Transport physics of ASDEX Upgrade current ramps: experiment and theory

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Abstract. Interpretative analysis of experimental data from the ASDEX Upgrade tokamak current ramps—up and ramps—down is carried out to shed light on the properties of confinement and transport in these particular phases of the plasma discharge. It is found that the two ramps are similar in parameters evolution, but are not symmetric with respect to the current level, for several reasons that will be elucidated. Theory—based energy transport modeling allows to understand the underlying transport processes at play, although there are limitations in describing the edge part of the plasma at very low currents, in particular during ramp—up. Possible reasons for this discrepancy are discussed. Finally, the relevant turbulence (linear) regime is identified simultaneously with calculations of quasi—linear particle transport, showing that a broad range of modes, from Trapped Electron Modes (TEM) to Ion Temperature Gradient (ITG) modes, is explored during both the ramp—up and ramp—down.

1. Introduction

Understanding the physics of transport in tokamak plasma current ramps at the beginning and at the end of the discharge is crucial to be able to predict the evolution of important global parameters like the internal inductance, the stored energy, the normalized plasma pressure parameter \( \beta_N \), and the required loop voltage in ITER [1], in view of defining the best operational space.

Current ramps are characterized by large changes in almost all the relevant plasma parameters as the current is varied. In addition the two ramps are not symmetric at the same current level, as for example the Ohmic heating power (OH) is large and peaked off—axis in the ramp—up, but small and peaked on—axis in the ramp—down. Current ramps are challenging from the theoretical point of view, since a comprehensive description would require the solution of a highly non—linear problem, where the non—linearities are present either at the microscopic level (turbulent fluxes) and at the macroscopic level (coupling of time—evolving parameters in the transport equations). Note that most of the interest is shifted on the electrons, since the electron temperature profile enters as a critical parameter in the internal inductance, in the loop voltage, and in the stored energy in case of OH cases in which the ions play then a minor role for the total stored plasma energy and in \( \beta \). On the other hand, looking at the ion behavior is instructive to croscheck the validity of the transport model employed and to understand the ion transport channel in more details.

In this work we approach the problem from both the experimental side, considering discharges from the ASDEX Upgrade tokamak, and from the theory side, with theory—based electron energy
transport modeling and turbulence calculations to identify the turbulent regime and compare predictions of quasi–linear particle transport with the experiment.

2. Transport phenomenology of ASDEX Upgrade current ramps

We start by considering a set of OH heated and inductively–driven current ramps from the ASDEX Upgrade shots database. In figure 1 we show the time evolution of the total plasma current $I_p$, the LCFS loop voltage $V_{loop}$, and the internal inductance $l_i$ [1]. The ramp–up (RU) of 1 MA discharge #25804 is shown in figure 1(a), while the ramp–down (RD) of 0.6 MA discharge #23522 in figure 1(b). With vertical dash–dotted lines we show the times at which the X–point is formed and auxiliary heating (NBI in this case) $P_{aux}$ is turned on.

In the RU case, $V_{loop}$ is found to be quite constant at $\approx 1.5$ Volts once the breakdown phase is decayed and the X–point is formed. The bump observed before the X–point formation is due to a rapid plasma volume expansion, which perturb both the plasma edge temperature through adiabatic cooling and the voltage itself due to inductive effects (Faraday’s law). The presence of an X–point has a large effect on both plasma conductivity and energy transport since it allows the edge electron temperature to reach higher values than in the limited configuration, impacting on plasma conductivity on one side, and on the other side reducing the OH power, thus decreasing transport. As illustrated in figure 1, $l_i$ is observed to have a trend which is common to most RUs: it starts from low values at the beginning of the RU, due to an almost flat, or even reversed, $q$ profile, it grows towards a peak, and finally attains a stationary value of $l_i \approx 1$.

Looking now at the RD case, we see that it behaves differently: $V_{loop}$ drops almost to zero, whereas $l_i$ increases monotonically up to large values of $l_i \approx 2$.

In figure 2(a–d), we show radial profiles of the electron temperature $T_e$ (a,c) and density $n_e$ (b,d) for the same RU (a,b) and RD (c,d) cases, at three time slices. The employed radial coordinate $\rho_V$ is defined as $\rho_V = \sqrt{V/V_b}$, where $V$ is the plasma volume enclosed by the flux surface under consideration. $T_e$ attains very low edge values at the beginning of the RU, before the formation of the X–point, and displays a steep gradient, whereas at later times it becomes hotter in the edge and broader. This is observed to be a general behaviour of $T_e$ to lose peaking as the ramp proceeds. $n_e$ is observed to initially have some degree of peaking, which at later
Figure 2. $T_e$ (a,c) and $n_e$ (b,d) profiles for RU #25804 (a,b) and RD #23522 (c,d) shown at different times: for the $T_e$ we show measurements from ECE (empty circles), Thompson scattering (stars) together with a spline fit (dashed lines); for $n_e$ we show the measurements from Thompson scattering (empty circles) together with the spline fit (dashed lines). For #25804, IDA [2] $n_e$ measurements are available and are shown in solid lines.

