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Abstract

Moving divertor plates could help solve some of the problems of the tokamak divertor through mechanical ingenuity rather than plasma physics. These plates would be passively heated on each pass through the tokamak and cooled and reprocessed outside the tokamak. There are many design options using varying plate shapes, orientations, motions, coatings, and compositions.

1. Introduction

A persistent problem for tokamak reactor design is the erosion of the divertor plates due to the high heat and particle flux [1]. The conventional solution to these problems, e.g. as implemented in ITER, is to stop machine operation when necessary to remove and repair the worn divertor plates [2]. The water-cooled divertor design in ITER is also subject to a potentially catastrophic loss of cooling accident (LOCA) due to transient heat loads [3], e.g. from disruptions or ELMs.

Here we discuss the possibility of replacing the conventional actively cooled divertor plates by a set of passively-cooled moving divertor plates. These plates would absorb the plasma heat flux with their thermal inertia, after which they would be removed from the vessel for processing. When outside the tokamak the plates could be cooled, cleaned, recoated, inspected, and then returned to the vessel. This scheme would avoid the need to stop machine operation for repair and would eliminate the possibility of a LOCA.

Several similar ideas for moving plasma-facing components have been proposed previously. The most closely related is a moving belt limiter [4,5], which cools and recoats the divertor surface using a flexible in-vessel moving belt. The pebble divertor [6,7] would perform similar functions, but with a gravity-driven stream of small pebbles falling through the divertor. The liquid wall divertor would perform the same functions with a moving liquid stream or gravity-driven droplets [8,9]. However, so far the only moving surfaces used in a tokamak were a rotating limiter tested on PLT [10] and a gallium droplet limiter tested on T-3M [8].

A moving plate divertor would have some advantages with respect to these previous ideas; for example, the plasma facing surfaces would be more similar to conventional divertor surfaces, and their mechanical structure would be more robust and predictable. The main difficulties of this scheme are in the area of mechanical engineering rather than in plasma or surface physics.

2. Conceptual design

The main difficulty for such a moving divertor plate scheme is mechanical: how can the plates be moved in and out of the tokamak *during* plasma operation ? Note that the divertor plates in ITER and tokamak reactor designs are already designed to be removable, but only very slowly when the tokamak is shut down for repair.

Figure 1 illustrates one concept for a moving divertor plate without any toroidal gaps or exposed edges. These plates could be inserted vertically down into position to cover the divertor strike points, which would face these surfaces as shown at the right, and then could be removed from below (blue lines). This plate exchange could be done at each toroidal segment, or the plates could be rotated in the toroidal direction within the vessel (see Sec. 4). The plates would be inserted and removed between the TF coils and carried on a conveyer belt to a plate processing area (see Sec. 5). Estimates for the plate parameters are discussed in Sec. 3, and some of the difficulties are discussed in Sec. 6.

3. Estimates for plate thickness and thermal diffusion time

If the divertor plates are not actively cooled, their thickness and thermal diffusion time within the tokamak will be determined by the maximum allowable surface temperature and the incident plasma heat flux. Here we make simple estimates for these plate parameters for typical cases, assuming for the moment that the plates are *not* moving (moving plates are discussed in Sec. 4).

We assume that a thermal heat load of Q (Watts) is absorbed by the plates over an area determined by the toroidal circumference $2\pi R$ (cm) and the width of the plasma-heated region of the divertor plates w (cm). The plate thickness d (cm) over which the heat penetrates during an exposure time τ (sec) can be estimated from the thermal diffusivity of the plate material χ (cm^2/sec) as:

$$\chi \sim d^2/3\tau \qquad [1]$$

where the "3" is a simplifying approximation. We take this distance "d" to be the optimal thickness for the plates. The thermal diffusivity is $\chi = \kappa$ (W/cm°C)/[c(J/g°C) ρ(g/cm^3)], where κ is the thermal conductivity, c is the heat capacity, and ρ is the plate density.

