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MODELLING OF THE SINGLE-NULL DIVERTOR OF INTOR: PLASMA EXHAUST AND GAS PUMPING

M. F. A. HARRISON
P. J. HARBOUR
E. S. HOTSTON

CULHAM LABORATORY
Abingdon Oxfordshire

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MODELLING OF THE SINGLE-NULL DIVERTOR OF INTOR: PLASMA EXHAUST AND GAS PUMPING

M F A Harrison, P J Harbour and E S Hotston
Culham Laboratory, Abingdon, Oxon, OX14 3DB, UK
(Euratom/UKAEA Fusion Association)

ABSTRACT

Properties of the single-null divertor of INTOR are predicted using a one-dimensional fluid model for plasma transport parallel to the magnetic field in the divertor scrape-off layer. Gas pumping properties are obtained from a neutral particle transport model which is one-dimensional but in the direction normal to the target. The temperature of the plasma at the separatrix is about 100 eV and falls to about 25 eV at the target. About 80% of the 75 MW conducted into the divertor is convected to the target across a plasma sheath, the rest of the power being radiated or convected to the walls of the divertor chamber by neutral particles. The pumping speed required to maintain an adequate exhaust of helium is about 10^5 ℓs^{-1}.

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1. Introduction

Properties of the single null divertor of INTOR are considered in relationship to the transport, parallel to the magnetic field, of plasma particles and energy in the toroidal scrape-off region and the poloidal divertor chamber. It is assumed that plasma transport is collisional and is equally distributed to the inner and outer targets, that only gas produced in the outer divertor can be pumped from INTOR and so the flow to the pumps must equal the flow entering the outer divertor. The efflux of neutral gas to the pumps is produced by plasma impact at the divertor target but is attenuated by ionisation in the divertor plasma. The model used is analytical[1,2], permitting the sensitivity to variation in physical parameters to be readily identified. Plasma transport is considered only in one dimension parallel to the field which in INTOR is almost parallel to the tungsten divertor target. The gas flow analysis is also one-dimensional but in the direction normal to the target.

2. The Model

Input specifications taken for INTOR are the power, $Q^{(tot)}$ transported to each channel of the divertor, (ie $2Q^{(tot)} \approx 75$MW for the standard condition), the plasma density $n_s = 5 \times 10^{19} m^{-3}$ in the scrape-off region, and the helium exhaust rate $\Gamma^{(o)}_{He,pump} = 2 \times 10^{20}$ atoms s^{-1} for 620 MW fusion power. The topology of INTOR is such that $A_{\parallel}$, the cross sectional area of the diverted magnetic flux, is given by

$$A_{\parallel} = 2\pi a\overline{\Delta}/q_{local} = 0.35 m^2 \quad , \qquad (1)$$

where a is the minor radius, $\overline{\Delta}$ is taken to be 0.14m and the safety factor, q_{local}, is about 3 in the divertor chamber.

The procedure adopted is shown schematically in Figs. 1 and 2. The power, Q_t, carried to the target by a flow, Γ_t, of particles at temperature T_t, is given by,

$$Q_t = \Gamma_t Y(T_t) = A_{\parallel} n_t M_t C_{s,t} Y(T_t) \quad , \qquad (2)$$

where $n_t, C_{s,t}$ are the plasma density and ion sound speed at the target and the corresponding value of the Mach number, M, is $M_t = 1$. The term $Y(T_t)$ in Eq. (2) represents the energy transported by ion pairs of each atomic species J(i.e. D^+, T^+, He^{2+} and tungsten) and is

$$Y(T_t) = \sum_J Y(T_t)_J = \sum_J [(1 - R_{E,t})(2kT_i + ZeU) + \chi_i + 2ZkT_e/(1-\gamma)]_J \quad , \qquad (3)$$

where $R_{E,t}$ is the energy reflection coefficient at the target, Z the ion charge state, U the potential of the sheath plus pre-sheath, χ_i the ionisation energy and γ, the coefficient for secondary electron emission, is taken to be zero for INTOR.

