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Simulation of different pumping configurations for the CIEL project on Tore Supra

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Abstract

In the framework of the CIEL project, allowing to improve Tore Supra heat and particle exhaust capability, a toroidal pump limiter will be implemented in the bottom of the machine. This paper presents the study of the pumping system associated with this limiter, in terms of pumping efficiency and extracted flux. Simulations have been performed for different configurations, using the EIRENE neutral transport code, and show that the pumping system should provide efficient density control for the scenarios contemplated for CIEL. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Pumping; Neutral gas modeling; Monte Carlo simulation; B2/EIRENE; Pump limiter

1. Introduction

Particle control is crucial for long pulse operation in future fusion devices. The Tore Supra tokamak, the goal of which is to achieve high performance stationary discharges, is particularly well suited to study particle exhaust over long duration. The importance of a powerful pumping system has already been clearly identified in Tore Supra: even though the control of long pulses has been demonstrated with discharges as long as 120 s [1], a density rise is often observed after 60 s or so, depending on the wall saturation, the type of plasma–wall interaction, the level of input power, and the plasma density [2]. In the frame of the CIEL project [3], allowing to improve the heat and particle exhaust capability of Tore Supra, particular attention has been paid to the pumping system. It should provide efficient plasma density control over long duration (design pulse length: 1000 s) and be able to exhaust the large particle source due to pellet injections foreseen to feed the discharge (up to 4 Pa m^3 s^{-1}, roughly equivalent to 10^{21} D_2 particles s^{-1}). It should sustain high heat fluxes (15 MW of conductive power expected in the scrape off layer (SOL)) and operate for the two main scenarios contemplated for the CIEL project:

- a standard scenario at full plasma current ($I_p = 1.7$ MA) and low density ($\langle n_e \rangle \sim 2 \times 10^{19}$ m^{-3}), where the current is sustained only by lower hybrid current drive,
- an advanced scenario, at lower plasma current ($I_p = 1$ MA) and higher density ($\langle n_e \rangle \sim 4 \times 10^{19}$ m^{-3}), where the bootstrap current fraction is expected to be important.

In this paper, we will describe the exhaust system designed for CIEL according to these requirements, and give the results of the simulation of the pumping performances expected for such a device in the different configurations mentioned above.

2. Description of the CIEL pumping system

In tokamaks, pump limiters have widely demonstrated their ability to control the plasma density [4]. In the framework of the CIEL project, a toroidal flat pump limiter (TPL), designed to remove a conductive power of 15 MW in a steady-state regime, will be installed at the bottom of the machine. The pumping system of the TPL

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consists of 12 discrete neutralizer sets, intercepting the ion flux in the SOL. They are located on the high field side, above each of the 12 vertical ports of Tore Supra, out of which 10 are devoted to pumping, while two are devoted to traversing diagnostics. The neutralizers are uniformly distributed around the torus (every 30°), although the vertical ports are not (two adjacent vertical ports in every 60° sector of the machine, separated by 20°, leaving a gap of 40° for the next sector vertical ports), so that the incident particle flux is evenly shared between them. Each neutralizer set is composed of four elements, called fingers, using the same technology as the elements of the TPL for heat removal (CFC tiles bounded to Cu–Cr–Zr tubes). These fingers are assembled in a V shape, in order to trap neutrals into a closed geometry. They communicate with the vertical port through an expansion box, located below the fingers, and a bellow, allowing the neutralization system to follow the TPL motion up and down. The pumping is ensured by a set of five cryomechanical pumps [5] (one for every two adjacent vertical ports), located 2 m below Tore Supra in order to avoid high magnetic fields. These pumps should be able to provide a high pumping speed over long duration (around 10–12 $m^3 s^{-1}$ per pump) and to extract different species (D_2, He, Ne, Ar). Fig. 1 gives an overview of the pumping system for two adjacent vertical ports, with the neutralizers located below the TPL, the expansion boxes, the vertical ports (not drawn here) and the ducts leading to the cryomechanical pump. In order to evaluate the pumping capability of such a system, simulations of neutral transport have been performed for the different scenarios contemplated for CIEL.

