Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Nuclear Materials 337–339 (2005) 471–474

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Pumping capability and particle balance in W7-X: a self-consistent 3D study

D. Sharma *, Y. Feng, F. Sardei, J. Kisslinger, H. Grote, P. Grigull, H. Renner

Max-Planck-Institut für Plasmaphysik, IPP-EURATOM Association, Teilinstitut Greifswald, Wendelsteinstr. 1, D-17491 Greifswald, Germany

---

Abstract

The W7-X stellarator, presently under construction in Greifswald will be equipped from the beginning with an open island divertor designed for stationary operation. In order to optimize the W7-X cryopumping system for an efficient particle control with good confinement in long-pulse operation, simulations are performed with the 3D EMC3-EIRENE plasma edge transport code. The establishment of stationary particle balance crucially depends on the divertor pumping efficiency, which, for a given particle input, sets a lower limit to the plasma density at the separatrix. This paper presents a self-consistent study with EMC3-EIRENE code on the particle balance and pumping capability of W7-X at stationary conditions for relevant ranges of magnetic configurations (ι = 5/5,5/4) and plasma parameters. Specifically, the pumping and recycling fluxes are obtained and lower limits for separatrix density are estimated for three major magnetic configurations with the required pumping parameters in various operating conditions.

PACS: 52.55.Hc; 52.25.Fi; 52.40.Hf; 52.65.−y
Keywords: Density control; Divertor plasma; Edge plasma

---

1. Introduction

A self-consistent analysis of edge plasma transport and neutral-particle balance is of importance for the successful steady-state divertor operation proposed for the stellarator W7-X. In addition to the optimization of the magnetic configurations and the target power load, the divertor design for W7-X is also being optimized for plasma-density control using the particle sources in the divertor region [1]. The present work aims at characterizing the particle balance for steady-state divertor operation of W7-X in order to determine an optimum magnetic configuration for successful operation with desired plasma conditions. In an island divertor configuration the simple balance of particle input and output is complicated by the effect of strong interaction of neutrals with background plasma and may put severe limitation on the flux of neutral particles which could be pumped to maintain the steady-state with desired plasma conditions. A limit on the plasma parameters emerges beyond which no steady-state operation is possible and the density control may be lost leading to a radiative collapse of the plasma. The pure geometrical estimates used to determine the optimum magnetic configuration are generally insufficient as they do not incorporate a direct relationship between the plasma profiles

---

* Corresponding author.
E-mail addresses: devendra@ipp.mpg.de (D. Sharma), sardei@ipp.mpg.de (F. Sardei).

0022-3115/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2004.10.038

and the achievable pumping flux of neutrals, where the latter itself is a sensitive function of recycling flux and various geometric effects.

In this paper we present the results of self-consistent 3D plasma-neutral simulations performed on three major W7-X island-divertor configurations using the 3D Monte Carlo code EMC3-EIRENE [2,3]. The first two cases are chosen to represent the effects of finite plasma β and finite control-coil currents respectively on the standard magnetic configuration ($\iota = 5/5$), the third case is a configuration with higher rotational transform, $\iota = 5/4$. The simulations are first performed to generate self-consistently 3D distributions of plasma density, flow and temperature in the W7-X edge region with the proposed island divertor geometry. In each case a given constant power of 10 MW is assumed to enter the scrape-off layer from the core region. The edge plasma density is fixed while the volume sources of particles and energy are used as generated self-consistently by the EIRENE code. At the target Bohm boundary conditions are used. In order to achieve a stationary particle balance, assuming a refueling given purely by 10 MW NBI, an equivalent neutral pumping rate of $10^{21}\,\mathrm{s}^{-1}$ must be maintained. However, a desired plasma density at the separatrix corresponds to a certain amount of recycling flux, a finite fraction of which must be pumped out to maintain the steady-state. The above dependence links the desired separatrix density to the minimum pumping requirement for stationary operation. A similar requirement would emerge for the long-pulse ECRH operations, where a central refueling of the same order is required to control the central density profile.

