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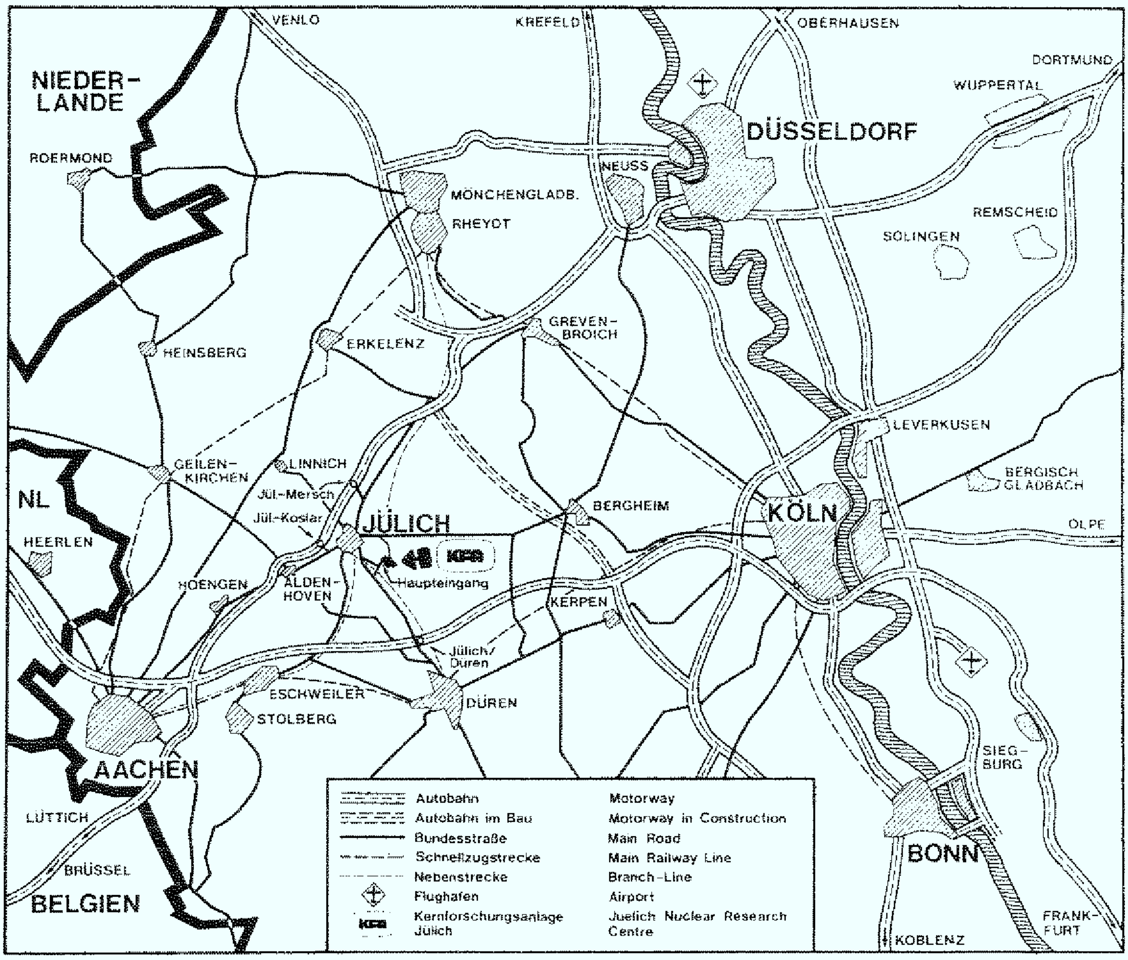

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Institut für Plasmaphysik der Kernforschungsanlage Jülich GmbH,
Ass. EURATOM-KFA, D-5170 Jülich, Federal Republic of Germany

Abstract

A method is proposed which should allow to pump the exhaust (including He) from a fusion reactor. The scrape-off-layer plasma which is neutralized at the limiter or divertor plate streams into a pumping discharge where it is ionized and is then guided along magnetic field lines into a separate pumping chamber where it is again neutralized. This procedure allows one to create an intermediate pressure step after which ordinary pumps can be used which are no longer exposed to direct neutron radiation.