3. Modeling

The performances of the pumping system have been evaluated in terms of global pumping efficiency and exhausted flux.

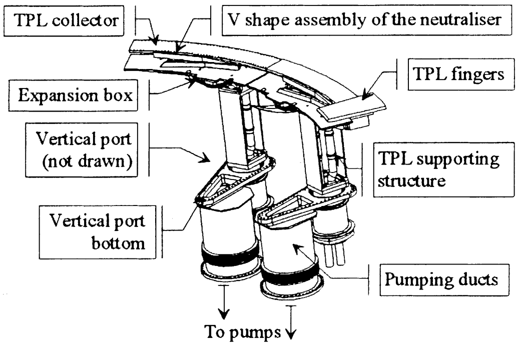

Fig. 1. Overview of the pumping system foreseen for the CIEL project.

In order to define the global pumping efficiency of the system, let us follow the particle flux balance in the SOL [1]. Let Φ_{out} be the net plasma outflux at the last closed flux surface. Φ_{out} can be written as

$$\Phi_{\text{out}} = \frac{N}{\tau_{\text{p}}}, \tag{1}$$

where N is the total number of particles in the plasma, and τ_{p} is the particle confinement time.

Taking into account the sheath conditions [6], the incident flux on the TPL Φ_{inc} is given by the following integration over the SOL

$$\Phi_{\text{inc}} = \int\limits_{\text{SOL}} \frac{1}{2} n c_{\text{s}} \, \text{d}S, \tag{2}$$

where n is the unperturbed particle density far from the limiter, and c_{s} is the ion acoustic velocity.

The incident flux Φ_{inc} can be related to the plasma outflux Φ_{out} through an amplification factor f_{A}, due to re-ionization in the SOL

$$\Phi_{\text{inc}} = f_{\text{A}} \Phi_{\text{out}}. \tag{3}$$

The throat of the limiter intercepts a fraction Φ_{inter} of the incident flux Φ_{inc}. We can then define the interception efficiency of the throat $\varepsilon_{\text{inter}}$, depending mainly on the position of the throat in the SOL compared to the radial decay length of the particle flux λ_{Γ},

$$\varepsilon_{\text{inter}} = \frac{\Phi_{\text{inter}}}{\Phi_{\text{inc}}}. \tag{4}$$

The pumps extract a fraction Φ_{ex} of the flux intercepted by the throat Φ_{inter}. We can then define a collection efficiency $\varepsilon_{\text{coll}}$, depending mainly on the design of the pumping system (conductance, pumping speed) and on the local plasma characteristics in the throat,

$$\varepsilon_{\text{coll}} = \frac{\Phi_{\text{ex}}}{\Phi_{\text{inter}}}. \tag{5}$$

The particle flux circulation described above is sketched in Fig. 2.

The global pumping efficiency $\varepsilon_{\text{pump}}$ of the system can then be defined as the flux extracted by the pumps Φ_{ex} divided by the net plasma outflux Φ_{out}, which gives according to Eqs. (1)–(5),

$$\varepsilon_{\text{pump}} = \frac{\Phi_{\text{ex}}}{\Phi_{\text{out}}} = f_{\text{A}} \varepsilon_{\text{inter}} \varepsilon_{\text{coll}}. \tag{6}$$

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[1] At this stage of the modeling, we will not introduce the action of the wall on the particle flux balance in the SOL, although it has been demonstrated to play an important role as a particle source or sink in Tore Supra [10]. For the long discharges foreseen (1000 s), we will assume that the system is at equilibrium, and that there is no pumping or outgassing by the wall.