The energy balance within the divertor is given by,

$$Q^{(tot)} = \sum_J [Q_t + Q^{(r)} + Q^{(o)}]_J \quad . \qquad (4)$$

Here the radiated power, $Q^{(r)}$, is estimated for DT by,

$$Q^{(r)}_{DT} = \Gamma_{DT,t} E^{(r)}_{DT} = \Gamma_{DT,t} [(16.4 + 210/T_t)_{eV}] \quad , \qquad (5)$$

which is derived using the total energy required to produce one ion pair in atomic hydrogen. $Q^{(r)}$ for helium and tungsten is by scaling from $Q_{DT}^{(r)}$. The energy deposited upon the wall of the divertor chamber by neutral particles of species J [$Q_J^{(o)}$ in Eq. (4)] is given by

$$Q_J^{(o)} = [(1 - R_{E,wall})E_{wall}^{(o)}\Gamma_{wall}^{(o)}]_J \quad , \tag{6}$$

where $E_{J,wall}^{(o)}$, the mean energy per particle, is evaluated for fast atoms directly back-scattered from the target, for charge exchange atoms from the plasma and for particles thermalised by previous wall collisions. $E_{J,wall}^{(o)}$ therefore depends on plasma temperature and sheath potential, on R_E at target and wall, on associated values of the particle reflection coefficient R_N and on $\overline{P}$ and R_p, which are defined below. The flow of neutral species J to the wall, $\Gamma_{J,wall}^{(o)}$ in Eq. (6), is related to that at the target, $\Gamma_{J,t}$ by

$$\Gamma_{J,wall}^{(o)} = [\Gamma_t\overline{P}(1 + R_p)]_J \quad . \tag{7}$$

Here $\overline{P}$ (evaluated for D^+,T^+ by a random walk model [3]) is the probability that fast and slow atomic species formed at the target can escape through the wedge-shaped plasma (shown in Fig. 2) of effective thickness ℓ and reach the walls. The factor R_p in Eq. (7) allows for charge exchange in the plasma of those particles returning from the wall.

Within the toroidal scrape-off region, the maximum temperature T_s is derived from the heat flux equation with $T = T_t$ at the target:

$$-(K_o T^{2.5})dT/dz = \alpha\, Q^{(tot)}/A_{\parallel}, \ [\text{with } dT/dz = 0,\ T = T_s \text{ when } z = 0] \ . \tag{8}$$

Here $K_o T^{2.5}$ is the parallel thermal conductivity, z is the distance along the field line, and α is a power distribution factor. Within the scrape-off plasma where $z < \pi Rq$, $\alpha = z/\pi Rq$, but within the divertor plasma $\alpha = 1$. The density n_s is related to that at the target by:

$$n_s T_s = nT(1 + M^2) = n_t T_t(1 + M_t^2) = 2n_t T_t . \tag{9}$$

The efficiency, g, for pumping gas from the divertor chamber is determined by the total conductances, S_D, of the ducts and the total speed of the vacuum pumps, S_P. The exhaust flow of particles of species J is thus given by

$$\Gamma_{J,pump}^{(o)} = (\Gamma_t \overline{P}\, g)_J \quad . \tag{10}$$

The vacuum pumping requirement is established when $\Gamma_{He,t}/\Gamma_{DT,t} = n_{He,t}/n_{DT,t} \approx 0.05$.

3. Results

In the analysis, T_t is an independent variable and its value consistent with the INTOR specification is determined by the condition that n_s, given by Eq. (9), is $5 \times 10^{19}\,m^{-3}$. Results for the standard conditions of INTOR are shown in Fig. 3 and variation of the operating point with exhaust power in Fig. 4. Also shown in Fig. 3 is $\Gamma_{W,t}^{(o)}$ which is the flow of tungsten sputtered from each divertor target. The dependence of $(n_{He}/n_{DT})_t$ upon the combination of duct conductance and vacuum pump speed (twelve ducts and pumps) is shown in Fig. 5. Details of the modelling and results can be found in Ref. 4 and in contributions to the INTOR Workshops[5].

