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Abstract

The Wisconsin Tokamak Reactor Design (UWMAK-I) incorporates a poloidal divertor to establish a plasma boundary away from the first wall and to reduce wall erosion by energetic charged particle bombardment and the subsequent release of impurities into the plasma. The divertor is axisymmetric and of the double-null type which produces a "D" shaped plasma surface. The particle collectors are a liquid lithium film flowing under gravity down a flat plate.

I. Introduction

The divertor is a device, first proposed by Lyman Spitzer(1) for avoiding contact between the hot plasma and the first material wall surrounding the plasma. By use of external coils, an outer shell of magnetic flux between the plasma surface and the wall is "diverted" away from the surface and led to special particle collectors. Charged particles diffusing out of the plasma enter this shell and follow the magnetic field lines to the collectors rather than striking the wall. Although originally proposed to reduce the release of impurities from the wall, it was soon realized that a divertor might also reduce the erosion of the first wall in a reactor. An additional benefit is that if the neutral pressure in the scrape-off region (diverted flux zone) is low, then the divertor acts as a thermal insulator between the plasma and the first wall. This results in a longer energy confinement time for the plasma and a flatter temperature profile and consequently a higher average power density, with obvious economic benefits.

Various types of magnetic field divertors have been devised for toroidal devices. All are based upon the idea of generating a neutral point in a component of the magnetic field. This generates a separatrix and field lines on the outside of this separatrix are carried away from the plasma surface as they pass by the neutral point. Magnetic flux surfaces on the inside remain closed within the plasma volume, as is necessary for confinement. The separatrix then becomes the boundary of the toroidally confined plasma. The toroidal divertor(2), used on stellarators at Princeton, generates a neutral point in the toroidal magnetic field. Unfortunately, it also produces a substantial perturbation in the center of the plasma. The bundle divertor(3), recently proposed by a Culham group for the DITE Tokamak, avoids this difficulty by using two adjacent opposing current loops near the plasma surface to divert a bundle of magnetic flux. Its use in a fusion reactor is questionable, however, because the coils would have to be placed outside the blanket and shield regions; this raises the currents required immensely. Further, several bundle divertors would be required in order to have 1) a sufficiently short path along the field lines between the collectors, and 2) sufficient collection area to handle the anticipated heat load from particles entering the divertor.

The poloidal divertor(4,5) is a natural for Tokamaks since it diverts the poloidal magnetic field without affecting the axisymmetry property. This is done by toroidal currents. In reactors, these divertor currents can be outside the blanket and shield and perhaps even outside the main toroidal field magnets. There is some freedom in the location of the neutral points and thus in the path of the field lines that guide the particles away from the plasma. We have chosen the double null design which has two neutral points placed symmetrically above and below the midplane towards the inside of the torus (see Fig. 1). This configuration requires less hardware in the central core of the torus, where things are already crowded, than some alternative schemes. From an optimization viewpoint, and the desire for a small aspect ratio, it would be desirable to place the neutral point on the outside of the torus. This does not appear to be feasible in a reactor since the divertor currents need to be relatively far from the plasma surface.

Since poloidal divertors preserve the axisymmetry of the Tokamak, banana orbits of particles are not affected and superbanana orbits, with their much larger radial excursions, are not produced. The toroidal and bundle divertors destroy the axisymmetry and lead to superbanana effects, especially near the separatrix. Even if the corresponding enhancement of diffusion is tolerable, a significant number of α particles born on superbanana orbits near the plasma edge may hit the first wall at high energy and produce erosion by blistering. This suggests that the poloidal divertor will better protect the first wall when the plasma is thermonuclear.

An additional possible benefit(6) of a poloidal divertor is that it may operate as a "magnetic limiter" during the current rise phase of the Tokamak cycle. The idea here is to initiate the discharge at a multipole null in the center of the vacuum chamber and control the position and size of the expanding plasma column as the plasma current rises by proper programming of the divertor currents. In this way, the generation of impurities during the initiation of the discharge may be avoided.