2. The plasma-neutral analysis

The three cases discussed here correspond respectively to the standard magnetic configuration with finite plasma $\beta = 4\%$ (case-I), the standard vacuum magnetic configuration with finite control coil currents (case-II) ($\iota = 5/5$) and an additional vacuum magnetic configuration with higher rotational transform $\iota = 5/4$ (case-III). Poincaré sections of these magnetic configurations are shown in Fig. 1 drawn at the symmetric plane. Case-II was judged a geometrically superior configuration in terms of pumping efficiency based on an earlier optimization using the control coil currents which shift the strike line positions relatively close to the pumping gap (see Figs. 1 and 2). The stationary plasma distributions for the three magnetic configurations are simulated by the EMC3-EIRENE code to produce estimates for the strength of the recycling neutral sources. Then the balance of neutral flux is simulated between the targets, where the source of neutral particles is located, and the pumping surfaces inside the divertor chambers [5,6] which act as sinks of neutral particles. In the low density range of interest the total recycling flux is coupled to the separatrix density n_{eS} and can be written as

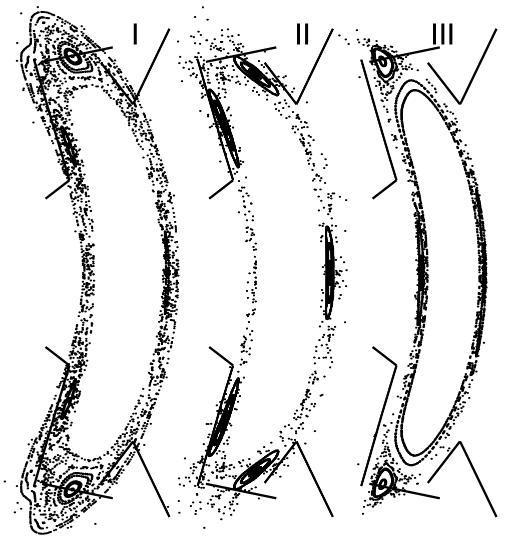

Fig. 1. Magnetic field Poincaré sections for the three magnetic configurations drawn at the toroidal location $\phi = 0$. The divertor plates are also shown.

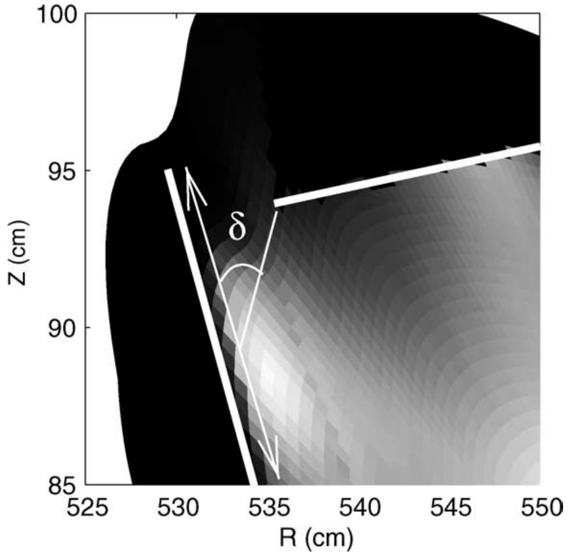

Fig. 2. The divertor plates and pumping gap configuration at symmatry plane. The angle δ represents geometrical exposure of the neutral source location to the pumping gap and arrows indicate the directions in which a test source is moved.

$$\Gamma_{\mathrm{recy}} = \beta n_{\mathrm{eS}}, \tag{1}$$

where β is approximately a constant for a small range of plasma parameters and is determined computationally for each of the three magnetic configurations analyzed here. What can also be derived computationally for each of the magnetic configurations is the ratio of achievable pumping flux to the total recycling flux

$$\Gamma_{\text{pump}} = \gamma \Gamma_{\text{recy}}, \tag{2}$$

where the factor γ depends, for a given pumping absorption coefficient α, on the plasma distribution of the corresponding magnetic configuration as well as on the divertor geometry, i.e. the geometrical exposure of recycling neutrals to the pumping surfaces (where α is defined as the fraction of the total incident neutral flux which gets absorbed on the pumping surface). Both these effects should be observable in the simulations while moving a test source of neutrals from a location which is better exposed to the pumps to another one which is strongly shielded by the background plasma. We discuss such an analysis latter in this Section.

