

Relation between Core Impurity Accumulation and Ion Loss due to toroidal Ripple in Tore Supra

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Introduction: Charge exchange spectroscopy (CXs) measurements of time-dependent radial profiles of carbon density show an interesting transient behavior (rapid expulsion) during a brief ICRH-power reduction from 4 to 2 MW. We also observe a clear correlation between fast ion losses due to toroidal field ripple and this transient event. As is well known, ripple in the magnetic field strength due to the finite number of tokamak toroidal field coils destroys the axisymmetry of the magnetic field, so that energetic ions can be trapped in ripple wells and drift vertically out of the plasma. On Tore Supra (TS), the ripple losses of fast ions during Ion Cyclotron Frequency (ICRH) heating have been extensively studied [1], since TS has a ripple of $\sim 7\%$ at the plasma edge. The ripple losses can be expected to modify the ‘ambipolarity’ constraint, which determines the radial electric field, through the requirement that the ion and electron fluxes be equal. The observed impurity response suggests that a major component of accumulative behavior could be due to the ripple loss, and not to inherent transport properties.

Experiment: After a high power lower hybrid (LH) heating phase, which was intended to produce an Internal Transport Barrier, the LH-heating is stopped and ICRH commences

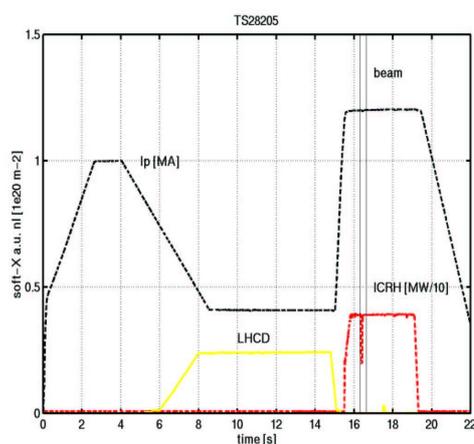


Fig.1 plasma current I_p and heating power

(fig.1). The CXs diagnostic beam was fired at 16.31s as the ICRH-power reaches its flat-top of 4MW. 20ms later the RF power (unintentionally) dropped to 2MW for 100ms. During these steps the profile changes of the fully ionized carbon were measured with a relatively fast time resolution (8ms). We use a fast filter spectrometer (FFS) [2] with 7 adjacent viewing lines in parallel with the classical

grating spectrometer, which is equipped with a CCD camera. The acquisition time is 80ms for an equivalent signal to noise ratio. During the transient RF-power reduction the core impurities are expelled, then re-accumulate.

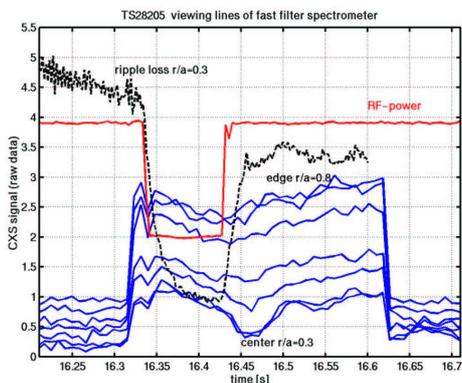


Fig.2 raw signal of FFS and ion ripple loss

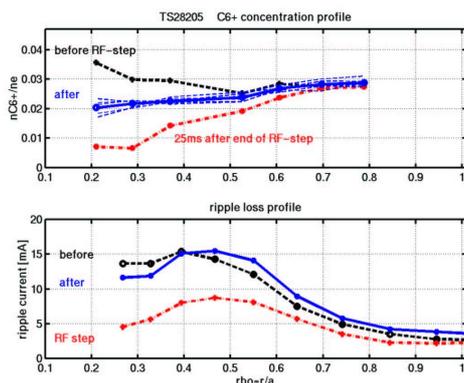


Fig.3 impurity and ion ripple loss profiles

This is seen on fig.2 where the fast filter spectrometer signal of the 7 viewing lines (from edge to center of the plasma) is shown along with the ripple loss signal. The measured, absolutely calibrated, ripple ion loss flux closely follows the RF-power step, whereas the carbon density in the plasma core changes with a slower time constant.

Between the edge ($r/a=0.8$) and the center ($r/a=0.3$) a delay of about 40ms is observed. Figure 3 shows the evolution of the carbon concentration n_{C6^+}/n_e and the ripple loss profiles before, during and after the RF-step. The magnitude and time dependence of the ripple loss is consistent with the observed change in central radial flux of impurities.

