Modeling of Recycling Coefficients and Wall Equilibration in Tore Supra*

P. K. Mioduszewski[1], L. W. Owen[1], and B. Pégourié[2]
[1]*Oak Ridge National* B. *Laboratory, Oak Ridge Tennessee, 37831, U.S.A*
[2]Equipe Tore Supra, CEA, Cadarache,France

Tore Supra will enter a new phase in the summer of 2001. The CIEL and CIMES projects on Tore Supra are aimed at long-pulse power and particle handling and long-pulse heating [1]. For efficient long-pulse particle handling, it is important to understand wall recycling. Wall recycling usually evolves as a function of time during the discharge from low recycling (depleted walls) to high recycling (saturated walls). Since the particle fluxes can vary over the vacuum vessel wall by up to five orders of magnitude, the recycling coefficients will vary correspondingly. Furthermore, since the particle fluence to the various parts of the wall evolves during a plasma discharge, the recycling coefficient evolves with the fluence or, at a given flux, with time. Hence, the actual recycling coefficient has strong spatial and temporal variations during a plasma discharge. To better understand which parts of the wall are pumping (sink) or fueling (source) throughout the time evolution of a discharge, we perform a detailed analysis of recycling during a long pulse discharge in Tore Supra as a function of location and time.

For this purpose we sub-divide the vacuum vessel into 73 poloidal segments (see Fig. 1) and use a neutrals transport code to calculate the particle fluxes to each of these segments. Then we define an analytical formula for a fluence-dependent recycling coefficient which is applied to each of the 73 segments to calculate the local recycling throughout the discharge. In this way we are able to predict as a function of time which parts of the wall are pumping (R<1) or fueling (R≥1). Since Tore Supra will have active exhaust via the CIEL pump limiter, wall pumping will also be compared with pump limiter exhaust.

In the present work we assume exponential dependences for the radial profiles of plasma density and temperature in the scrape-off layer (SOL). The density and temperature ($T_e = T_i$) at the last closed (tangency) flux surface are taken to be 1.25 x 10^{19} m^{-3} and 50 eV, respectively. The core plasma is described by quadratic profiles with n = 5 x 10^{19} m^{-3} and T = 2 keV on axis. These parameters are appropriate for a discharge in which the volume-averaged density is approximately 4 x 10^{19} m^{-3} [1]. The ion particle flux decay length in the SOL and at the limiter is assumed to be 2.3 cm [1] and the corresponding integrated ion flux to the toroidal limiter is 3 x 10^{22} s^{-1}. The major and

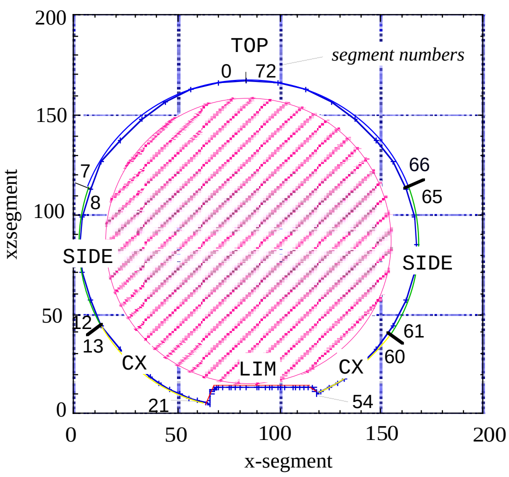

Fig.1 Tore Supra plasma-facing components, divided into: top-, side-walls, cx-area, and limiter.

minor radii of the plasma are 0.72 m and 2.4 m, respectively. The distributions of neutral particle flux and energy on the limiter and vacuum vessel wall segments are determined with the Monte Carlo neutrals transport code DEGAS [2]. In the simulations the vacuum vessel receives particle flux only from charge-exchange and Franck-Condon neutrals. The total core plasma charge-exchange rate (1.28×10^{22} s^{-1}) is 20% larger than the core ionization rate. These energetic core charge-exchange neutrals constitute a large fraction of the particle flux on wall segments that are remote from the toroidal limiter.

Particle fluxes on plasma-facing surfaces can vary between 10^{10} $cm^{-2}s^{-1}$ at the top of the vacuum vessel to 10^{18} $cm^{-2}s^{-1}$ at the limiter. Due to this wide variation of the fluxes, an average recycling coefficient for the vacuum vessel is not very meaningful and, therefore, we divide the vacuum vessel and the limiter into 73 segments and calculate the fluxes for each of the segments. To make the main features of the calculations more transparent, we also group several segments of similar fluxes into a total of four zones. Figure 1 shows a poloidal cross section of the Tore Supra vacuum vessel, with the limiter and the plasma and the four zones, which comprise the top wall, the side walls, the charge-exchange zone around the limiter, and the pump limiter. The distribution of the segment areas as well as the particle fluxes and energies for each segment are depicted in Fig. 2.