By assuming a required input power of 10 MW purely through NBI, the pumping system would need to handle an associated particle flux of about $2 \times 10^{21}\,\text{s}^{-1}$. This particle flux, Γ_{input}, should therefore be equated to the pumped flux Γ_{pump}, thus for stationary conditions,

$$\Gamma_{\text{input}} = \Gamma_{\text{pump}}. \tag{3}$$

Γ_{pump} is further related to the separatrix density which can now be written as

$$n_{\text{eS}} = \frac{\Gamma_{\text{input}}}{\gamma \beta}. \tag{4}$$

As the plasma conditions and input power are to be chosen independently, the pumping system must adjust to handle the associated input flux of particles. For given plasma conditions, i.e., for an operational separatix density, input power and magnetic configuration, Γ_{recy} is computed and the parameter β is determined using Eq. (1). In subsequent runs the achievable pumping flux is computed with different values of pumping absorption coefficient α. This procedure yields the fraction $\gamma(\alpha)$ of the total recycling flux that could be pumped. Eq. (4) relates these values of α to the corresponding minimum values of separatrix density which could be maintained during a stationary operation. This dependence is plotted in Fig. 3 for the three given magnetic configurations. The profiles show, for a given absorption coefficient α, lower limits of the separatrix density in stationary operation for which the steady-state condition (3) is satisfied. The regions below the respective curves indicate the parameter space where the input flux, Γ_{input}, exceeds the achievable pumping flux Γ_{pump} making a stationary operation impossible. A comparison between the three cases indicates that the case-II and case-III configurations are comparatively suitable for low density operation as they allow lower densities for realistic values of the absorption coefficient. The case I is suitable only for operation at higher density since densities as low as $4 \times 10^{18}\,\text{m}^{-3}$ are possible only with higher absorption coefficient of about 10%. An increase in the absorption coefficient (or an alternate increase in the pump area) to permit lower separatrix densities is effective only at low values of α due to rapidly decreasing slope of the curves.

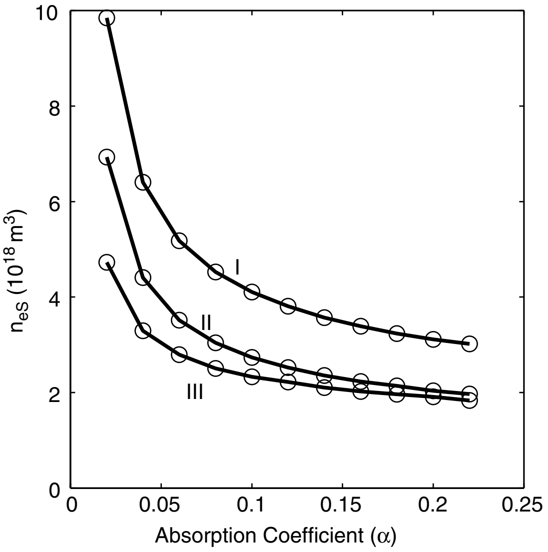

Fig. 3. The minimum separatrix density n_{eS} allowed for the cases I, II and III respectively as function of pump absorption coefficient α. Region below the respective curves indicates the inaccessible density values.

It can be noted that the curves II and III lie relatively close to each other and yield approximately similar density limits for the stationary operation, despite the difference in the values of the rotational transform and the fact that the geometrical locations of the strike lines (recycling neutral source) differ considerably in both magnetic configurations. In view of the fact that case-II is geometrically superior to case-III, the result indicates the possibility that the background plasma has an additional shielding effect on the neutrals in these cases. That is, the shielding is capable of suppressing the geometrical advantages and is able to equalize the neutral flux entering the divertor chamber in the two cases. As mentioned earlier, the presence of this shielding effect could be verified by measuring the pumped flux generated by a test source of neutrals localized on the vertical target of the divertor. The source is moved into the plasma along the target from the divertor chamber through the pumping gap into the main chamber. The result is shown in Fig. 4, where the pumped flux is plotted against the angle δ which is the angle subtended by the pumping gap on the test source location in radial-poloidal plane and defines the geometric exposure of neutral source to the pumping gap (Fig. 2). The reduction in the pumped flux clearly shows two characteristic decay lengths in two different ranges of angle δ. At larger