II. Wisconsin Poloidal Divertor

The UWMAK-I poloidal divertor is shown in Fig. 1. The divertor coil currents, which in conjunction with the plasma current determine the magnetic field geometry, are located outside the main toroidal "D" magnets. This facilitates construction and disassembly since interlocking coils are avoided but is expensive since it requires larger currents and has more energy stored in the poloidal magnetic field. this energy must be supplied from the line or from an energy storage system when the plasma and divertor currents are energized. In addition to locating the neutral points and separatrix, the divertor currents also have the job of proving the vertical magnetic field for radial equilibrium with the proper shaping for radial and vertical stability. The spacing between the separatrix and the first wall (50 cm) has been chosen such that a 3.5 MeV α particle born at the edge of the plasma cannot hit the wall without first undergoing collisions with ions and electrons. These collisions will cause slowing down and thermalization as well as spatial diffusion so that relatively few α-particles hit the wall at MeV energies.

The particles diffusing out of the plasma cross the separatrix into the scrape-off region and, hopefully, follow the field lines to the particle collectors. Some considerations important for determining what the plasma really does is considered in the next section. The collectors proposed by us are a set of stainless steel plates with a liquid lithium film flowing under gravity down the face exposed to the impinging particles. The incident particles are imbedded in the lithium film, trapped chemically at high efficiency(7) by formation of lithium hydride, and removed from the system in the flowing lithium for external processing. A schematic of the liquid lithium collectors is shown in Fig. 2. The 1 mm thick lithium film enters the vacuum chamber at 200°C, exits at 325°C, and has a mean residence time in the charged particle beam of ~1/2 second. At the exit temperature of 325°C the vapor pressure of lithium is ~5 x 10^{-6} torr;

substantially no re-emission of particles occurs.

The liquid lithium film is exposed to the particle fluxes and surface heat load shown in Table I. The flow rate is such that no additional cooling of the stainless steel plates is required; the heat is absorbed by the flowing lithium. Since the film thickness is considerably less than the thermal skin depth, the exit temperature of the lithium will be quite uniform.

In addition to collecting the energetic charged particles, the lithium film provides a major share of the total pumping speed for neutral gas during the shutdown and reload portions of the burn cycle.

Table I

Lithium Collector Surface Loads

Particle	Mean Energy	Flux (cm^{-2} sec^{-1})	Surface Heat Load ($Watts/cm^2$)
D^+	23 kev	6.4×10^{15}	23
T^+	23 kev	6.4×10^{15}	23
e^-	23 kev	1.4×10^{16}	47
He^{++}	23 kev	4.7×10^{14}	1.2
He^{++}	~100 kev	1.7×10^{13}	.3
x-ray	~10 kev		5-10
n	.1-14 Mev	4.4×10^{14}	---

III. Plasma Phenomena in the Scrape-Off Region

The ability of the divertor to reduce erosion of the first wall and the release of impurities into the plasma is determined by a complexity of plasma physics problems in the scrape-off region. For discussion purposes, we consider the outer divertor only (the one on the right in Fig. 1).

The magnetic field structure in the scrape-off region is essentially the same as in the plasma. The poloidal field is responsible for carrying the particles to the collectors, but the gradient of the toroidal field provides magnetic mirrors and guiding-center drifts. For the outside divertor the magnetic field increases as the particle follows the field line toward the neutral point. Consequently, the divertor resembles a magnetic mirror machine. There exists a loss-cone and only particles whose velocity vector lies inside the loss-cone can reach the collectors. Particles whose velocity vector lies outside the loss-cone must be scattered, either by collisional or collective processes, into the loss-cone before they can reach the collector.