The average temperature rise T_{ave} (°C) of the plates over the thickness d after an exposure time τ is:

$$T_{ave} \sim Q\tau/[c\rho 2\pi Rwd] \qquad [2]$$

If this heating process is limited by some maximum T_{ave}, the time over which they can remain exposed to this heat is:

$$\tau \sim T_{ave}\, c\rho V/Q \sim Tc\rho(2\pi Rwd)/Q \qquad [3]$$

Substituting this time into Eq. [1] results in an estimated plate thickness:

$$d \sim 6\pi\, \chi T_{ave} c\rho Rw/Q \qquad [4]$$

Thus the optimal plate thickness is linearly proportional to the assumed average temperature and inversely proportional to the local power density on the plate. The corresponding thermal diffusion time is proportional to the square of the plate thickness, as seen from Eq. 1.

Alternatively, the surface temperature can be estimated from [11]:

$$T_{surf} = 2\ q\ [\tau/(\pi\kappa c\rho)]^{1/2} \qquad [5]$$

where q(Watts/cm^2) = Q/2πRw. Substituting τ from Eq. [3] and then d from Eq. [4] gives $T_{surf} = 2T_{ave}$, independent of Q or material properties.

Some potential divertor plate material properties are given in Table 1, and some potential tokamak parameters are given in Table 2. The Q values for the divertor heating are taken to be half the total plasma exhaust powers P in Table 2 (i.e. assuming half the power is radiated).

The resulting plate thickness and thermal diffusion times are given in Table 3 for an assumed w=20 cm and T_{ave}=300 ºC or 600 ºC. For example, for T_{ave}=300 ºC the plate thicknesses for the ITER CFC case is d ~ 2 cm (similar to the divertor plate thickness of present ITER divertor design), and the thermal diffusion time for this case is τ ~ 1 sec.

4. Plate motion

As the heated plate exits the divertor strike zone from below in Fig. 1, a new cold plate would enter from above with a negligible vertical gap between them. Thus the plate replacement section would need have a vertical height of ~2-3 plates in order to keep one plate in the plasma strike zone at all times. The required vertical plate speed will be determined by the thermal diffusion times of Table 3 and the width of the heated region at the divertor strike points. For example, the vertical plate sweep rate in the divertor region V_{plate} could be adjusted to V_{plate} ~ w/τ so that a new region of each plate is exposed whenever the plate was near its local temperature limit.

Table 4 shows some resulting plate parameters for ITER CFC cases. For example, for T_{ave}=300 ºC, the vertical sweep rate would be V_r ~ w/τ ~ 20 cm/sec, so if the vertical plate height was ~ 200 cm the residence time of the plate in the divertor region would be ~ 10 sec, and the corresponding vertical sweep rate and residence time for T_{ave}=600 ºC would be ~ 5 cm/sec and ~ 40 sec.

Another mechanical degree of freedom is toroidal plate motion, as illustrated in Fig. 2. Instead of having the plates exchanged at every toroidal segment (i.e. between each TF coil), the plates could also move in the toroidal direction through several segments before they are removed. These vertical and toroidal movements can be combined so that the plates would sweep vertically move toroidally at the same time, i.e. a plate would enter one toroidal segment with its bottom edge just above the divertor strike zone, and be exit at another with its top edge just above the divertor strike zone. For example, in the T_{ave}=300 ºC case of Table 4, in order to move the full toroidal circumference within a plate residence time the required toroidal plate speed would be ~ 500 cm/sec.

There are other methods for plate motion if a small fraction of the plasma strike zone is allowed to remain uncovered. In Fig. 3(a) the plates are shown entering and leaving in one continuous loop, which can also incorporate vertical sweeping as in Fig. 2. These plates can each be slightly curved in the toroidal direction (not shown) to minimize heating of the leading edges at the toroidal gaps. In Fig. 3(b) the plates are shown as toroidal segments which are inserted and removed radially, and also swept toroidally. If the plate circle was offset with respect to the strike zone center (as shown), the plates would effectively be swept radially as well.

The number of plate replacement sections could be increased to reduce the required plate speed, at the cost of additional mechanical complexity. In general, there are many design options using variable plate size, shape, tilt, and/or rotation. All plate motions could be under computer control to keep the plate temperatures within specified limits.

