Transport Analysis for Current Build-Up in ASDEX and JET

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Abstract
Neoclassical resistivity describes the current penetration for MHD stable current ramp-up in ASDEX with $\dot{I} \leq 1$ MA/s showing monotonously increasing q(r) profiles during current rise. Simulations for JET yield the same current ramp rates, bute these can be increased by a factor of 3 if the current is ramped up together with the toroidal field.

1. Introduction

In a tokamak discharge MHD activity increases with increasing rate of current rise and finally disruptions occur. On the other hand, lowering the current ramp rates leads for large experiments like JET to current rise times amounting to a large fraction of the main field pulse duration.

Experiments on current ramp rates in ASDEX /1/ showed that for current rises below 1 MA/s MHD activity could be avoided. But too strong gas puffing during current rise leads also to hard disruptions of the high density limit type. In the present paper the current start up phase of ASDEX is analyzed, and optimum current build-up scenarios for JET are developed and simulated numerically with the 1d-Baldur transport code /2/.

2. Current Build-Up in ASDEX

In standard operation the plasma current I in ASDEX is ramped up in two stages. Up to a current between 50 and 100 kA the initial current rise is rapid with $1.5 < \dot{I} < 3$ MA/s, and then a much slower one follows with $\dot{I} \leq 1$ MA/s to reach 300 to 450 kA. Electron temperature T_e (ECE, Thomson scattering) and density n_e (HCN-interferometry) measurements show rather flat radial profiles at the beginning of the discharge peaking up towards the end of the current rise. Using the time development of these measured profiles together with the loop voltage, β_p and l_i the current ramp has been simulated with the Baldur transport code and neoclassical resistivity. Anomalous electron thermal diffusivity in the form $\chi_e = \frac{3.4 \cdot 10^{15} B_t a/R}{n_e^{0.8} T_e q}$ [m^2/s, T, m^{-3}, keV], a particle diffusion coefficient $D = 0.2\chi_e$ and an inward drift velocity $v = \frac{3r^2}{a^3} \cdot D$ are taken /3/. As impurities the species iron (produced by a sputtering model) and oxygen (influx is varied to get the measured Z_{eff} and the bolometrically measured radiation losses) are taken into account using a noncoronal diffusion model /4/. The simulations start typically 10 ms after the discharge has started with an I of 30 to 50 kA. The measured T_e and n_e profile evolutions are obtained as well as the onset time of sawtooth activity which is taken from the calculations as the time when $q(o) = 1$ is reached (see Fig. 1). No hollow $T_e(r)$ or toroidal current density $j(r)$ profiles are found and the $q(r)$ profiles are monotonously increasing towards the boundary. Increasing the current ramp rate above 1 MA/s after the first rapid rise yields skin currents and nonmonotonous q-profiles, which can be unstable to double tearing modes /5/.

The electron density rise is kept below $\dot{\bar{n}}_e = 1.5 \cdot 10^{20}\ m^{-3}\ s^{-1}$, but has to be even lower for dirty discharges. Increasing the density rise above that limit for $\dot{I} = 1$ MA/s leads to hollow density profiles in the simulations which seem to be vulnerable for density limit disruptions. Writing the density limit for low Z_{eff} ohmic discharges as

$$\bar{n}_e \leq 1.25 \cdot 10^{20}\ B_t/(Rq_a^*) = 0.25 \cdot 10^{20} \frac{I}{b \cdot a} \frac{2K}{K^2+1}\ [m,T,MA]\ (K = b/a)$$

yields for ASDEX $\bar{n}_e \leq 1.5 \cdot 10^{20}\ I$ [m,MA] which is equal to the critical value during current rise.

3. Current Build-Up in JET

Simulations for JET ($a_{eff} = \sqrt{b \cdot a} = 1.6$ m, R = 3 m) with the same model as described above lead to a minimum current rise time of 3 sec for a current increase from 1.5 MA to 4.5 MA ($B_t = 3.1$ T) both with a constant density of $\bar{n}_e = 1.5 \cdot 10^{19}\ m^{-3}$ and with a density increase of $\dot{\bar{n}}_e = 0.25 \cdot 10^{20} \frac{\dot{I}}{ba}$ [m,MA,s] to avoid nonmonotonous $q(r)$ profiles and hollow density profiles. High Z_{eff} (> 3) values with radiation losses up to 50 % of the ohmic input power allow only slightly higher ramp rates. $q(o)$ values between 1.5 and 2 are obtained at the end of current rise. With longer rise times

($\dot{I} < 0.6$ MA/s) q(o) = 1 is reached during the ramp-up. Current ramp from 0.2 MA to 2.2 MA at 2.2 T need equal ramp rates (a_{eff} = 1.1 m), and with $\dot{I}$ = 0.67 MA/s q(o) = 1 is already reached during ramp-up after 1.8 sec in agreement with experimental results.