Figure 3. Database points for several plasma parameters plotted versus the plasma current $I_p$. Open circles belong to ramp-up (‘RU’) cases, while dots belong to ramp-down (‘RD’) cases. Radially–dependent quantities are shown averaged over the interval $0.35 < \rho_V < 0.6$.

times will be more or less lost, depending on the evolution of the other parameters, in particular $T_e$. Note also that the behaviour of $n_e$ can be influenced in case of strong gas fueling at the edge. In the RD an analogous situation emerges for $T_e$, which decreases at the edge and acquires a larger peaking as the current is decreased. For $n_e$ the behaviour is more striking: it strongly peaks as the ramp proceeds, much more than what it does in the RU at the same current. This difference in $n_e$ behaviour between the two ramps will be discussed later in the context of particle transport simulations.

In figure 3 we plot several parameters averaged in the radial interval $0.35 < \rho_V < 0.6$, for all the studied RU cases (empty circles) and for the RD cases (dots) versus plasma current $I_p$.

The behaviour of the parameters with respect to the current appears to be almost symmetric for some parameters ($R/L_{Te}$, $R/L_n$, $\rho_s$, $\nu_s$), but as said before this is more of a coincidence than of a fundamental property. In particular the local magnetic shear, calculated from a magnetic equilibrium reconstructed with ASTRA [3] and the SPIDER code [4], behaves very differently: it is almost constant during the RU, even being lower at lower currents in that phase, while in the RD it monotonically increases as current decreases. Another interesting parameter is $\tilde{v} \div \sqrt{\frac{\nu_a qR}{\nabla T}}$, which represents the impact of collisions on electron banana orbits. High
values of this parameter, which are reached at low currents, can change the relative importance on transport of trapped vs passing particles. Note also that the collisionality itself ($\nu_{\text{eff}}$) can become quite large at low currents, and the same is also valid for (not shown) the effective charge $Z_{\text{eff}}$, making it necessary to consider collisional effects on turbulence, neoclassical transport, and the impact of impurities on transport.

We have not mentioned the ion temperature profile, since almost no information is provided during the ramps. Therefore the behavior of the ions will be studied semi-empirically by modeling them in some way and checking that global properties like the total plasma energy obtained from measurements is consistent with the modeled ion temperature profiles.

3. Theoretical modeling of electron heat and particle transport

We now address the interpretation of the data with theory–based modeling of heat and particle transport.

3.1. Heat transport

Modeling of electron and ion heat transport is done via combined ASTRA–GLF23 simulations, whereas the density is prescribed. ASTRA is employed as the transport modeling framework, for which the internal magnetic equilibrium is reconstructed with the SPIDER code. The GLF23 model provides the turbulence–driven energy diffusivities for $\rho_V \leq 0.9$, outside which radius the profiles are experimentally prescribed. In figure 4(a) we show the comparison between the experimental $T_e$ (solid lines) and the GLF23 predicted $T_e$ (dashed lines) at different times for RU #25804 (left column) and RD #23522 (right column). GLF23 works pretty well either when the RU has already progressed, or when the RD is at the initial stage. At the beginning of the RU it strongly differs in the outer part of the plasma, and the same happens at the end of the RD, although differences arise depending on the case under study. At the beginning of the RU it strongly differs in the outer part of the plasma, and the same happens at the end of the RD, although differences arise depending on the case under study. This emerges clearly when computing the relative difference $dT_e/T_e = \langle |T_e^{\text{GLF}} - T_e^{\text{EXP}}|/T_e^{\text{EXP}} \rangle$, where $\langle \ldots \rangle$ indicates radial averaging, shown in figure 4(b) for all the simulated cases (solid lines for RUs and dashed lines for RDs) plotted versus the plasma current $I_p$: the tendency of the model is to produce larger deviations at lower currents, with absolute values that can depend on the case.
reason behind the discrepancy is that the model does not give sufficient diffusivity at the edge, as compared to the experimental estimate. However, a difference exists between RUs and RDs: in RUs most of the OH power is deposited off-axis, due to the loop voltage profile, and so there is a high sensitivity to the details of transport in the outer plasma, resulting in large discrepancies on the $T_e$ profiles. On the other hand, in RDs the OH power is strongly peaked on-axis, leading to an integrated heat flux in the outer plasma which is very small, or even zero if some loss is accumulated on the way (i.e. radiative losses and power exchange to the ions); therefore, details of transport in the edge region are less important. It must be said that, looking at the eigen-frequencies provided by GLF23 in the edge region during the ramps, ITGs are found to be the dominant modes. It is then tempting to conclude that the underestimate by GLF23 of edge transport could be resolved if a TEM-dominated regime takes place. In some sense, an indication that this should be the case when analyzing edge turbulence is given in Ref. [6], although, as mentioned in that reference, one must be careful since edge turbulence has a high degree of non-linearity which can invalidate the quasi-linear approach.

