupling logic including the plasma model

Now that all the pieces are set for the coupling, the latter can be performed. It is assumed that the system code consists of a main "optimizer" (or say, a main place where gross engineering parameters are defined). This will provide the following parameters:

- to plasma model (INPUT): major radius R, reference field $B_{\rm T}$, plasma shape parameters (e.g. for a three-moment-type description: k, δ, a), plasma safety factor q_{95}. It would also tell the plasma which constraints to satisfy: loop voltage must be lower than $x \rightarrow$ requires auxiliary current drive; divertor heat loads /temperature must be lower than $x \rightarrow$ requires impurity seeding; plasma density must be $x \rightarrow$ requires fueling; $P_{\rm sep}/P_{\rm LH}$ must be between $x_1 - x_2 \rightarrow$ requires either impurity puffing or auxiliary heating (alternatively, $P_{\rm fus}$ itself could be given as additional requirement), fuel mix (D-T ratio).
  Once the plasma model has run, it produces a set of parameters and requirements to be delivered back to the technology side:
- from plasma to technology (OUTPUT): required $P_{\rm aux,CD}$ for current drive; required $P_{\rm aux,heat}$ for heating; required impurity seeding for core and for divertor; required fueling in terms of required D, T