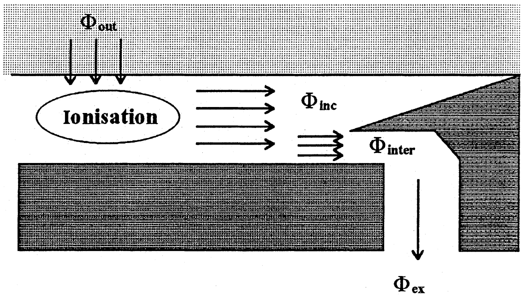

Fig. 2. Definition of the pumping efficiency.

In order to evaluate the global pumping efficiency, the three components of Eq. (6) are computed. The amplification factor f_A is estimated from an analytical neutral transport code [7], calculating the fraction of the incident flux re-ionized in the SOL. The interception efficiency ε_{inter} is estimated from the integration of the incident flux over the throat, taking into account the magnetic configuration (Shafranov shift, ripple, shadowing of other objects in the chamber). The collection efficiency ε_{coll} is estimated from simulations of neutral transport from the throat to the bottom of the vertical port, using the 3D Monte Carlo neutral transport code EIRENE [8].

The extracted flux Φ_{ex} is then derived from normalizing the EIRENE calculations by the flux entering the throat Φ_{inter}.

The main input parameters for the modeling are the plasma position on the limiter, the density and temperature profiles in the SOL and the effective pumping speed at the bottom of the vertical port S_{eff}, taking into account the pumping speed of the cryomechanical pumps and the conductance of the pumping ducts. The plasma profiles are supposed to be exponentially decaying in the radial direction, therefore they are defined by giving $n_e(a)$ and $T_e(a)$ at the last closed flux surface, and the decay lengths λ_n and λ_T. Furthermore, at this stage of modeling, the plasma is supposed to be pure deuterium (no impurities) so $n_e = n_i$ and we suppose $T_e = T_i$.

4. Simulation of the pumping system

4.1. Sensitivity to plasma conditions at the last closed flux surface

The performances of the pumping system have been evaluated for a wide range of plasma density [$n_e(a) = 10^{18}$–1.5×10^{19} m^{-3}] and temperature [$T_e(a) = 30$–200 eV], going from a typical ohmic discharge to the full power scenario contemplated for CIEL, with 15 MW of conductive power in the SOL. It has to be noted that Tore Supra is expected to operate at medium densities for the CIEL long pulse scenarios, in order to keep an effective non-inductive current generation. This explains the relatively low densities and high temperatures chosen for the plasma parameters scan. The decay lengths of the density and temperature profiles in the SOL are chosen amongst typical values for Tore Supra discharges, as deduced from Langmuir probe measurements or thermal analysis of plasma facing components [9], $\lambda_n = 3.3$ cm and $\lambda_T = 3.7$ cm, giving for the particle flux $\lambda_\Gamma = 2.3$ cm and for the heat flux $\lambda_q = 1.4$ cm [2]. The throat plasma parameters, used to define the background plasma in the EIRENE input, are deduced from the above values at the last closed flux surface and decay lengths, assuming a radial exponential profile. The effective pumping speed at the bottom of the vertical port is taken to be 4 m^3 s^{-1}.

Fig. 3(a) gives the global calculated pumping efficiency ε_{pump} as a function of the density and the temperature at the last closed flux surface. The pumping efficiency is seen to increase from 4% in the low density and temperature case, up to 12% in the high density and temperature case. According to the experience gained on Tore Supra, these values should be sufficient for plasma density control [10], and moreover, they belong to the relevant range to fulfill the helium exhaust requirements in a future reactor [11].