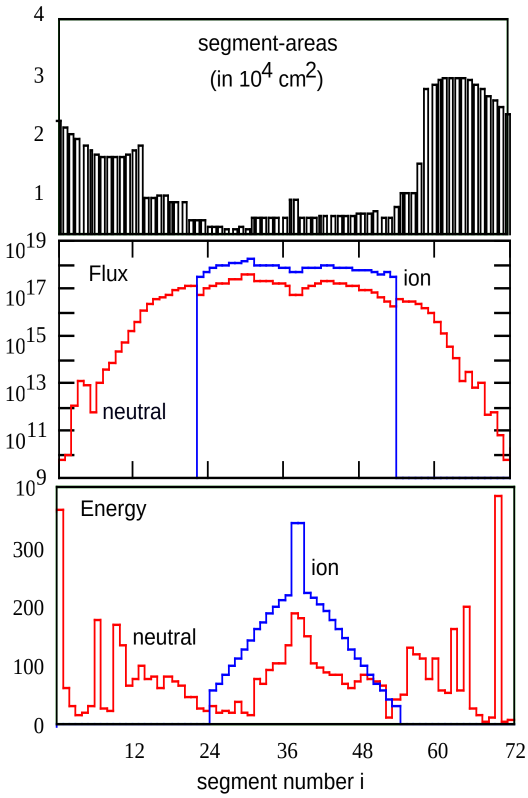

Fig.2 Distribution of segment areas and particle fluxes and energies

During a plasma discharge the local recycling coefficients evolve as functions of the trapped fluence which is usually a function of time. To follow this evolution, we have constructed an analytical formula for the recycling coefficient which is a good approximation of measured values [3] and also of TRIM calculations published by W. Eckstein [4]. This simple formula can then be applied to all 73 wall segments for which the particle fluxes have been calculated. The fluence-dependent recycling coefficient as a function of the trapped particle density n_{tr} is expressed as:

$$R(n_{tr}) = a \cdot \tanh\left\{\frac{n_{tr} - n_{sym}}{\delta}\right\} + c. \tag{1}$$

The four coefficients a, c, n_{sym}, and δ are used to adjust R according to initial value, particle energy, and depth distribution (mono-energetic or Maxwellian); more details are discussed in [5]. Here we use the coefficients for 100 eV and Maxwellian distribution, and R = 0.4 for the initial value.

In the following, we calculate the evolution of the recycling coefficients assuming constant plasma density and constant fluxes to the walls. The recycling coefficient for each segment is then a function of the trapped fluence in that particular segment. That is, the trapping rate of atoms per unit area depends on the number of atoms already trapped in the surface. With ϕ_{in} the incident particle flux, this rate is described by the differential equation:

$$\frac{dn_{tr}}{dt} = \phi_{in} \cdot (1 - a \tanh\left\{\frac{n_{tr} - n_{sym}}{\delta}\right\} + c) \tag{2}$$

which is solved numerically for all 73 segments to yield the number of trapped atoms as a function of time. Equation (1) can then be used to calculate the recycling coefficient for each segment as a function of time. The result is depicted in Fig. 3. Here we show the recycling coefficients for some characteristic segments in the top-wall, side-wall, charge-exchange zone, and pump limiter segments for a pulse length of 200 s. It is clear from Fig. 3 that the segments on the limiter are saturated in less than a second into the discharge. As the recycling coefficients approach unity, the corresponding wall segment changes from net pumping to net fueling. This change occurs on the limiter at around 1 s, at the charge-exchange zone at approximately 10 s, at the side walls at several 100 s, and at the top wall at thousands of seconds. So, during the discharge, some parts of the plasma-facing components saturate and begin acting as a net fueling source, while other parts still act as a sink.

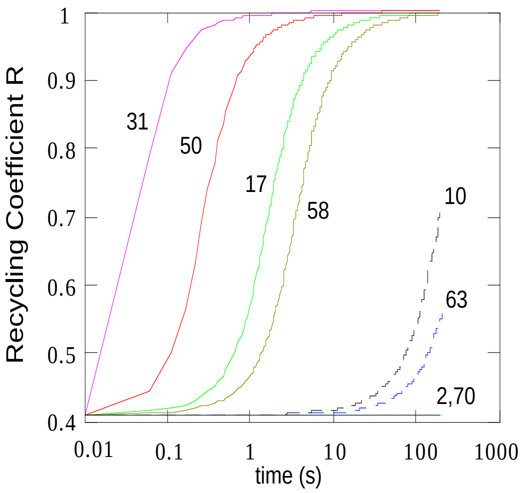

Fig. 3 Recycling coefficients for selected segments: 31, 50 on the limiter leading edges; 17,58 in cx zone; 10,63 on side-wall; and 2,70 on top-wall