4. References

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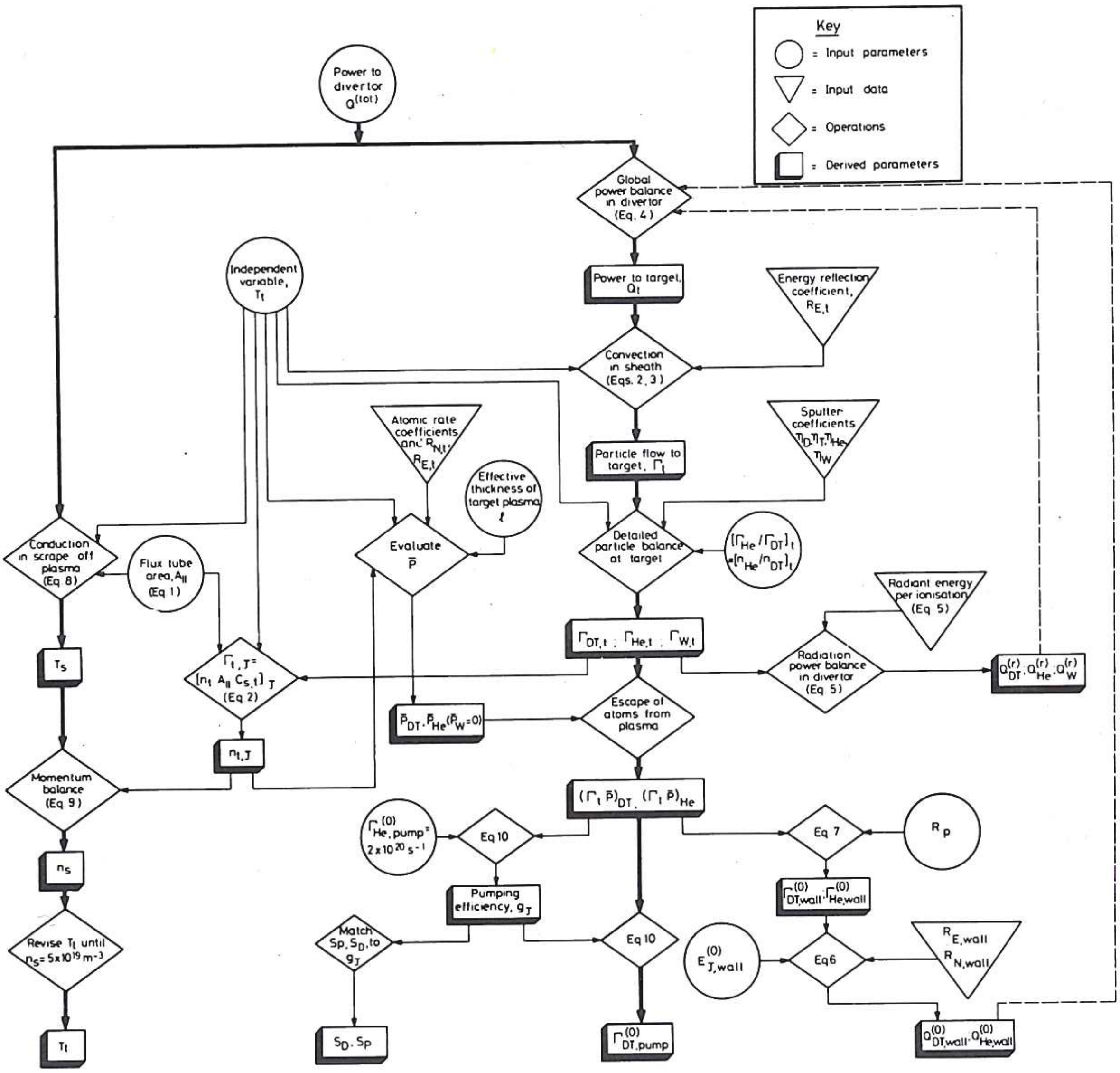

Fig.1 A simplified schematic representation of the procedure used to derive parameters for the single-null divertor of INTOR.

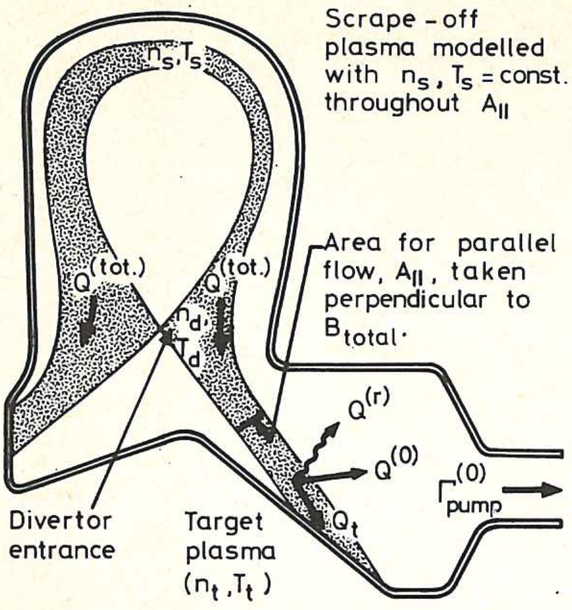

Fig.2 Schematic diagram of INTOR in the plane of the minor cross-section showing key parameters of the exhaust.