5. Plate cooling and processing

When the hot plates are removed from the tokamak they can be sent through various processing stages, as illustrated schematically in Fig. 4. Similar processes steps were described previously for the other moving divertor ideas [4-9].

The plates will need to be actively cooled during processing. Some initial cooling would come from radiation, but most cooling could be done by pressing the hot plates against an actively cooled metal plate inside the processing chamber. Table 5 shows ANSYS calculations of the cooling time for hot plates pressed onto a cold copper heat sink, which is either 273°K (room temperature) or 80 ºK (liquid nitrogen temperature). To increase the thermal contact between the divertor and the copper plate, a 0.14 mm layer of high conductivity Grafoil [14] is chosen and 1 MPa pressure is applied between the plate and the copper heat sink to increase the contact area. Both one-sided and double-side cooling options are shown. Typical cooling times to bring these plates to near room temperature are in the range 10-40 sec, which is comparable to the heating time of the plates (Table 4).

The plate surfaces can then be cleaned by light abrasion or other mechanical or chemical processes. This step should remove the undesirable surface layers, including the unused tritium and dust. The plates can then be coated with whatever is best for their use in the tokamak, e.g. boron or lithium. The final step can be an inspection by various standard techniques, e.g. x-ray or ultrasonic inspection for cracks, laser metrology for dimensional tolerances, and various surface characterization techniques. Worn or defective plates could be removed by computer control as in a normal assembly line. After these processing step the plates should be ready to return to the tokamak in their optimum condition.

The plate processing time can be minimized by having a stock of new plates ready to replace any defective plates. If the total processing time was (say) 10 times longer than the plate residence time inside the tokamak, the number of plates in the system would have to be increased by a factor of 10 above the number in the vessel to keep the system in steady state. This should not be prohibitive since the plates are relatively simple and should be inexpensive (compared with conventional divertor plates).

Given the flexibility of such a moving plate system, it would be fairly easy to try various alternative divertor materials. For example, the plates could have a composite structure to increase their strength, or a copper backing to increase their thermal inertia, or could have surfaces such as lithium designed to melt inside the vessel. The average temperature of the plates would also be controllable, e.g. they could be designed to enter the tokamak well above room temperature.

6. Potential Difficulties

There are many potential difficulties with such a moving divertor plate scheme which would need to be addressed in a detailed engineering design and eventual testing. Some of these mechanical difficulties have already been addressed in design of the Kazakhstan tokamak [15], which has divertor plates which can be rotated toroidally and removed under vacuum for surface analysis (although not during plasma operation).

a) Divertor configuration

The first issue is whether the plasma and divertor configuration can be made consistent with a moving plate geometry, e.g. with a vertical divertor plates as in Fig. 1. Such flexibility should be possible magnetically, but the effect of such an 'open' divertor geometry on the impurity level, H-mode access, helium ash pumping etc. would need to be tested experimentally. The width and exact location of the divertor strike zones does not seem to be an issue if the plate location can be swept inside the vessel.

The surface structure of the plates can be varied to optimize divertor performance, and many versions could be tried by replacing the plates within the processing chamber. The plasma-facing surfaces of the plates could be designed with grooves or slots to increase the surface area or to locally trap impurities, hydrogen isotopes, and/or helium. The plates could have "on-board" gas injection or electrical biasing, which could be recharged or refueled on each cycle in the processing chamber. The plates could also be designed as 'pumped limiters' without any magnetic divertor.

b) Plate movement

The most difficult issue is ensuring the rapid and reliable movement of these plates inside the tokamak vacuum system. However, there are many industrial systems with mechanical movement under computer control, and motion in vacuum is routinely done e.g. in space programs.