1. Introduction

For the economical operation of a fusion reactor the burn time should be several hundred seconds at a high duty cycle. During the burn phase He will be created and extinguish the reaction when it reaches a concentration of about 10 %. Depending on the reactor parameters this would happen after some tens of seconds, unless the accumulation is prevented by continuous pumping. Pumping of the D-T fuel and possible impurities except He seems to be feasible (e.g. with sorption or getter pumps). The problem with the He arises because those pumps, which could handle He, e.g. turbo pumps, cannot be brought close enough to the plasma boundary so as to provide enough pumping speed.

Pumping from a fusion reactor imposes a few more requirements as just pumping speed. They are:

a. Economy

The amount of energy E_p spent per He atom to be pumped has to be

$$E_p \ll \eta E_f / f_b \qquad (1)$$

where η is the efficiency by which the fusion energy E_f can be converted to the energy needed for pumping and f_b is the burn up ratio [1].

b. Impurities

The plasma neutralized at the wall can release impurities. To keep the impurity flux low, the plasma edge temperature should be low, possibly below 50 eV [2]. According to eq. (1) and [1] this seems to be in contradiction to an economical pumping. As will be shown below, this problem can be solved by direct recycling. No impurities should be produced by the pumps.

c. Space

The pumping should take a minimum of space from the blanket and the magnetic field volume.

d. Radiation

Pumping ports have to be shielded from neutron outflux and therefore long ducts should be avoided.

e. Assembly

The reactor will have to be made up of modules.

Because of a. and b. the pumping problem is closely related to the plasma parameters in the scrape-off-layer.

2. Particle and energy exhaust considerations

20 % of the energy released by the D-T fusion process is given to α-particles E_α. A fraction f_α of this energy is deposited by charged particles at the limiters or divertor plates, the rest is radiated or brought by neutrals to the wall. The balance of energy production to loss is:

$$\oint_V n_\alpha f_\alpha E_\alpha dV = \oint_V \text{div } Q dV = \oint_A Q dA \qquad (2)$$

where V is the burning core volume, A the flux surface at the separatrix between the core and the boundary layer and Q is the energy flux transported by charged particles. We approximate $\nabla \approx 1/a$ and assume that the particle mean velocity across field lines is some fraction ε of the velocity v along field lines (this need not imply that the loss is convective). Then we can write for the power balance [3, 4]

$$n_\alpha a f_\alpha E_\alpha = \gamma \varepsilon n_b v k T_b \qquad (3)$$

where n_b and T_b are the density and temperature in the boundary region and γ is a power coupling factor at the surface and depends e.g. on surface properties as secondary electron emission. [1, 5] or potentials in a divertor throat [6, 7]. In the simplest case where

$$Q = 2\ kT\ \frac{nv}{4} \quad \text{one has} \qquad \gamma = 0.5$$

Under the same assumptions the α-particle balance of production versus pumping gives

$$n_\alpha a = \varepsilon n_b v c_\alpha\ (1 - f_r) \tag{4}$$

where c_α is the α-particle concentration (or He^{++} + He^{+} + He) in the boundary which could in the simplest case equal the value in the core and f_r is the fraction of recycled neutrals from the limiter and the pump. From eqs. (3) and (4) we get values

$$kT_b = \frac{f_\alpha E_\alpha c_\alpha\ (1 - f_r)}{\gamma} \tag{5}$$

$$n_b = \frac{n_\alpha a}{[(1 - f_r)c_\alpha]^{3/2}\varepsilon} \sqrt{\frac{m\gamma}{2f_\alpha E_\alpha}} \tag{6}$$

At the plasma boundary a low temperature is desired to keep sputtering low. Eq. (5) tells that this can be done by, increasing radiation, good energy coupling (e.g. using secondary electron emission), by low He concentration (e.g. using gas puffing) and by recycling. The latter was not considered in [1] because they assumed that all particles which enter the divertor are pumped away, in this case $f_r = 0$ and c_α is the burn up ratio. As will become clear, a high recycling rate is more desirable from the pumping point of view and might be the only way to pump He economically and have a low edge temperature at the same time.