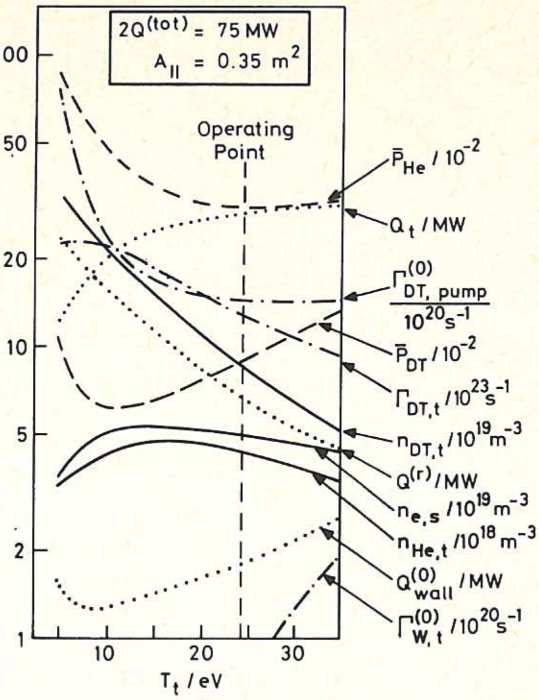

Fig.3 Data for INTOR plotted as a function of plasma temperature close to the target. The operating conditions are shown for $n_{e,s} = 5 \times 10^{19}$ m^{-3} and $(n_{He}/n_{DT})_t = 0.05$.

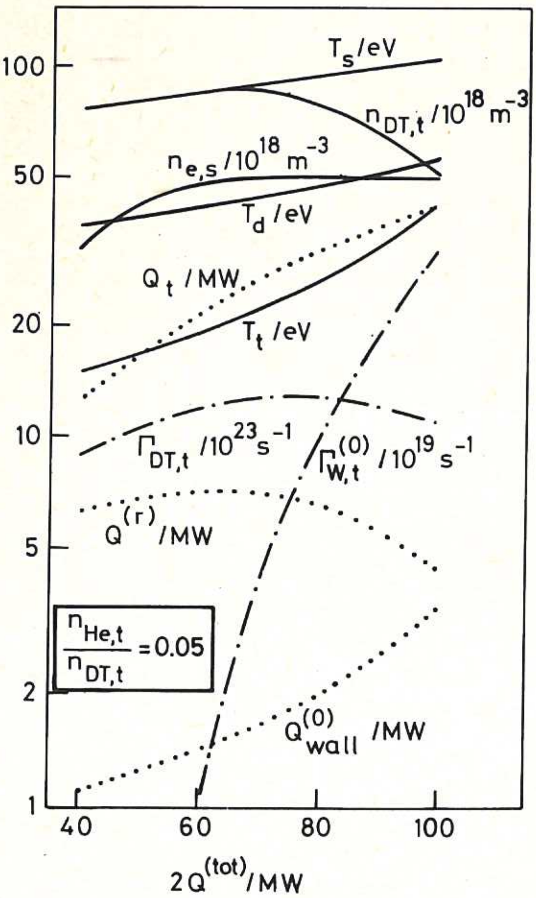

Fig.4 Variation of operating conditions with exhaust power.

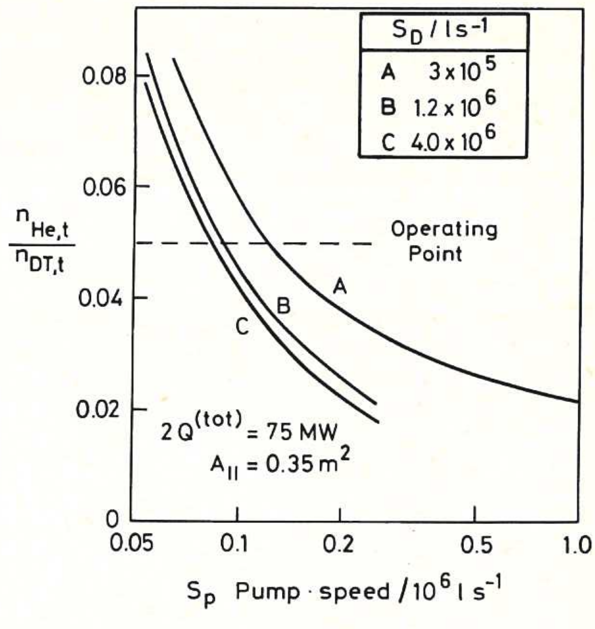

Fig.5 Dependence of $(n_{He}/n_{DT})_t$ upon the combination of duct conductance, S_D, and vacuum pump speed, S_P (i.e. the total for 12 ducts and pumps).