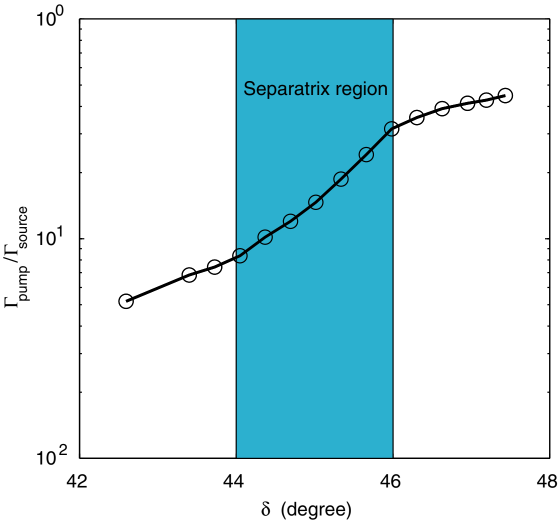

Fig. 4. The relative pumped flux for a test source as function of angle δ representing the geometrical exposure of neutral source to the pumping gap. An additional drop, compared to higher δ values, is seen in the pumped flux when the test source is moved in the separatrix region.

δ, which corresponds to the locations close to the pumping gap, an expected regular change in pumped flux is noted with δ due the geometrical reasons, however, an extra reduction was noted beyond an angle when the test source was moved through the dense plasma in the separatrix region and brought close to the main strike point on the target. This observation verifies that a large fraction of the neutral flux generated at the target is reionized in the separatrix region amounting to a strong shielding of the recycling neutrals by the divertor plasma. The location of a sudden change in the pumping flux characterizes the boundary of the region where the background plasma begins to shield the neutrals which enter the divertor chamber and subsequently reach the pumping surface.

Other important factors, which may influence the steady-state operations and need to be involved in the optimization procedure, include the relative efficiency of the cryopump panels to pump the neutral atoms and molecules. Considering that the molecules form a dominant part of the pumped neutral flux, problems may arise from the fact that the achievable pumping flux of molecules is found to saturate at relatively lower values of α [4]. Thus a simple increase in pumping power may not result in an increased pumping flux and a further optimization of the magnetic configuration is required to identify a suitable magnetic configuration. As another major contribution to the particle balance, the surfaces of the divertor and main plasma chambers may pump or emit the neutral gas at various stages of the discharges depending on the surface temperature. This is likely to disturb the equilibrium at these surfaces as it was assumed in the present simulations. The process is also expected to put an additional load on the pumping system which has a limited pumping area.

3. Conclusions

3D plasma-neutral simulations were performed for three major magnetic configurations in the W7-X stellarator. The achievable pumping rate and its dependence on the magnetic configuration for a successful stationary operation was analyzed. In a typical operation where the plasma is assumed to be refueled by a 10 MW NBI – equivalent particle source, the separatrix plasma density was found to have a lower limit beyond which steady-state conditions can not be maintained. Three major magnetic configurations were analyzed to identify the optimum case from the view point of an efficient divertor operation and particle refueling in order to achieve a better density control during the stationary operation. Two of the cases, namely standard configurations ($\iota = 5/5$) with a finite control-coil current (case II) and with higher rotational transform ($\iota = 5/4$) (case III), respectively, were identified to have a better divertor operation as compared to the standard magnetic configuration ($\iota = 5/5$) with $\beta = 4\%$ (case I). Additionally, case-III was found to have similar performance as compared to case-II which corresponds to a geometrically superior configuration. Both the cases II and III were found to have similar results in terms of minimum separatrix densities allowed for stationary conditions due to the effect of a strong shielding of neutrals by the background plasma. The shielding leads to the reduction in the neutral flux entering the divertor chamber compensating the desired geometrical advantages.

References

[1] H. Renner et al., Nucl. Fusion 40 (60) (2000) 1083.
[2] Y. Feng et al., J. Nucl. Mater. 266–269 (1999) 812.
[3] D. Reiter, 1984 Technical Report Jül-1947, KFA Jülich, Germany.
[4] D. Sharma et al., 13th EPS Conference, St. Petersburg, July 2003, ECA 27A, P-1.14.
[5] H. Renner et al., Fusion Sci. Technol. 46 (2) (2004) 318.
[6] H. Grote et al., 14th Int. Stellarator Workshop, Greifswald, September 2003.