Multi-machine comparison of drift fluid dimensionless parameters

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The behaviour of magnetic fusion plasmas is discussed in the framework of dimensional analysis [1]. Normally, in the study of physical phenomena, dimensionless parameters are obtained using one of these two methods: 1) *Dimensional analysis*, which is a formal procedure that does not require to specify a physical/mathematical model (i.e. a set of equations) that describes the phenomenon, but only a set of variables that play a role in its determination (how these variables are chosen is left to physical intuition). In other words, the problem is cast in the form: $f(Q_1,Q_2,Q_3,\ldots)=0$, where f is not determined and Q_i is the *i*th relevant dimensional variable. Buckingham Π theorem is then used to reduce the parameter space of the problem by normalizing the dimensional variables (which are typically more than the dimensionless variables). An application of this technique in plasma physics is given by Kadomtsev [2]. 2) *Scale invariance,* which starts from a specific mathematical model and identifies its invariant transformations. These, in turn, provide constraints on how derived quantities (e.g. thermodynamic fluxes or confinement times) can vary within the given model, thus providing their relation to combinations of dimensional variables. These combinations can be cast in the form of the dimensionless parameters that we seek. This method was used by Connor and Taylor in [3]. Neither approach provides a unique set of dimensionless parameters, so that some degree of arbitrariness is still left. The standard set employed in plasma physics was suggested by Kadomtsev in his seminal paper [2]. The parameters that we discuss here were obtained in the framework of drift-fluid models [4] derived from Braginskii's equations [5] and are particularly well suited to characterize different turbulence regimes. Our approach can be seen as a mixture of both methods. Since most of them are a recombination of Kadomtsev’s, our dimensionless parameters are model independent, but their choice is based on the physical insight provided by a specific set of equations, in this case the drift-fluid (and in particular Ohm’s law). This allowed us to identify some of the parameters with well defined physical effects, which lead us, for example, to recognize the importance of the balance between parallel and perpendicular physics (see below).

Three main dimensionless parameters are analysed, which directly affect the adiabatic response of the plasma and hence control the electron response. They represent the electromagnetic induction, $\hat{\beta}=\beta(L_{//}/L_{\perp})^2$, electron inertia, $\hat{\mu}=(m_e/m_i)(L_{//}/L_{\perp})^2$ and collisions,

$C = 0.51\nu_* \hat{\mu}^{1/2}$, in Ohm's law (with gyro-Bohm normalization): $\hat{\beta}\partial_t A_{//} + \hat{\mu}\left(\partial_t + \vec{V}_E \cdot \nabla\right)J = \nabla_{//}(p_e - \varphi) - CJ + 0.71\nabla_{//}T_e + S_{eq}$. Here β is the ratio between kinetic and magnetic pressure, ν_* is Kadomtsev's collisionality, m_e/m_i is the electron to ion mass ratio, $L_{//}=qR$ is the parallel wavelength of the perturbation (assuming ballooning effects, with q the safety factor and R the major radius), $L\perp$ is the perpendicular equilibrium length scale. In Ohm's law, $A_{//}$ is the parallel vector potential, J is the parallel current, φ the electric potential, p_e and T_e the electron pressure and temperature and S_{eq} is the equilibrium source term that feeds the fluctuations.

Using experimental density and temperature profiles, most of which extracted from the ITPA databases, for existing divertor machines (ALCATOR C-MOD, ASDEX Upgrade, JET and MAST), these parameters, originally introduced by Scott [4] and Rogers and Drake [5], are evaluated in different regions of the plasma, moving outwards from the core to the divertor. This analysis is repeated for future devices (ITER, DEMO and MAST Upgrade), based on predicted density and temperature profiles. Where possible, a statistical analysis of the ITPA data was performed in order to identify *typical* values of the relevant quantities (e.g. density and temperature, but also magnetic field and safety factors). The chosen devices differ substantially in size, aspect ratio, magnetic field and heating power. However, clear multi-machine trends, suggesting a quasi-universal behaviour of the plasma, are found in all the three main parameters (see Fig. 1).