Fig. 3(b) gives the corresponding extracted flux Φ_{ex}, expressed in Pa m^3 s^{-1} for an equivalent D_2 molecule flux at 300 K. Indeed, as discussed in [12], the temperature of the neutral molecules and atoms plays an important role in the extracted flux given in Pa m^3 s^{-1}, the pressure being directly proportional to the species temperature. The molecules are rapidly at the wall temperature (a few hundreds of K), while the atoms, starting at a few tens of eV in the throat plasma (average between the Franck–Condon population around 4 eV and the more energetic charge exchange neutrals) are still at a few eV when they reach the bottom of the vertical port. This explains why neutral atoms, even though their density at the bottom of the vertical port is roughly a factor 1000 lower than the molecules density, still contribute significantly to the pressure (from a few percent in the low density and temperature case up to more than 25% in the high density and temperature case, where the atomic population reaches higher energies due to enhanced charge exchange with the plasma). However, it has been chosen here to express the extracted flux as

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[2] The interception efficiency ε_{inter} is of course strongly dependent on the ion flux decay length λ_Γ, varying from 2 to 9% for λ_Γ going from 1.5 cm to 4 cm. However, on Tore Supra, λ_Γ is generally found to range between 2 and 3 cm (roughly 2 λ_q) in most experimental conditions, and a reference value of 2.3 cm has been chosen for this study.

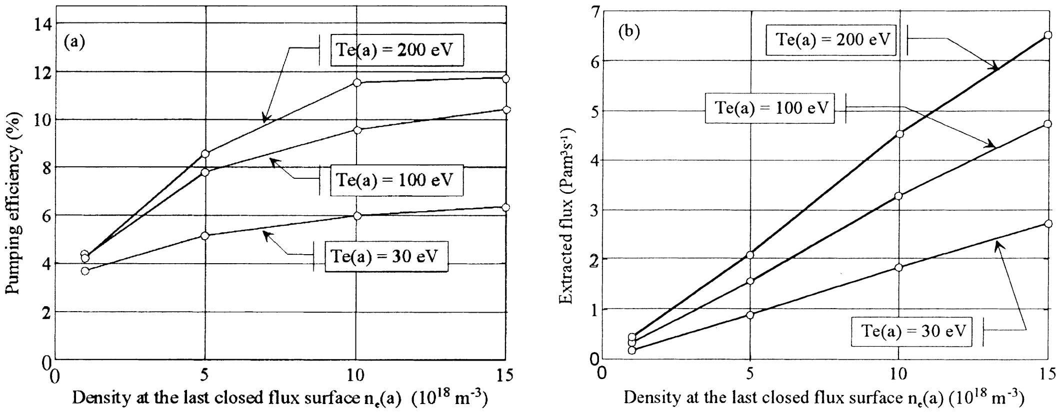

Fig. 3. Pumping efficiency (a) and exhausted flux (b) as a function of density and temperature at the last closed flux surface.

molecules at 300 K, since this is a usual unit for particle injection [3]. For the 10 vertical ports devoted to pumping, the extracted flux goes from 0.5 up to 6.5 Pa m^3 s^{-1}, which should allow the exhaust of the large particle source due to pellet injection foreseen to feed the central plasma in CIEL scenarios (4 Pa m^3 s^{-1} being the upper limit of the Tore Supra pellet injection system).

We will now concentrate on the evolution of the global pumping efficiency $\varepsilon_{\text{pump}}$ as a function of plasma parameters, by looking at the three components of Eq. (6). The interception efficiency $\varepsilon_{\text{inter}}$ is constant here, since it depends only on λ_Γ and on the limiter geometry (around 5.7% for 10 pumping vertical ports). The collection efficiency $\varepsilon_{\text{coll}}$ calculated by EIRENE is seen to depend only weakly on the plasma conditions (going from 55% to 65%). In the system modeled by EIRENE (throat plasma and pumping system, see Fig. 4), deuterium ions are launched from the throat entrance along the magnetic field lines, accelerated in the sheath, and neutralized on the fingers. Particles are then followed until they are either pumped at the bottom of the vertical port (fraction χ_{ex}), or lost back to the SOL at the throat entrance (fraction χ_{lost}), or re-ionized in the throat plasma (fraction χ_{ion}). This re-ionization leads to a local amplification factor in the throat,

$$f_{\text{loc}} = \frac{1}{1 - \chi_{\text{ion}}}. \tag{7}$$

Using the fact that $\chi_{\text{ex}} + \chi_{\text{ion}} + \chi_{\text{lost}} = 1$, the collection efficiency can be written as

$$\varepsilon_{\text{coll}} = f_{\text{loc}}\chi_{\text{ex}} = \frac{1}{1 + \frac{\chi_{\text{lost}}}{\chi_{\text{ex}}}}. \tag{8}$$