The density in the boundary layer cannot exceed an upper limit; if $\partial n/\partial r$ becomes positive plasma diffuses towards the core and the density raises there. The upper limit for the boundary density is therefore the core density (unless there were a sink in between). If we use this limit n_c, solve eq. (5) for $c_\alpha(1 - f_r)$ and put it into eq. (4) we get (cf. figs. 1 and 2)

$$kT_b = \left(\frac{f_\alpha E_\alpha na}{n_c \gamma \varepsilon}\right)^{2/3} \left(\frac{m}{2}\right)^{1/3} \tag{7}$$

for INTOR the value is

$$kT_b = 12 \left(\frac{f_\alpha}{\gamma\varepsilon}\right)^{2/3} \text{ eV} \tag{8}$$

From the pumping point of view it is more attractive to increase ε because this increases the flow of plasma and the He contained therein to the wall. This is however in contradiction to the requirement of plasma confinement unless the large value of ε (e.g. anomalous transport) is restricted to a region near the plasma boundary. A more direct method to increase ε locally could be field line ergodization in the boundary layer [8, 9] only which can be produced by resonant helical magnetic fields. Ergodicity is created by many field line revolutions, the charged particles are, however, lost when they first strike the wall. Under this aspect the concept of ergodization is not much different from the helical divertor [10] and ε is then given by the island with Δr, the torus circumference $2\pi R$ and the number of turns N a field line takes to go from one island side to the other [11]

$$\varepsilon \approx \Delta r/2\pi\, NR \tag{9}$$

A value of $\varepsilon \approx 10^{-3}$ can be achieved without distroying the flux surfaces in the core. Under these circumstances it should be possible to have a low temperature (< 200 eV) edge plasma with a He-concentration $c_\alpha \approx 5\cdot10^{-2}$.

3. Pumping with a discharge

The plasma, which is neutralized at the divertor plates or at scarpe-off limiters [11, 12] is partly reionized within the boundary layer plasma and recycled in this manner. The other part may enter pump holes and could be pumped, if sufficient pumping speed could be provided.

It is well known that a discharge absorbs neutral gas. The absorption is almost complete if the ionization mean free path

$$\lambda_i = \frac{v_o}{n \langle \sigma v_e \rangle} \qquad (10)$$

is short as compared to the plasma diameter. A stationary pumping action can be achieved, if the particle transport within the discharge is preferentially in one direction. This condition is well met for a plasma in a magnetic field.

A pumping scheme for a tokamak based on these considerations is given in fig. 3. The neutral gas emerging from a target surface streams across the magnetic field lines into a discharge located within the blanket. In order to save costly space one should keep the radial thickness of this discharge small i.e. make the ionization mean free path short. If we assume that the neutrals are after a few bounces at wall temperature, a few cm of a plasma with a density $n \approx 10^{12}\ cm^{-3}$ and an electron temperature at the maximum of ionization rate $kT_e \approx 10\ E_i$ (E_i = ionization energy) is sufficient to ionize and absorbe the neutrals. Because this plasma is, in a tokamak type fusion reactor, located in a magnetic field, the above criteria are met. The ionized particles can be guided along the tokamak field into a separate pumping chamber where they are again neutralized. The surface of the neutralizers can be kept smaller than the target plate because they do not have to absorbe as much energy (see below). We can assume that almost all the particles which get into the discharge ultimately hit these neutralizers and because there is a reduction in surface area, there has to be higher density (pressure) in front of these neutralizers as compared to the space between the target and the discharge in order to maintain flux continuity.

The gain from the proposed pumping scheme is so far:
- the pumping ports can be shielded from neutron outflux
- a density (pressure) step is produced
- He can be pumped.

Optimization, however, needs some considerations about the nature of the discharge, which should have the following properties:

a. fully ionized (no backstreaming)
b. $n_e \approx 10^{12}$ cm^{-3}, $kT_e \approx 10\ E_i$ (100 ... 200 eV)
c. low impurity release from the walls.