From these considerations, one expects that the plasma in the scrape-off region ought to have an anisotropic distribution function and consequently may exhibit the high frequency microinstabilities characteristic of mirror devices. Two important modes for consideration are the Post-Rosenbluth(8) convective loss-cone mode and the drift-cone mode.(8) The former is unstable if the field line length L to the mirror throat exceeds ~100 ρ_i where ρ_i is the ion gyroradius. For any conceivable device L/ρ_i ~10^3-10^4 so that the mode ought to be grossly unstable unless T_e sufficiently exceeds T_i. In this case, the mode may be stabilized by electron Landau damping.

The drift-cone mode may also be unstable if the density gradient is strong enough in the scrape-off region. The (approximate) criteria is

$$\frac{\rho_i n'}{n} > \left(\frac{\omega_{pi}}{\omega_{ci}} \right)^{-4/3} .$$

Both of these modes ought to cause a greatly enhanced rate of pitch angle scattering over the classical rate. Consequently, the loss-cone ought to fill in rapidly and the time for a typical ion to reach the collector is approximately L/v_{Ti}, where v_{Ti} is the ion thermal velocity.

If $T_e \sim T_i$, then the electron thermal velocity is much faster then the ion velocity. In order to maintain electrical neutrality in the scrape-off region, there must exist at the collector a Debye sheath which reflects most electrons. Consequently, the electrons are electrostatically confined and the plasma in the scrape-off region will have a positive electrostatic potential relative to the collectors. This is different from the usual ambipolar potential for toroidal devices. An impurity ion in the scrape-off region is subjected to two frictional forces. First it wants to diffuse up the plasma ion density gradient, according to classical diffusion, and thus into the main body of the plasma. Second, it is being dragged by collisions with ions towards the collectors. The effectiveness of the divertor in preventing impurity ions from reaching the main body of the plasma will depend on who wins the competition between these two effects. The effectiveness of the divertor in preventing neutral impurity atoms from getting into the plasma will also depend on the probability of the neutral atom being ionized in the scrape-off region.

The lithium collectors will generate lithium impurity atoms by evaporation and sputtering. Fortunately, lithium is only Z=3 so that a substantial concentration can be tolerated compared with higher Z materials. For example, 10% lithium gives a Z_{eff} of 1.5, which is a clean plasma by most standards. Since some lithium atoms will escape the divertor and get into the plasma, an important but yet unanswered question affecting the suitability of lithium for collectors is the transport processes for lithium in the main body of the plasma. Given a steady source of lithium atoms, will the lithium density increase forever or saturate at a tolerable level? If the transport is classical, the lithium will build up to too high a level. However, it is conceivable that the lithium could participate in anomalous diffusion due to trapped particle modes; this may lead to a saturated lithium concentration at a tolerable level.

The plasma in the scrape-off zone may also be unstable to low frequency modes driven by density or temperature gradients. These modes can cause cross-field transport without affecting the rate of pitch-angle scattering since they preserve magnetic moment. These modes would tend to reduce the effectiveness of the divertor in preventing particles from reaching the wall.

We have considered a simple model which assumes the high frequency modes are sufficient to give $\tau_{\parallel} = L/v_{Ti}$ for the parallel transport but low frequency modes produce Bohm diffusion. The density falls off outside the separatrix with a scale length $\lambda \approx \sqrt{D_{\perp}\tau_{\parallel}}$, where $D_{\perp}$ is the cross field diffusion coefficient. About 90% of the particle flux crossing the separatrix is collected by the particle collectors, but the density at the separatrix is only $\sim 10^{10}-10^{11}\,\mathrm{cm}^{-3}$ so that the divertor is not effective in screening impurity neutrals from the main plasma. Different assumptions for parallel transport and cross field transport will of course give different results. It appears from a variety of simple calculations that divertors can reduce the charged particle flux to the first wall by a significant amount but more precise calculations and experimental data are necessary to pin this down better and to predict the quantity and energy spectrum of particles incident on the first wall.