In figure 4(c) we show the time evolution of the heat diffusivities $\chi$ evaluated at $\rho_V = 0.6$. In the top subplots we compare the electrons (circles) and the ions (diamonds) total diffusivities: the ions always display a larger diffusivity, moreover both diffusivities strongly decrease in the RU case, while they stay almost constant in the RD case. In the bottom sub-plots we split the diffusivities into the turbulent ($eG$ for electrons, $iG$ for ions) and neoclassical ($eN$, $iN$) contributions: in the RU case the neoclassical ion diffusivity dominates at earlier times, thus explaining why the ions are always less confined than the electrons, since a $q$ scaling arising from the neoclassical contribution is well known to go as $\propto q^2$. In the RD case a $q$ scaling seems to be absent, essentially because the variations in $q$ in the core are much less important in the RD than in the RU.

3.2. Particle transport: quasi-linear estimates

Particle transport is modeled via quasi-linear calculations performed with the GS2 code [7], run in linear, electrostatic mode. The magnetic equilibrium is obtained from the Miller parametrization. All profiles are experimentally evaluated, except the ion temperature which in this context is estimated employing the semi-empirical Coppi-Tang transport model [8], which includes fitting coefficients that are varied to match the experimental total plasma energy. For the spectral analysis we employ 12 toroidal modes between $0.08 \leq k_y \rho_i \leq 1.5$ and three species are taken into account: deuterium, electrons, and an impurity species ($A = 24$, $Z = 12$) with concentration given by the experimental value of $Z_{eff}$ and a normalized density gradient of $0.3R/L_n$. The turbulence-driven part of the electron particle flux must fulfill the following balance equation:

$$\Gamma^e_{turb} = -n_e V_W - \frac{1}{(\nabla \rho_V)^T} \int_0^{\rho_V} \frac{\partial V'}{\partial t} d\rho_V$$  \hspace{1cm} (1)$$

where $V_W$ is the Ware pinch velocity, $V'$ is the volume derivative over $\rho_V$. Since $\Gamma^e_{turb}$ is a function of the normalized density gradient $R/L_n$, we perform a scan in this parameter to find the value that satisfies equation (1). We close the problem by assuming a saturated electrostatic potential of the form shown in Ref. [9]. The absolute value of the saturated potential is not needed as in practice we calculate equation (1) normalized to the heat flux $Q_e$, such that on the left-hand side we have a ratio of turbulent fluxes (negligible electrons neoclassical flux is assumed), while for the right-hand side we use the experimentally estimated power–balance heat flux.

In figure 5(a) we show the results for RU #25804 (left column) and RD #23522 (right column). In the top sub-plots we compare the experimental (circles) and the predicted (lines) value of $R/L_n$, at $\rho_V = 0.64$ for the RU and $\rho_V = 0.56$ for the RD, as function of time. The
two radial positions are chosen in the high gradients region not affected by sawteeth. The agreement is pretty good and shows that the code correctly gives the decay (build-up) of the density peaking as the RU (RD) proceeds. The relevant turbulent regime is shown in the bottom sub-plots, where we clearly see a transition from TEM-dominated turbulence ($\omega^{QL} > 0$) at the beginning of the RU, to an ITG-dominated regime ($\omega^{QL} < 0$) towards the flat-top, and vice versa for the RD. The frequency spectrum is shown in figure 5(b), for the RU (top) and for the RD (bottom), at four time slices (in the legend). The observed agreement in $R/L_n$ between code results and experimental data and the behaviour in frequency domain are found to be quite sensitive on the input parameters, of which the ion normalized gradient $R/L_Ti$ is one of the most important. In fact, if $R/L_Ti$ is, say, reduced, then the RU case would have more TEM, eventually leading to lower $R/L_n$ values. This has indeed been checked and for other cases (not shown) $R/L_Ti$ had to be readjusted to obtain good agreement. Luckily the readjustment involved does not require unrealistic values for $R/L_Ti$. In the future, discharges are planned where ion profile measurements will be undertaken during the ramps. Finally, in figure 5(c), we plot the time evolution of the ratio $L_{Te}/L_n$ predicted by the code, which shows that this parameter tends to be maximum when the turbulent regime is between the TEMs and the ITGs, at a value of $L_{Te}/L_n \approx 0.5$, as expected from a previous study [10].

4. Conclusions
In this work we have analyzed the properties of energy and particle transport and confinement observed during current ramp-up and ramp-down phases in ASDEX Upgrade. Parameters variation point out asymmetries between RUs and RDs. Electrons kinetic profiles are found to become more peaked at lower currents. As regards energy confinement, a clear improvement in time is observed in RU, while no significant change is observed in RD. Theory-based transport modeling is in agreement with the observed trends for confinement, although there are severe limitations on the description of edge transport. GLF23 predicts for these cases a marginal role for a $q$–scaling of turbulent origin. On the other hand ion neoclassical transport is found to be relevant. Quasi-linear calculations of particle transport show good agreement between predicted and experimental values of $R/L_n$, in trend and in amplitude. The relevant turbulent regime is found to change from a TEM-dominated regime at low $I_p$ to an ITG-dominated regime at
higher $I_p$. Accordingly, the ratio $L_{Te}/L_n$ follows, being maximal when the regime is closer to TEM, as expected from previous studies [10].

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