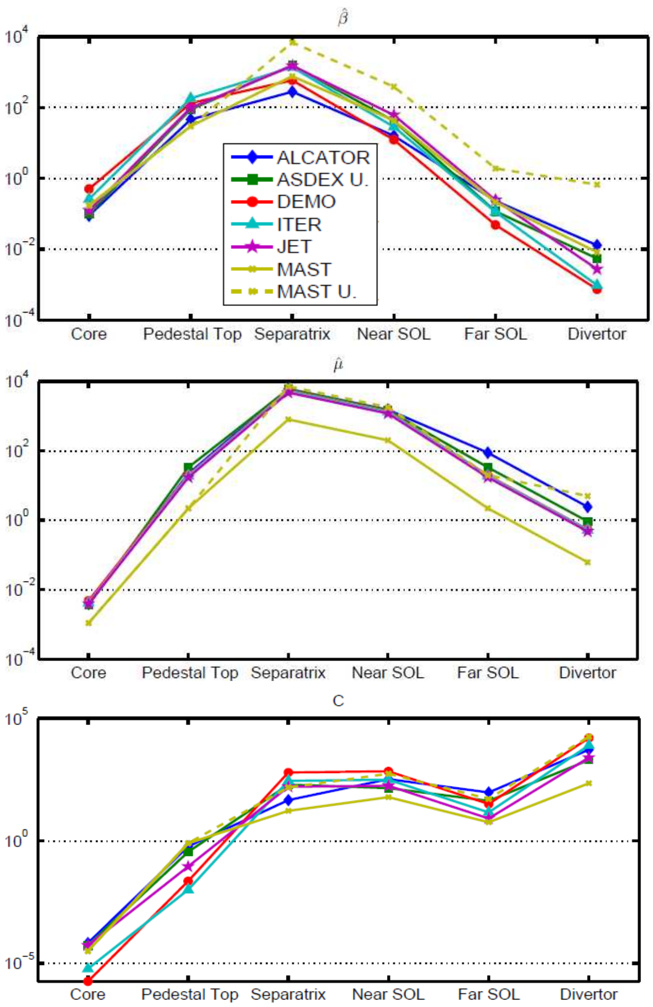

Figure 1: the dimensionless parameters $\hat{\beta}$, $\hat{\mu}$ and C in the six regions of the each machine (H-mode).

In particular, the trends show a clear separation of the plasma into six distinct regions: core, edge (divided into pedestal top and separatrix), Scrape-Off Layer (divided into near and far) and divertor, each of them characterized by a different

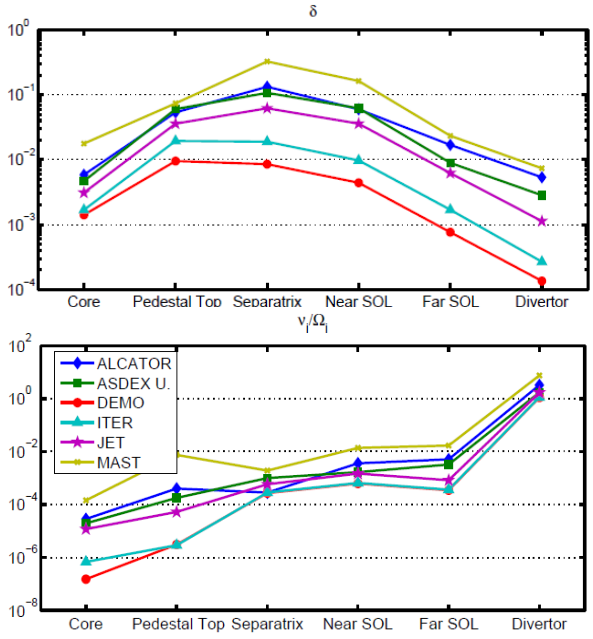

Figure 2: the dimensionless parameters δ and ν_i/Ω_i in the six regions of the each machine (H-mode).

set of parameters which, in turn, lead to significant variation of the dominant physical mechanisms across the machine. For example, both the electromagnetic and electron inertia effects are relevant in the edge region, and in particular at the separatrix, while they become less prominent in the core and in the outmost regions of the plasma. Not surprisingly, the collisional effects are instead becoming more important as we move from the core to the divertor, as the temperature is quickly decreasing. The dimensionless parameters show similar qualitative trends in both H- and L-mode, although the absolute value of the former is typically a few orders of magnitude larger in the edge/SOL region as a consequence of the steeper equilibrium gradients associated to the pedestal (i.e. smaller $L_\perp$).