These requirements are met e.g. by a microwave discharge operated at electron cyclotron resonance. The microwave frequency is determined by the magnetic field at the resonance zone.

$$\omega = \frac{e}{m} B = 2\pi\nu$$

These discharges use the extraordinary wave, one can however say that the plasma density is about 0.3 of the cut-off density of a corresponding ordinary wave ($\omega = \omega_p$).

To produce a plasma density $n=10^{12}$ cm^{-3} one needs a microwave frequency of $\nu = 16$ GHz corresponding to B = 0.58 T. In a tokamak this low field is in the ripple between or even behind the coils. Further in where the field is larger one has to use higher frequencies and gets higher plasma densities. The trade-offs are listed in table 1.

Table 1

Frequency	low (16 GHz)	high (100 GHz)
B	0.58 T	3.6 T
ionization mean free path	5 cm	0.13 cm
compression	−	+
cost	+	−
availability of microwave equipment	+	−
space requirement	−	+
power	+	−

The toroidal magnetic field along the outside circumference of a torus is similar to Elmo bumpy torus [13]. On top of that the poloidal field of the tokamak causes a shift of the field lines. A poloidal cut of the discharge volume is depicted in fig. 4. There is a certain outflux of field lines (and plasma) at the upper and lower end. The number of toroidal turns a field line stays in the discharge volume depends on its poloidal extension, q and ß. It will be close to 1 because the discharge can extend over 40 % of the poloidal circumference and $q \approx 2.5$ for a reactor.

It is recommended from this field line pattern to locate the neutralizers at the upper and lower side of the discharge volume (cf. fig. 4) and neutralize the plasma which streams out there naturally. The required total neutralizer surface (or rather its projection onto a poloidal cut) is twice the area of the poloidal cut of the discharge volume (e.g. 0.8 m^2 we use INTOR [14] parameters from now on). If the ions can be kept cold (10 eV cf. [15, 16]) they are not confined in the mirror (cf. [5, 6]) because electron loss dominates and an electric field pulls the ions through the throat. The outflux of ions is

$$N = \frac{nv}{4} A \approx 5 \cdot 10^{21} \; s^{-1} \qquad (11)$$

The feed from the scrape-off limiters is

$$N \approx N_\alpha / c_\alpha \approx 4 \cdot 10^{21} \; s^{-1} \qquad (12)$$

and slightly below the value from eq. (11). Therefore the discharge might need some extra gas inlet, which is also suggested from [13] where it was found that the discharge needs a minimum gas pressure of several 10^{-6} Torr.

To estimate the required power we use values from [15] which are 130 μs for the confinement time, 1.2 kW for the microwave power and 8.6 l for the volume. If we take $n = 3.10^{11}$ cm^{-3} this leads to an average energy of 372 eV to produce an electron ion pair. Because [15] describes a device intended to produce multiply charged ions with high ionization energy we can expect that we can have a lower figure for our case. If we take 200 eV to create an ion electron pair, the required microwave power would be $P_m \approx 160$ kW and the electron power ($\eta = 0.3$) $P_e \approx 530$ kW.

This is only a fraction $5 \cdot 10^{-3}$ of the reactor's electric power. If, however, the concept of complete pumping and subsequent gas puffing instead of direct recycling is used to maintain a cold boundary the required power is increased by a factor 100. A microwave discharge is also not likely to contain impurities from sputtered wall material. No such material (Cu) was detected from the ion spectra measured in ref. [15]. Although a sizeable fraction of the electrons are high energetic, the sheath potential and the ion energy are below the threshold for sputtering [15].

4. Conclusions

A pumping scheme was proposed which offers the possibility to pump the He-ash from a fusion reactor together with the neutralized scrape-off plasma. Depending on the particular technical solution a pressure at the prepump side of $p \approx 10^{-3}$ Torr could be achieved, suitable e.g. for prepumping with cooled sorption pumps. The economy of the proposed scheme requires a large recycling rate at the limiters if a cold boundary layer is mandatory.

The proposed pumping scheme seems to be compatible with the different requirements for a fusion reactor.