Interpretation: An empirical analysis, using only the measured time-dependent carbon profiles $Nz(r,t)$, shows the occurrence of a strong outward impurity flow correlated with the ripple ion loss. In the source free region of C^{6+} the continuity equation $\frac{1}{\rho} \frac{\partial}{\partial \rho} (\rho \Gamma_z) = \frac{\partial Nz}{\partial t}$ is solved for the impurity flux $\Gamma_z(\rho,t)$ (see

fig.4 upper right). We parametrize the anomalous impurity flux $\Gamma_z = -Da \frac{\partial Nz}{\partial \rho} + Nz \cdot Va$,

(Da and Va are defined, respectively, as the anomalous diffusion coefficient and the pinch velocity) and plot $\Gamma_z(\rho,t)$ versus $\frac{\partial Nz}{\partial \rho}$. The pinch flux $\Gamma_{pinch} = Nz \cdot Va$ is obtained for $\frac{\partial Nz}{\partial \rho} = 0$ (intersection with the y-axis on the lower left figure of fig.4).

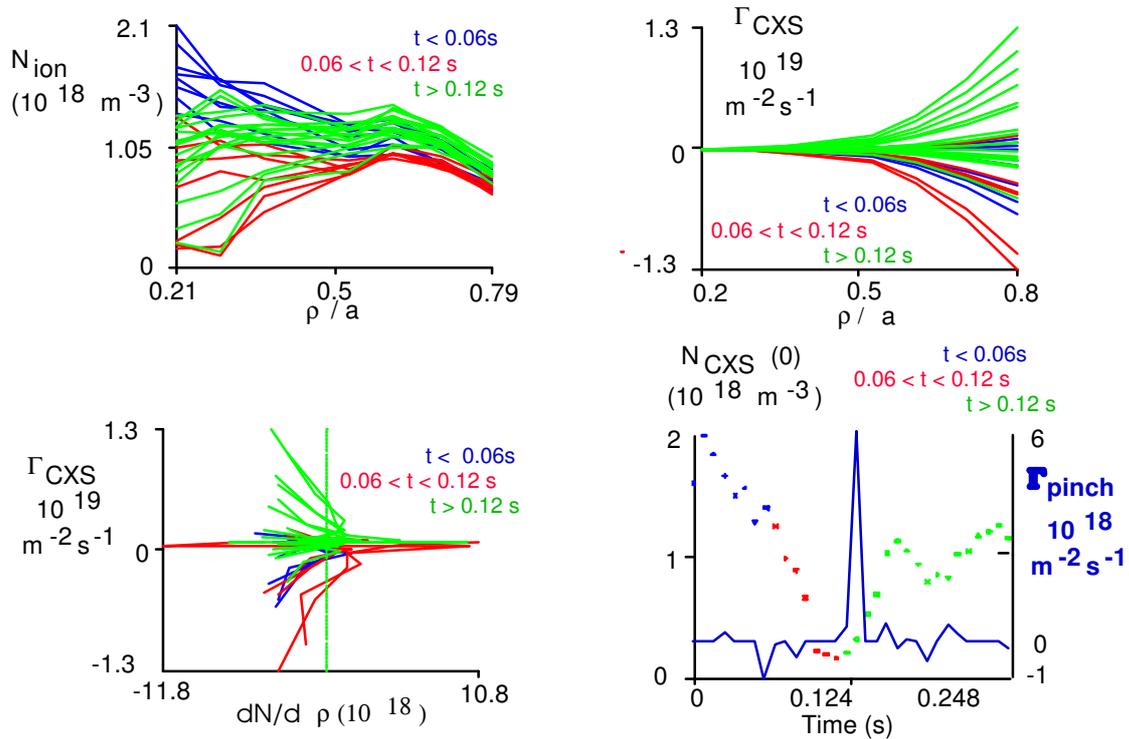


Fig.4 C^{6+} profiles and calculated flux Γ_{CXS} (upper left and right), Γ_{CXS} versus $\partial N/\partial \rho$, Γ_{pinch} and central carbon density $N_{\text{CXS}}(0)$ (lower left and right). Before (blue), during (red) and after (green) power transient. Time-steps between profiles 8ms, from 0 to 248ms.