In the low density and temperature case, χ_{ion} is low (less than 5%), leading to quite high χ_{ex} and χ_{lost} while the situation is reversed in the high density and temperature case, with χ_{ion} as high as 88%. But in all cases, the ratio $\chi_{\text{lost}}/\chi_{\text{ex}}$ is roughly constant, leading to similar collection efficiencies. Therefore, at low density and temperature, particles are trapped into the closed geometry (mechanical trap) whereas at high density and temperature, re-ionization in the throat plays a major role (plasma trap).

As a consequence, the global calculated pumping efficiency $\varepsilon_{\text{pump}}$ depends mainly on the amplification factor in the SOL f_{A}, varying from close to 1 in the low density and temperature case up to 3.5 in the high density and temperature case.

In Fig. 5, the data of Fig. 3 (a) are plotted against the conductive power, calculated from n_{e} and T_{e} profiles as the integral of the heat flux over the SOL,

$$P_{\text{cond}} = \gamma_{\text{s}} \int_{\text{SOL}} n c_{\text{s}} kT \, \text{d}S.$$

where γ_{s}, the total heat transmission factor through the sheath, is taken to be 10 [6]. According to this calcula-

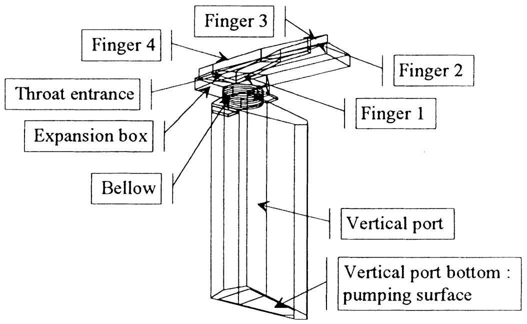

Fig. 4. Modeling of the pumping system for the EIRENE simulations.

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[3] Moreover, the atoms remaining at the vertical port bottom still have a long way to go before they reach the cryomechanical pumps, and their contribution to the pressure should have become negligible by then.

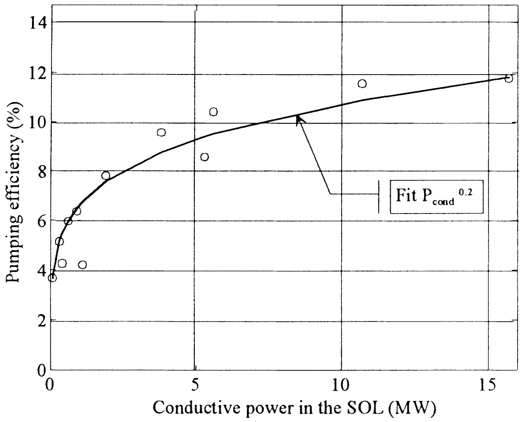

Fig. 5. Pumping efficiency calculated as a function of the conductive power in the SOL.

tion, the case $n_e(a) = 1.5 \times 10^{19}$ m^{-3} and $T_e(a) = 200$ eV corresponds roughly to the nominal conductive power of 15 MW expected in the full power scenario for CIEL. The pumping efficiency is seen to increase with the conductive power as $P_{cond}^{\ 0.2}$, which is compatible with experimental trends already observed for pump limiters in Tore Supra [13].