Acknowledgement

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Figure captions

Fig. 1 Plasma edge temperature versus density according eq. (7) and INTOR parameters $N_\alpha = 2 \cdot 10^{21}\ s^{-1}$ (after [4])

Fig. 2 Required pumping speed $f_p = (1-f_r)$ according eq. (6) parameters as fig. 1 ([4])

Fig. 3 Pumping scheme for a fusion reactor using scrape-off limiters encircling the plasma in a poloidal cut in front of the pumphole and a limiter elsewhere. The neutralizers might be mounted above and below the depicted plane in order to give a large confinement time of the HF plasma and reduce power consumption

Fig. 4 Poloidal cut of the pumping scheme with a toroidal scrape-off limiter

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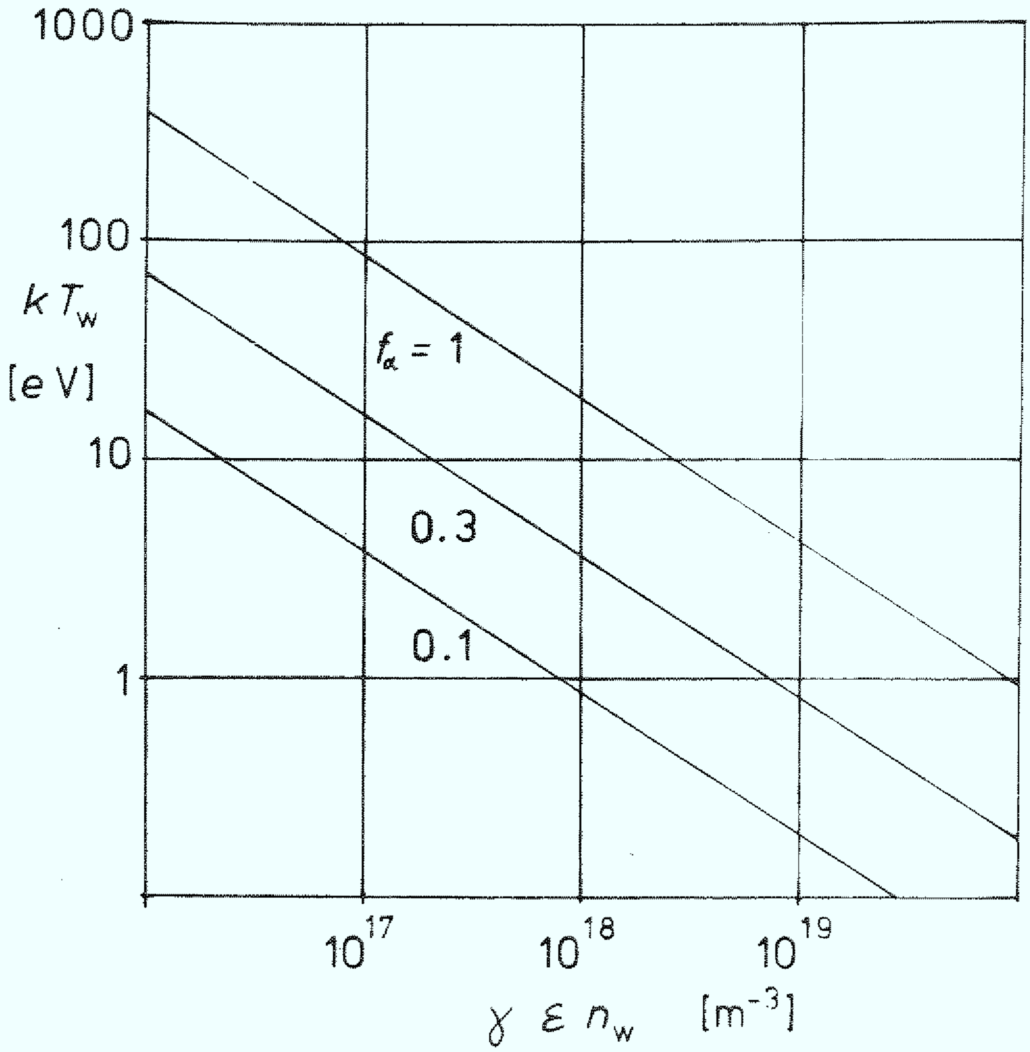
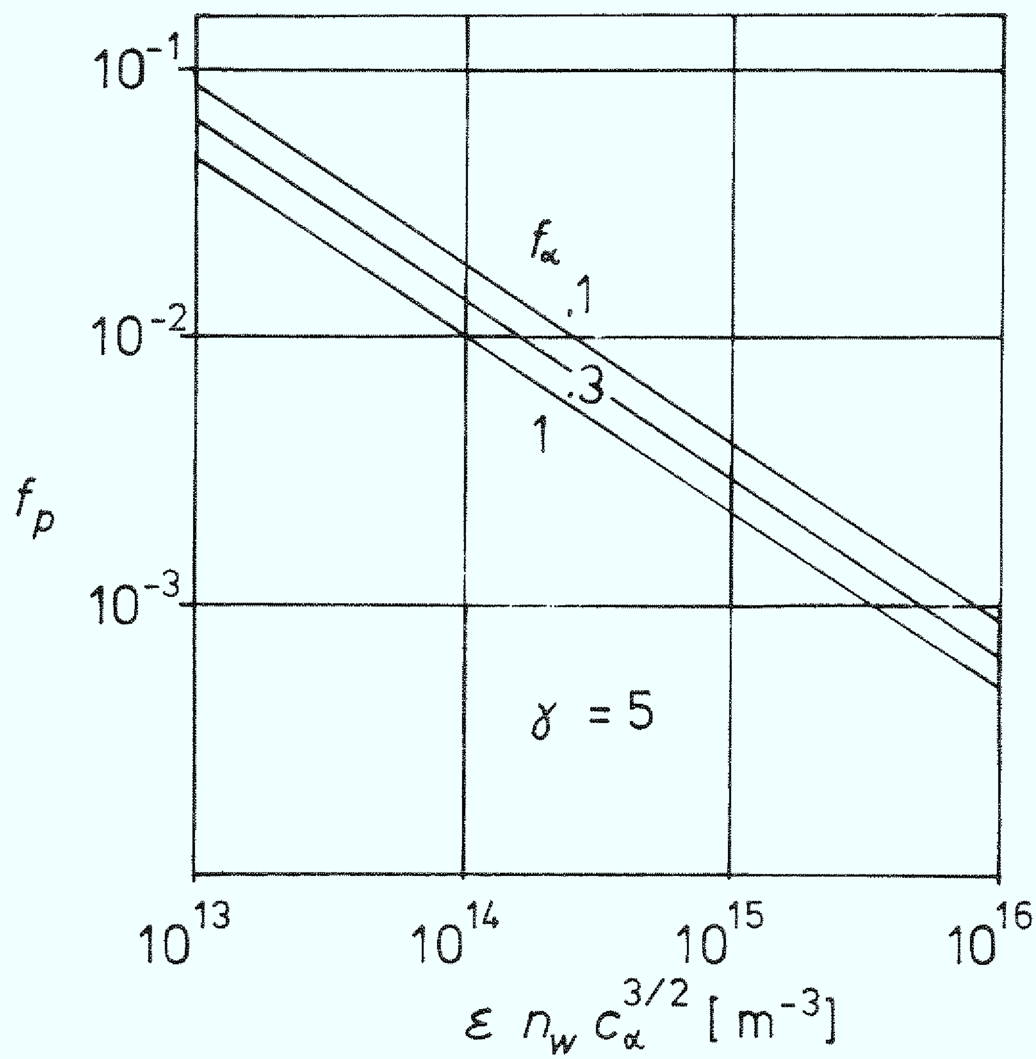

1000
100
10
1
kT_w
[eV]
$f_\alpha = 1$
0.3
0.1
10^{17}
10^{18}
10^{19}
$\gamma\,\varepsilon\,n_w$ [m^{-3}]

Fig. 1



10^{-1}
10^{-2}
10^{-3}
f_p
f_α
.1
.3
1
$\gamma = 5$
10^{13}
10^{14}
10^{15}
10^{16}
$\varepsilon\ n_w\ c_\alpha^{3/2}\ [\mathrm{m}^{-3}]$