The plates could be moved on rails with secure wheels like a roller coaster or train. Lubrication of the moving surfaces without sticking is an issue, but the wheels can be cleaned and re-lubricated on every pass through the processing system, e.g. using 'vacuum grease'. The force needed to move the plates will depend on the resulting friction and also on any eddy currents induced by the plate motion across the tokamak magnetic field. The simplest way to move the plates would be using a cable driven from outside the tokamak, as in a cable car or funicular. The wheels could also be powered with internal electric motors, as on the lunar rover, with phased JxB torques made using the tokamak magnetic field, driven by on-board capacitors recharged on every pass through the processing system.

c) Thermal and mechanical stress

Any passively cooled plate design would have to withstand the potentially high thermal stress due to the cyclic heating and cooling. An initial analysis of the maximum thermal strain was done using ANSYS model for two cases of Table 5, with the number cycles to failure estimated from the data in ITER material properties handbook. For a typical case (pure Tungsten at 815ºC and low cycle fatigue data) the number of cycles to failure was > 1e9 for both the 300º and 600º. Even a much higher level of failure would not be a problem, since the plates could be examined for damage during every cycle through the processing system.

The plates inside the vessel would also have to withstand the transient heat loads and MHD-induced forces during disruptions. Disruption-induced heat loads on moving divertor plates would be approximately the same as for stationary plates. Disruption-induced forces would depend in detail on the current paths, and could be minimized by electrically floating the plates with respect to vessel ground. If the plates were severely damaged during disruptions they might have to extracted by a remote manipulator similar to the system already designed for ITER.

d) Processing system

After cooling, the external plate processing steps should be relatively straightforward, as discussed in Sec. 5. It should be possible to partially isolate the plate processing from the high vacuum of the tokamak chamber using a differential pumping chamber with a narrow apertures for the plates, or a plasma window [16]. These processing and inspection steps could all be developed on test stands without a tokamak [e.g. as in 5,8].

7. Summary

Moving divertor plates could potentially help solve some of the persistent difficulties associated with tokamak divertor systems. There are many design options using varying plate shapes, orientations, motions, coatings, and compositions. The advantages of such a system would be:

a) no down-time needed to replace or refurbish worn divertor plates,

b) no loss-of-coolant accident due to damaged divertor plates,

c) divertor plates could have nearly ideal surfaces at all times,

d) divertor plate surfaces or materials could be changed quickly.

The potential difficulties of a moving divertor plates system are mainly mechanical in nature, and so are potentially solvable through existing technology. Research on the main difficulties such as motion in vacuum and rapid plate cleaning and inspection can be done without a tokamak [e.g. 5,8]. It is not yet clear whether a moving plate system would be more or less feasible than other similar ideas for movable divertors, e.g. moving belts [4,5], pebble divertors [6,7], or liquid walls [8,9]. Perhaps the main advantage of the moving plate system is that the plasma facing surface will be more robust and more similar to conventional divertor plates than these other systems.

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Table 1: Some possible divertor plate material properties

material	heat capacity c (J/g ºC)	density ρ (g/cm^3)	heat conductivity κ (W/cm ºC)	heat diffusivity χ (cm^2/sec)
tungsten	0.13	19.3	1.74	0.7
carbon fiber	~ 0.7	~ 2	~ 2	1.4
beryllium	1.82	1.85	2.01	0.6

Table 2: Some possible tokamak parameters

machine	major radius R (cm)	exhaust power P (MW)	P/R (MW/m)
ITER [1]	620	130	21
ARIES-AT [12]	520	370	71
NHCX [13]	100	50	50

Table 3: Plate thickness and thermal diffusion time (w=20 cm, Q =65 MW)

		T_{ave} = 300 ºC		T_{ave} = 600 ºC	
machine	material	d (cm)	τ (sec)	d (cm)	τ (sec)
ITER	tungsten	1.8	1.6	3.6	6.4
ITER	CFC	2.0	1.0	4.0	4.0
ITER	Beryllium	2.1	2.5	4.2	10.0
ARIES-AT	tungsten	0.56	0.15	1.1	0.6
ARIES-AT	CFC	0.62	0.10	1.2	0.4
ARIES-AT	Beryllium	0.65	0.23	1.5	0.9
NHTX	tungsten	0.8	0.3	1.6	1.2
NHTX	CFC	0.9	0.18	1.8	0.7
NHTX	Beryllium	0.9	0.5	1.8	2.0

Table 4: Plate parameters for ITER CFC cases
(w=20 cm, Q = 65 MW)