Other secondary dimensionless parameters were analysed in order to provide a more complete picture of the plasma behaviour in the different regions. To be magnetized, the plasma should be characterized by δ and ν_i/Ω_i much smaller than unity, where δ is the ratio between the ion sound Larmor radius, ρ_s, and $L_\perp$, ν_i is the ion-ion collision rate and Ω_i is the ion gyration frequency. The evaluation of these two dimensionless parameters shows that δ is indeed small in most of the machines, although in the separatrix region of MAST and ALCATOR C-MOD the condition is only marginally satisfied, and that ν_i/Ω_i is always negligible but in the divertor region (see Fig. 2). This implies that fluid theories, which rely on the smallness of δ, might be inaccurate around the separatrix, and that at the divertor the perpendicular transport approaches the level of the parallel transport, since the magnetic field loses its ability to confine the plasma. An important implication is that detachment models based on multi-fluid codes with constant cross-field transport coefficients underestimate the radial fluxes and hence the degree of detachment.

The last of our secondary dimensionless parameters is the ratio between the neutral penetration length and the minor radius, λ_{iz}/a. Figure 3 shows that the machines in operation follow a different trend from the future machines. In particular, in ITER and DEMO the penetration distance is much shorter, which implies that fuelling techniques based on gas puffing might prove inefficient.

To summarize, using experimental density and temperature profiles, we identified clear trends in the main and secondary dimensionless parameters in several devices. We have shown that, despite the difference in engineering parameters, all the machines show a similar behaviour in the main dimensionless parameters. This can be read as an indication that this is an appropriate parameterization of the plasma and that an almost universal behaviour is present. In addition, our analysis shows that the magnitude of the same dimensionless parameter can significantly change from one region to another. This translates into a clear separation between core, edge, SOL and divertor regions, in which different mechanisms dominate the turbulence and can be represented with simplified local models. We interpret the observed universal behaviour as a consequence of a high degree of self-organization in the plasma. On this basis, dimensionless analysis can also be seen as a tool to increase the confidence in larger machine extrapolations. At the same time, it can be used as guidance and provide physical insight for new conceptual designs, such as the Super-X divertor in MAST-Upgrade.

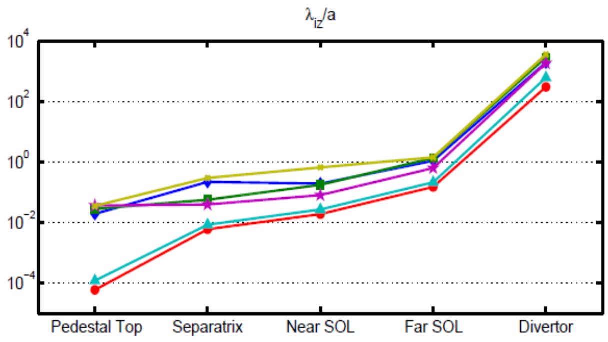

Figure 3: the dimensionless parameters λ_{iz}/a in the six regions of the each machine (H-mode).

Finally, it is interesting to note that the separatrix region emerges as the most complex, in which all three non-adiabatic effects are important. This implies that any realistic integrated model of the plasma must include finite $\hat{\beta}$, C and $\hat{\mu}$. In addition, it is worth mentioning that in this region the neutral particles recycled from the wall and the divertor, and the stochastization of the magnetic field due to the non-axisymmetric fluctuations further complicate the picture.

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