Fig. 2

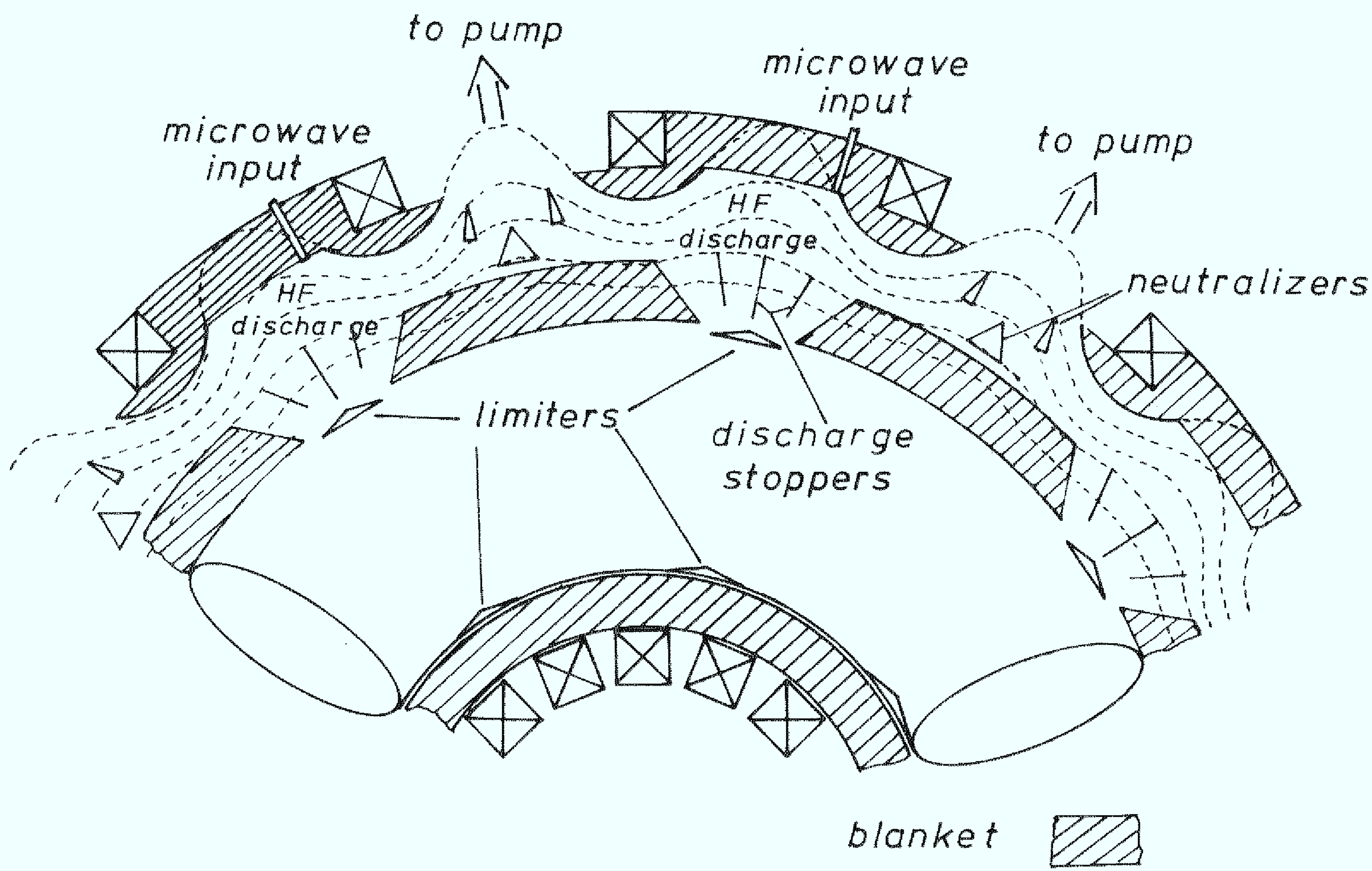

to pump
microwave
input
microwave
input
to pump
HF
discharge
HF
discharge
neutralizers
limiters
discharge
stoppers
blanket