Parameter	T_{ave} = 300 ºC	T_{ave} = 600 ºC
plate thickness	2 cm	4 cm
plate diffusion time	1 sec	4 sec
plate width	250 cm	250 cm
plate height	200 cm	200 cm
# of plates in vessel	18	18
plate mass (each)	200 kG	400 kG
plate energy (each)	40 MJ	160 MJ
plate residence time	10 sec	40 sec
vertical plate speed	20 cm/sec	5 cm/sec
horizontal plate speed (360º rotation)	500 cm/sec	100 cm/sec

Table 5: Plate cooling by contact with cold heat sink

time to cool the divertor (divertor final temperature)				
material and initial temperature	one-side cooling		double-side cooling	
	cooling plate temperature		cooling plate temperature	
	80K	273K	80K	273K
tungsten (873K/600ºC)	23.5 s (77ºC)	39 s (127ºC)	12 (27ºC)	16 s (127ºC) 24.75 (77ºC)
tungsten (573K/300ºC)	16.5 s (27ºC)	32.35 s (77ºC)	6.6 s (27ºC)	13 s (77ºC)
CFC (873K/600ºC)	26.5 s (77ºC)	39 s (127ºC)	11 (27ºC)	14 s (127ºC) 19.5 s (77ºC)
CFC (573K/300ºC)	20 s (27ºC)	33.5 s (77ºC)	6.4 (27ºC)	11 s (77ºC)
Beryllium (873K/600ºC)	30 s (97ºC)	39.25 s (177ºC)	17 (27ºC)	23 s (127ºC)
Beryllium (573K/300ºC)	22.75 s (27ºC)	40 s (87ºC)	9.2 (27ºC)	18.2 s (77ºC)

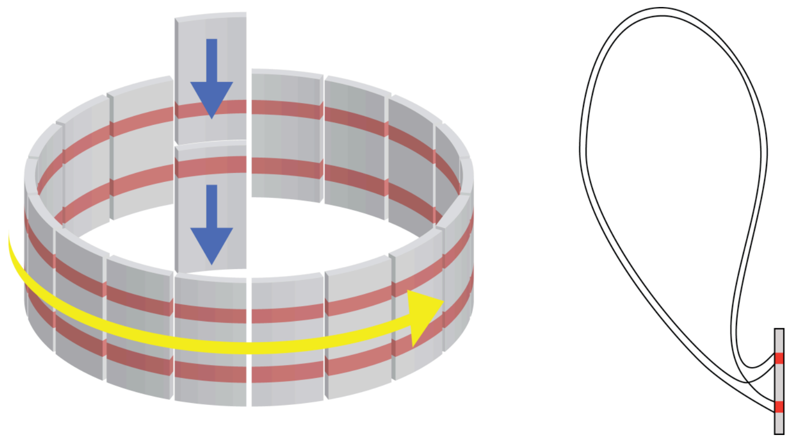


Figure 1 - Conceptual design of a moving divertor plate system in a tokamak. The plates form a ring around the bottom of the tokamak, with the divertor strike zones indicated by the red stripes. The plates could be inserted and removed vertically (blue arrows), and could also be moved toroidally (yellow arrow).