Modelling of this transient behavior has also been carried out with a 1-D radial transport code (MIST – R.Hulse, PPPL) and a 3-D code for the edge/scrape-off layer (BBQ - ORNL). The 3-D edge/SOL model is important because a substantial fraction of the impurity influx occurs through fuelling by multi-charged ions, rather than by neutral impurities, as is often assumed. A “reference transport model” established with and without ICRH-heating is applied before the transient ICRH-power step. As shown in fig.5, the calculated radiated power Prad closely follows the measured bolometric values. This means that the C, O concentrations deduced from Z_{eff} and CXS-measurements account for the total radiated power. The carbon concentration is simulated for three time steps: before, during and after the power transient (lower left and right of fig.:5).

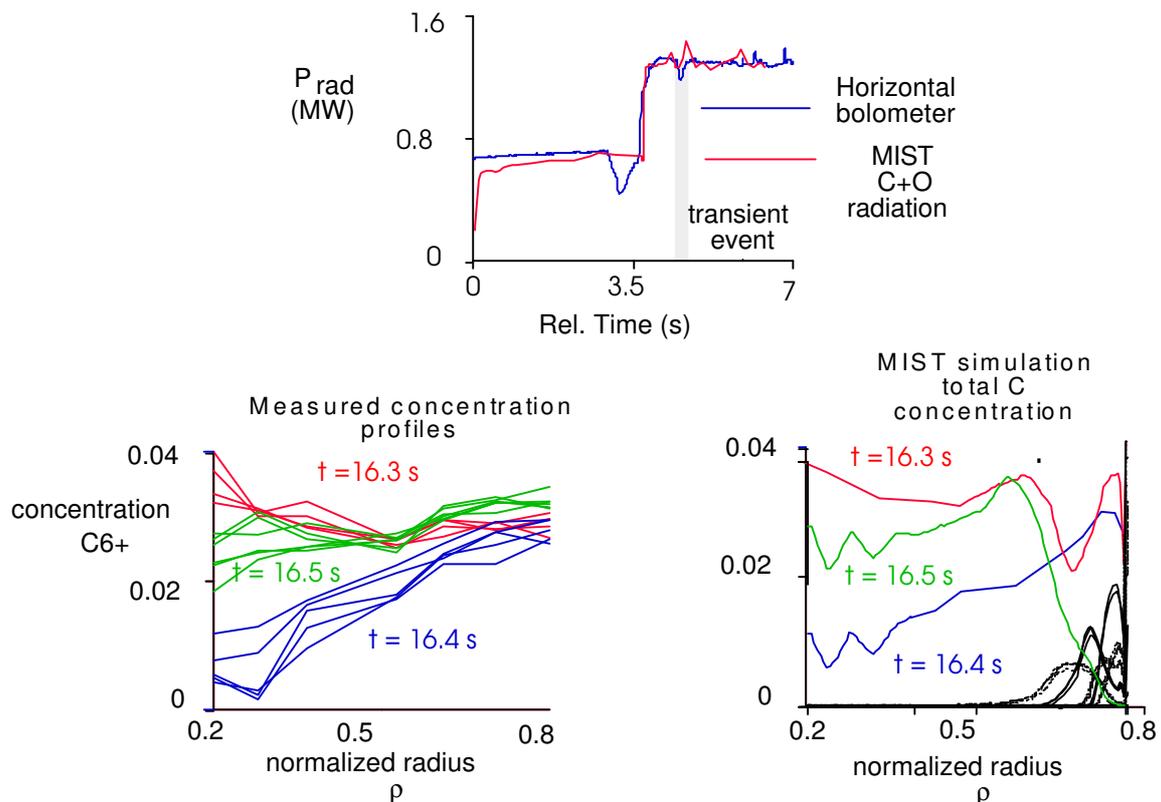


Fig.5 MIST simulations; upper figure P_{rad} ; lower left: CXS-measured C^{6+} profiles; Lower right: Carbon concentrations before, during, after the power transient.

Transport theory: As the energetic ions (protons due to H-minority heating) drift vertically out of the plasma, the radial electric field $E_r = -\partial\Phi/\partial r$ maintains the ambipolarity of the plasma [3]. The driving term for the ripple induced flux of the impurities is the change of the total flux of the positive ions $\sum Z_a \cdot e \cdot \Gamma_a$ due to the change in the ion ripple loss $\partial N_{ripple}/\partial t$. The magnitude of the radial flux change (from D,V) is shown to be consistent with the change in radial flux produced by the change in ripple loss, through the ambipolarity condition. This analysis suggests that a major part of the accumulative behavior (a typical feature of Tore Supra ITB conditions) could be due to the ripple ion loss.

References:

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