4.2. Sensitivity to pumping speed

Fig. 6 shows the collection efficiency ε_{coll} for the full power case [$n_e(a) = 1.5 \times 10^{19}$ m^{-3} and $T_e(a) = 200$ eV], as a function of the effective pumping speed at the bottom of the vertical port. The straight line represents what the limit of the collection efficiency would be for an infinite pumping speed (corresponding to a "sticking" probability of one for an incident particle on the vertical port bottom). The collection efficiency is shown to increase from 30% for $S_{eff} = 0.5$ m^3 s^{-1} up to 69% for $S_{eff} = 6$ m^3 s^{-1} while the limit for an infinite pumping speed is around 71%. Therefore, it is seen that there is not much to gain by working above the 4 m^3 s^{-1} pumping speed expected for CIEL (leading to a collection efficiency of 60%) since the pumping performances become essentially limited by the conductance of the expansion box and the vertical port.

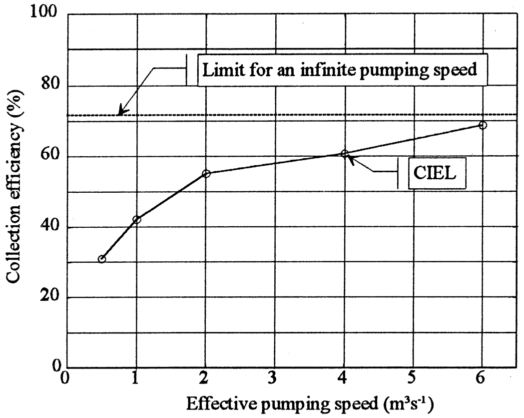

Fig. 6. Collection efficiency calculated as a function of the effective pumping speed at the bottom of the vertical port for the full power case $n_e(a) = 1.5 \times 10^{19}$ m^{-3} and $T_e(a) = 200$ eV.

4.3. Sensitivity to the magnetic configuration

The two main scenarios contemplated for CIEL, operating at different plasma current, lead to different magnetic configurations (change in the helicity of the magnetic field lines), as illustrated in Fig. 7, where a top view of two consecutive neutralizers is shown. The particle trajectories from one neutralizer to the next one are represented, the 6° angle with the toroidal direction corresponding roughly to the standard scenario ($I_p = 1.7$ MA), and the 4° angle to the advanced scenario ($I_p = 1$ MA). The consequence is that the area wetted by the plasma will vary, going from fingers 1, 2, 3 in the standard scenario, to finger 1 alone in the advanced scenario. The effect of the magnetic configuration on the pumping performances has been investigated with EIRENE by varying the direction of the magnetic field [4] so that the deuterium ions launched at the throat entrance reach the correct fingers, and by defining some shadowed zones in the throat where the plasma is turned off. Simulations have been performed for the low density and temperature case [$n_e(a) = 10^{18}$ m^{-3} and $T_e(a) = 30$ eV] and for the high density and temperature case [$n_e(a) = 1.5 \times 10^{19}$ m^{-3} and $T_e(a) = 200$ eV]. In both cases, the magnetic field direction is shown to have no influence on the collection efficiency of the pumping system, probably because the neutral particles travel for a sufficiently long time in the throat to forget their birth place on a particular finger of the neutralizer. The introduction of a shadowed zone does not make any significant difference either. Therefore, the pumping performances of the neutralization system should be robust to any magnetic configuration contemplated for the CIEL scenarios.

4.4. Comparison with an open geometry

The closed configuration of the V shaped neutralizer allows to efficiently trap the neutrals, but the price to pay for such a geometry is the presence of a secondary leading edge on the tip of finger 1, quasi perpendicular to the heat flux. Therefore, the advantage in terms of

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[4] A user supplied routine has been added to the code in order to vary the angle between the toroidal direction and the magnetic field direction, followed by the ions launched as test particles from the throat entrance.