Fig. 3

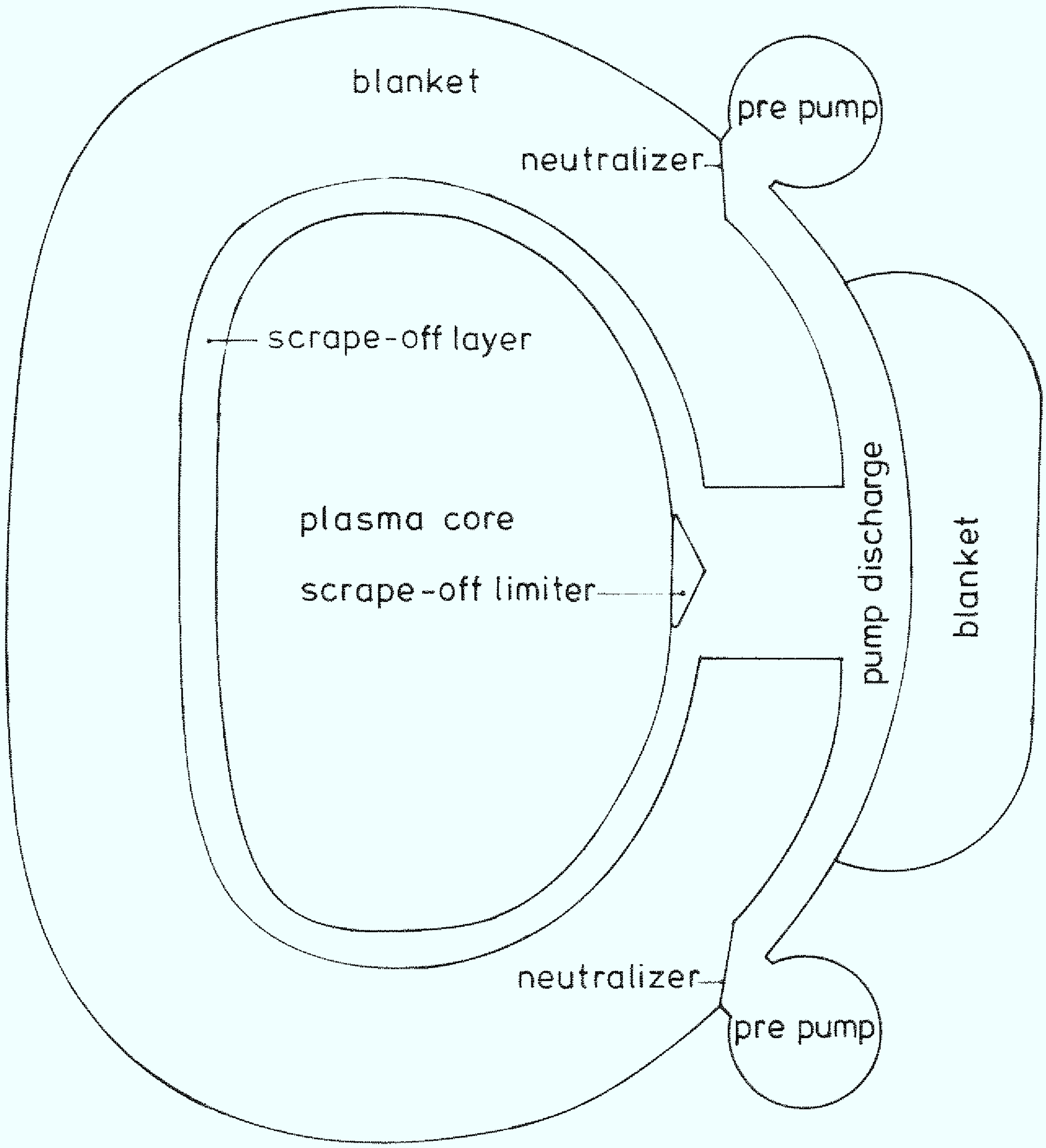

blanket
pre pump
neutralizer
scrape-off layer
plasma core
scrape-off limiter
pump discharge
blanket
neutralizer
pre pump

Fig.4