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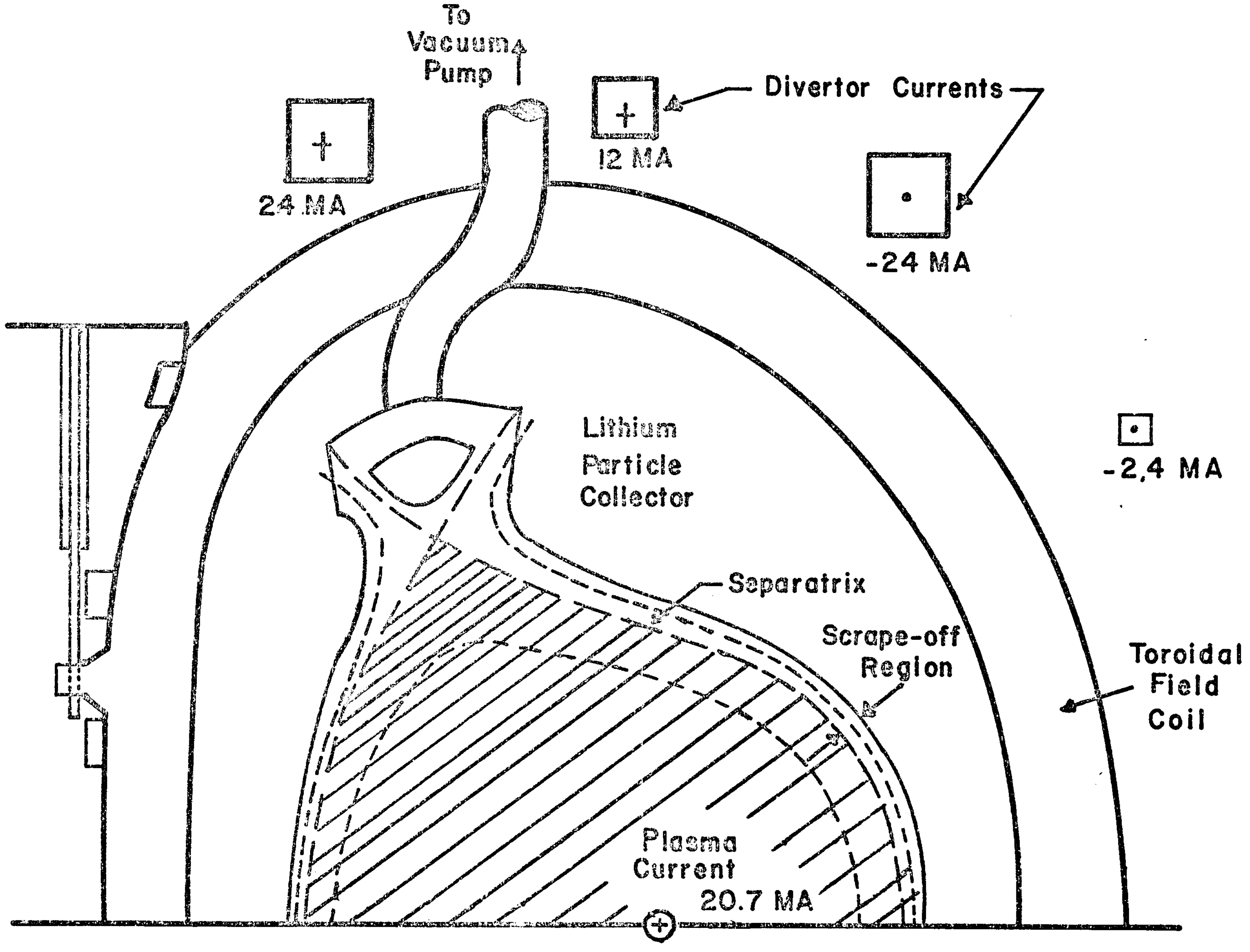
Figure 1