Efficient use of the JET main field pulse capabilities suggests to carry out the current build-up contemporary with the B_t-increase, which according to the scaling laws of the main field compression should eliminate the tendency for skin current formation keeping q at the plasma boundary fixed. Therefore main field compression at fixed toroidal radius has been included in the Baldur code by varying at the beginning of each time step plasma parameters in correspondence with the laws of adiabatic flux conserving compression followed-up by the solution of the diffusion equations.

Different combined B_t and I ramp-up scenarios have been investigated for JET parameters and Fig. 2 compares computed profiles after 1 sec rise time with and without ramping from 1.03 T to 3.1 T for $I_p = 1.5\text{MA} \rightarrow 4.5$ MA, $\bar{n}_e = 1.5 \cdot 10^{19} \rightarrow 4.5 \cdot 10^{19}$ m^{-3}, R = 3.05 m, a_{eff} = 1.6 m and Z_{eff} = 1.5. Without B_t ramping q_a^* decreases from 9 to 3, whereas it is kept at $q_a^* = 3$ with B_t ramping. Current rise starts in both cases with the same T_e and n_e profiles. With B_t ramping monotonous q(r) profiles and peaked density profiles result, but the profiles obtained with a constant B_t would show strong MHD activity during ramp-up and with strong gas puffing (the case shown here) probably a density limit disruption.
Notice that also with peaked temperature profiles skin currents are possible during the start-up phase.

Due to the adiabatic compression of the poloidal flux with B_t ramp-up the toroidal current density in the plasma is increased by an amount depending on the relation between compression time and diffusion time. The resulting higher T_e-values lead to a lower resistive loop voltage, and less resistive flux is needed from the OH transformer which is clearly seen in the transport calculations. On the other hand, due to the increase of $\frac{l_i}{2}$ from 0.6 to 0.9 an appropriate flux change $I \cdot \Delta L$ has to be provided by the OH circuit which might counterbalance the flux gain seen in the transport calculations. With the faster current penetration q(o) = 1 is reached earlier, and the corresponding onset of sawtoothing should help to suppress dangerous m = 2 MHD activity.

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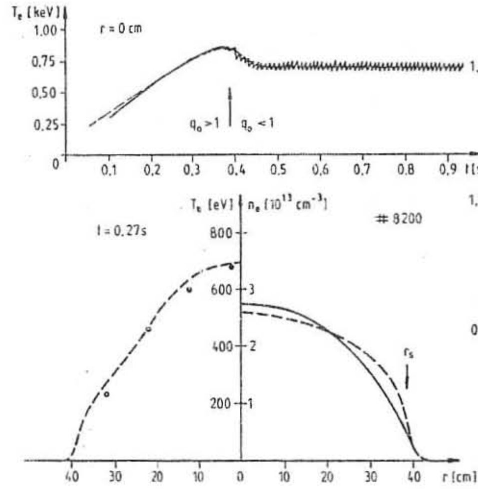

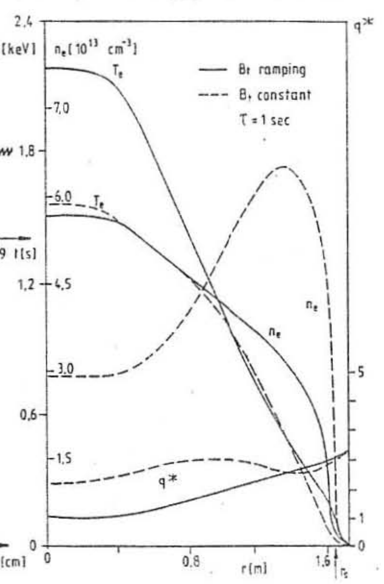

Fig. 1: T_e (r = 0 cm) vs. time and T_e and n_e profiles after current ramp-up at 0.27 s in ASDEX discharge # 8200
measured values: ——, •
calculated values: -----

Fig. 2: Calculated $T_e(r)$, $n_e(r)$ and q(r) profiles after 1 sec current ramp-up in JET from 1.5 to 4.5 MA at constant B_t = 1.3 T (---) and with simultaneous B_t ramping from 1.03 to 3.1 T (——). Electron density increases from 1.5 to $4.5 \cdot 10^{19}$ m^{-3} in 1 s.

The authors would like to thank A.Eberhagen and O.Gehre for the measurements.