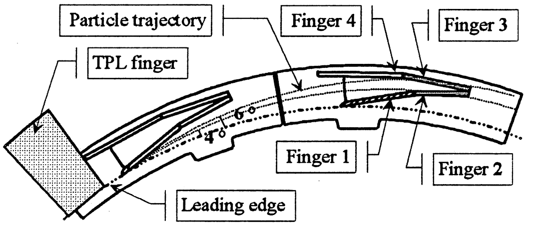

Fig. 7. Top view of two consecutive neutralizers, with particle trajectories and the corresponding wetted area on the neutralizer shown for two magnetic configurations.

pumping efficiency should be quantified. Simulations of an open geometry, with a purely toroidal neutralizer, allowing to avoid any leading edge, have been performed with EIRENE by keeping only fingers 3 and 4 in the modeling (see Fig. 7). Calculations have been done for the low density and temperature case and for the high density and temperature case, with $S_{\mathrm{eff}} = 4$ m^3 s^{-1}. For the open configuration, particles are considered as lost for the system when they pass the TPL leading edge. In both cases, the collection efficiency is seen to decrease drastically, roughly from 60% for the closed geometry to 10% for the open geometry. The ionized fraction χ_{ion} is about the same in both configurations, but the ratio $\chi_{\mathrm{lost}}/\chi_{\mathrm{ex}}$ is much more favorable for the closed configuration.

5. Summary

In the frame of the CIEL project, a new toroidal pump limiter will be implemented in Tore Supra, in order to improve the heat and particle exhaust capability of the machine. The neutralization system of the TPL has been modeled in order to estimate the pumping performances of the device for the scenarios contemplated for CIEL. According to the calculations, the global pumping efficiency, defined as the ratio between the extracted flux and the net plasma outflux, should increase from 4% (low density and temperature ohmic discharge) up to 12% (high density and temperature full power discharge), which should allow for an efficient density control. It also has to be noted that this range of efficiency is relevant for helium exhaust requirements in a future reactor. The pumping speed foreseen for the cryomechanical pumps of CIEL (around 10 m^3 s^{-1}) seems well adapted to the pumping system, the performances of the device being limited by conductance. The system is robust to changes in the magnetic configuration, keeping the same pumping efficiency for standard scenarios at full plasma current and for advanced scenarios at lower plasma current. Finally, the loss of pumping performances for an open configuration, allowing to avoid any secondary leading edge, has been estimated: the pumping efficiency drops roughly by a factor 6, justifying the closed V shape geometry of the neutralizers.

In further work, the pumping system modeling should be refined, by performing some plasma–neutral coupled simulations, using the B2-EIRENE code package, in particular for highly radiating scenarios with very low plasma temperature, also contemplated for CIEL.

References

[1] D. Van Houtte and the Tore Supra team, Nucl. Fusion 33 (1993) 137.
[2] C. Grisolia and the Tore Supra team, these Proceedings.
[3] P. Garin et al., Proceedings of the 20th SOFT, Marseille, to be published.
[4] P.K. Mioduszewski, in: Physics of Plasma–Wall Interaction in Controlled Fusion, Proceedings of NATO Advanced Study Institute Val-Morin, 1984, NATO ASI Series, vol. 131, Plenum Press, New York, 1986, p. 891.
[5] J.P. Périn et al., Proceedings of the 19th SOFT, Lisbon, Portugal, vol. 2, 1996, p. 1165.
[6] P.C. Stangeby, G.M. Mc Cracken, Nucl. Fusion 30 (1990) 1225.
[7] E. Tsitrone et al., Proceedings of 22nd EPS Conference on Controlled Fusion and Plasma Physics, Bournemouth, vol. 19C, Part IV, 1995.
[8] D. Reiter, Technical Report Jül-2599 KFA-Jülich, 1992.
[9] E. Tsitrone et al., Proceedings of 19th SOFT, Lisbon, 1996, p. 451.
[10] T. Loarer et al., Nucl. Fusion 36 (1996) 225.
[11] M. Chatelier, Vacuum 47 (6–8) (1996) 963.
[12] H-S Bosch et al., Plasma Phys. Control. Fusion 39 (1997) 1771.
[13] B. Pégourié et al., J. Nucl. Mater. 241–243 (1997) 494.