UWMAK-I Double Null Poloidal Divertor



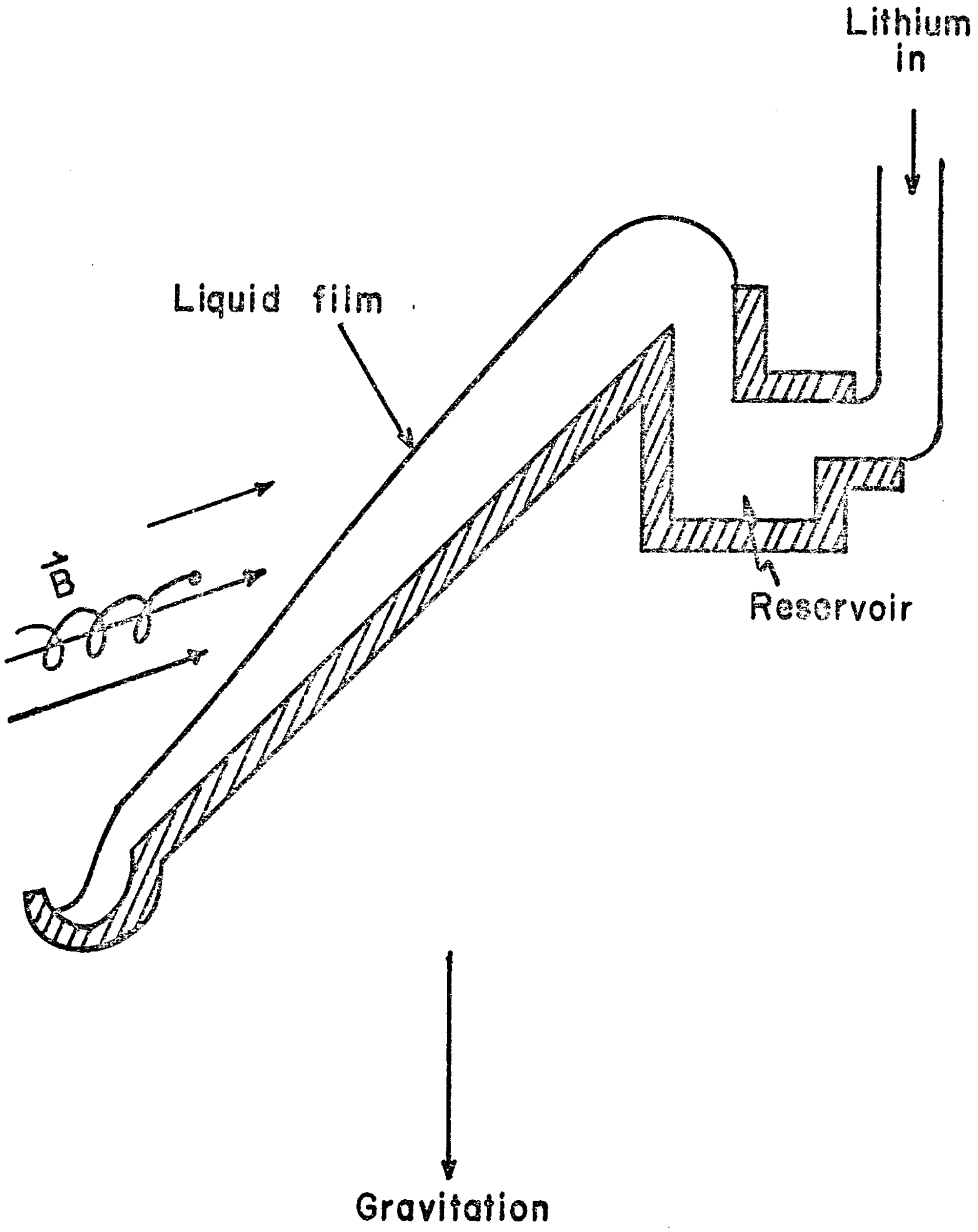


Figure 2
Lithium Film Particle Collectors