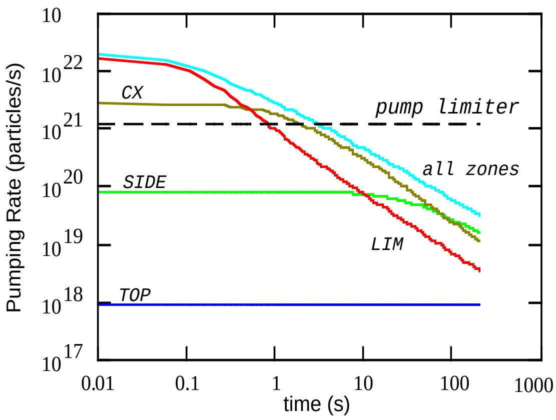

Fig. 4 Pumping rates for each zone and the pump limiter

The pumping rates in the four zones as a function of time are depicted in Fig. 4. Also plotted is the summation over all zones which represents the total wall pumping. For comparison the particle removal by the pump limiter has also been simulated. For this case we assume that the segments which make up the pump limiter slot have a constant recycling coefficient of R = 0.5. As we can see from Fig. 4, at the start of the discharge the limiter zone dominates the wall pumping with an initial pumping speed of 44 Pa m^3/s that drops rapidly. At 0.8 s the cx-zone, initially with 5.2 Pa m^3/s, dominates the pumping at a level of 4 Pa m^3/s. From 1 s to about 100 s pumping by the cx-zone exceeds that of the limiter and side walls, after which the side walls dominate, but at levels below 0.1 Pa m^3/s. During the whole discharge the top wall is pumping at a negligibly low 2 x 10^{-3} Pa m3/s. This analysis shows that the relevant wall pumping happens at the limiter and at the cx surfaces near the limiter. The summation over all zones shows that the effective wall pumping lasts several seconds. For the parameters chosen here, the pump limiter exhaust is 2.4 Pa m^3/s and dominates the overall pumping for times t > 3 s. This example shows that for short pulses (2-3 s) the pump limiter exhaust does not have a large effect on the overall pumping whereas for longer pulses (above ~3 s) the pump limiter exhaust dominates the overall particle sink.

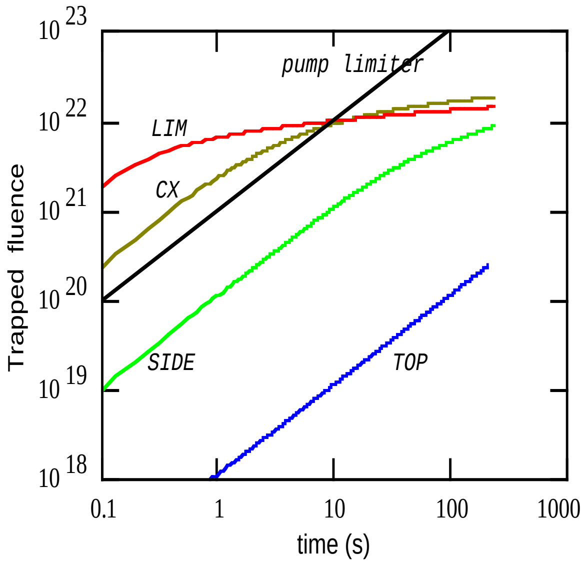

Fig. 5 Trapped particle fluence for each zone and pump limiter

For the particle balance it is also of interest to examine the total trapped fluences for the four zones and the pump limiter exhaust. During the first 10 s the trapped particle fluence is largest in the limiter surface and at about 10s equals that in the cx zone. For t > several 100 s, the inventory of the side walls begins to dominate.

For particle balance considerations in long-pulse operation, a detailed analysis of the wall pumping and particle inventories is necessary. The present model allows one to follow the evolution of wall recycling for each part of the wall with its particular particle flux. The analysis shows that significant wall pumping lasts only for a few seconds and for particle control beyond times of about 3-4 s, active exhaust through a pump limiter or pumped divertor becomes necessary. Future improvement of the model will include further differentiation of the recycling coefficient according to particle energy distribution.

*Oak Ridge National Laboratory is managed by UT-Battelle LLC for the U.S. Department of Energy under contract number DE-AC05_00OR22725.

REFERENCES:

[1] The Tore Supra team, "CIEL Project - Application for Preferential Support - Phase 1 and Phase 2", EUR FU (96) CCFP 69/8.3, December 1996.

[2] D. B. Heifetz, D. Post, et al., J. Comp. Phys. 46 (1982) 309-327.

[3] A. Haasz et al., J. Nucl. Mater. 232 (1996) 219.

[4] W. Eckstein, “Calculated Trapping Curves of D in C and Si,” Garching Report IPP 9/33, October 1980.

[5] P. K. Mioduszewski and L. W. Owen, J. Nucl. Mater. 290-293 (2001) 443-447