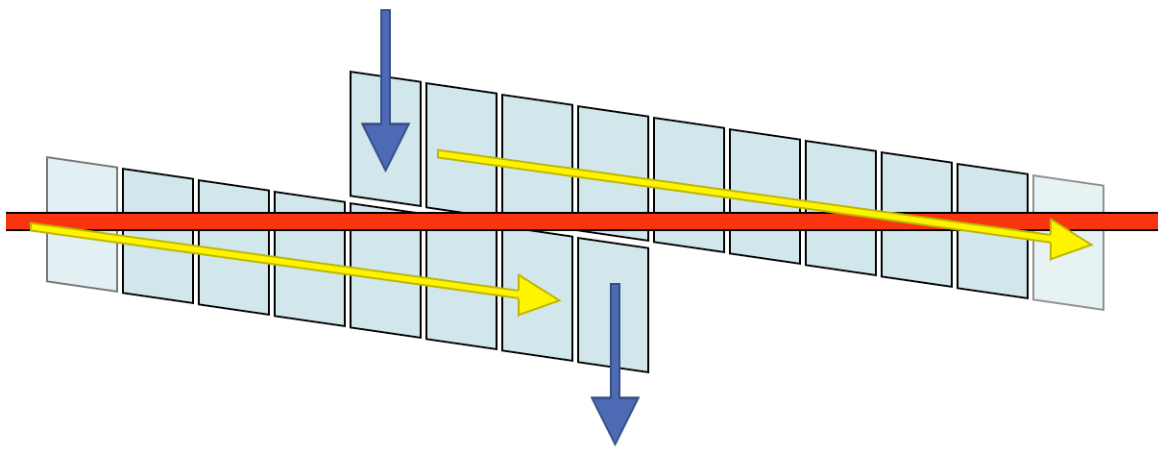
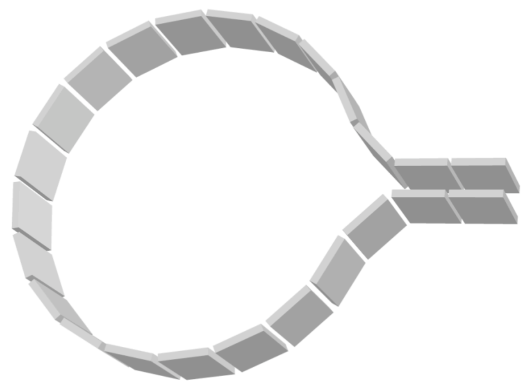


Figure 2 – Method to sweep the plates both in both the toroidal and vertical directions simultaneously in order to reduce the number of plate exchange locations inside the tokamak. The toroidal direction is horizontal in this 2D view, and a plasma strike zone is shown as a red line. The blue arrows show the location of the plate insertion and removal.

(a)



(b)

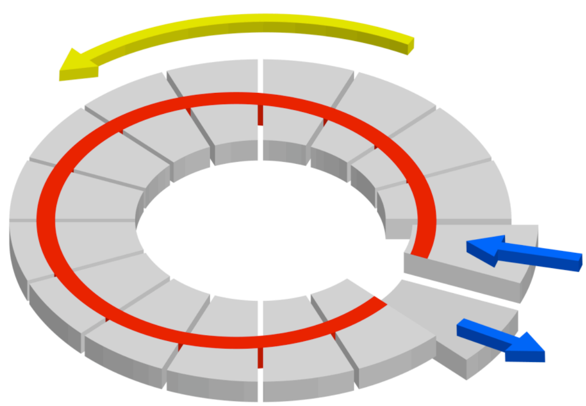


Figure 3 - Alternative methods for plate location and motion in which some of the plasma strike zone is allowed to become uncovered. In (a) the plates are vertical and enter and exit the tokamak in a continuous loop, In (b) the horizontal plates are replaced with a radial motion and rotated in an offset toroidal direction to sweep the heat flux over the plate radius.

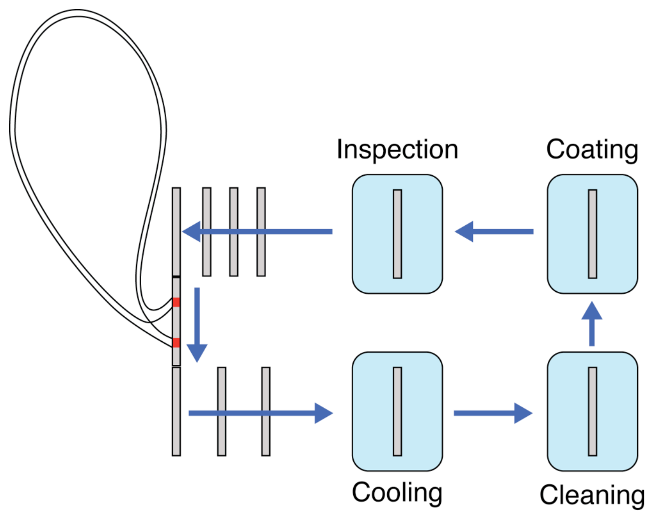


Figure 4 – Plate processing outside the tokamak. Once the plates are removed from the main chamber they can be processed and returned in optimum condition. External processing would also allows rapid testing of redesigned divertor plates.

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