Physical challenges and numerical issues in controlled fusion plasmas

Yanick SARAZIN, CEA, IRFM - 13108 Saint-Paul-Lez-Durance

In the route towards harnessing controlled fusion on Earth, the international ITER ("the way" in Latin) project represents a major step forward. ITER, currently under construction at Cadarache, France, is a *tokamak*, a device in which a hot plasma at about 150.10^6 Kelvin is confined by strong magnetic fields of a few Tesla within nested toroidal magnetic surfaces. Critical physical issues arise from this specific configuration. First of all, the magnetic configuration, which partly results from the current flowing into the plasma, should be stable with respect to large scale magneto-hydrodynamical (MHD) instabilities. Secondly, the insulating property of the magnetic topology should be optimum as it governs the overall fusion performance, i.e. the ratio of fusion power over injected power. It turns out that the energy confinement is mostly governed by micro-scale turbulence in tokamak plasmas when MHD activity is quiescent.
So far, the main physical parameters (size, shape, *etc.*) of new tokamaks, including ITER, have been chosen on the basis of empirical scaling laws, which predict how the energy confinement time τ_E varies with critical dimensionless parameters. Both the inherent dispersion of the multi-machine data points, of about 16%, and the fact that this τ_E curve is extrapolated out of the operational regime of current devices, ask for grounding these scaling laws within well understood theoretical bases. Importantly, controlled fusion will operate with small margins in terms of performance, so that optimization is required. Reliable understanding and control are therefore mandatory. Hence the need for first principle modeling of both MHD instabilities and turbulence dynamics, in view of understanding, predicting − including outside the current experimental domain − and possibly controlling the plasma confinement.

Two main models are currently being used to address these issues, namely 3 dimensional fluid models for MHD stability and transport studies at the plasma periphery, and 5 dimensional so-called gyrokinetic models for core turbulence. First, these intrinsically nonlinear models reveal extremely challenging from the numerical point of view, partly because of the broad range of involved spatial (3 to 5 orders of magnitudes) and temporal (5 to 7 orders of magnitude) scales, and also because of the strong anisotropy of the dynamics, fast along field lines and slow transverse to them. As a matter of fact, each of the associated codes already uses several tens of millions CPU hours per year on the largest supercomputers worldwide, and would require even more for ITER relevant parameters. Second, these models however suffer critical limitations, which would need being overcome in the near future. Two kinds of limitations can be distinguished : either intrinsic, within each model, or extrinsic, i.e. requiring the treatment of all the various physical issues within the same description to look for possible competing and/or synergistic effects. In that respect, accounting for the coupling to specific classes of particles – fast particles in the plasma core and neutrals at the edge – reveals particularly challenging and of uttermost importance.
The talk will review the main physical challenges in tokamak plasmas and the current status of the first principle models, from a theoretical and a numerical point of view. The GYSELAX, JOREK and SOLEDGE3X codes, which are developed and/or used at IRFM, will serve as examples : their development involves multi-disciplinary teams and spans several years, in between 10 and 20 years. The last part of the talk will address their limitations, discuss tentative ways to overcome them and possible numerical bottlenecks.

Contact : yanick.sarazin@cea.fr