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DESIGN CONSIDERATIONS FOR DIVERTORS
IN TOROIDAL FUSION REACTORS

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ABSTRACT

It is well-known that a divertor would be a desirable feature of a toroidal reactor. A conceptual design of an axisymmetric poloidal field divertor for a Tokamak reactor is discussed. The design has the advantage that the divertor coils are located outside of both the blanket and the divertor chamber. The total wall area is approximately equal to the reactor wall area. The hot ions streaming into the divertor initiate a wall-plasma interaction producing neutrals which, in turn, are ionized and form a relatively cold plasma. The cold plasma cannot be contained in the divertor; its temperature must be kept below 25 eV to prevent excessive wall erosion.

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We want to discuss some of the processes that would be expected to occur in a poloidal field divertor for a tokamak reactor together with some design considerations for such a reactor. In particular we consider the poloidal field divertor conceived for the 5000 MW(th) tokamak reactor currently under study by the Reactor Studies Group at the Princeton Plasma Physics Laboratory in the United States. A sketch of this reactor, showing the overall geometry, is shown in fig. (1). The major and minor radii are, respectively, 10.5 and 3.2 meters. The toroidal magnetic field on axis is 60 kilogauss. The value of "q" at the plasma edge is nominally 2. The reacting plasma is a 50-50 mixture of deuterium and tritium at a peak ion density of 10^{14} cm^{-3} and an edge temperature of about 10 KeV. The total throughput is slightly less than 10^{23} atoms per second. The applied vertical magnetic field, which is required to achieve equilibrium for the tokamak discharge, produces a null in the poloidal magnetic field on a circle at the inner edge of the discharge. The resulting separatrix surface has two symmetric arms curving back, both top and bottom, over the discharge

region. These arms define the diverted magnetic field lines which, in turn, are bounded by the divertor. The locations of the coils and their relative current strengths that produce such a magnetic field configuration are shown in fig. (2) (which shows only the top half of a symmetric arrangement). All the divertor coils are located at least two meters from the tokamak discharge and hence are outside the blanket and shield region. Therefore it is feasible to design the coils as superconductors rather than normal conductors and thereby realize a considerable savings in operating power.

The tokamak discharge current is represented by a single filament of current of unit strength located somewhat outside the nominal centerline of the discharge. Three magnetic surfaces lying near the separatrix are also shown in fig. (2). The separatrix acts as a magnetic limiter: Hot plasma that diffuses across the separatrix flows along magnetic field lines that wind around the machine's major axis of symmetry several times before reaching the collecting regions of the divertor. This region outside of and adjacent to the separatrix is called the "scrape off" region. We note the magnetic field strength is dominated by the toroidal field which varies inversely as the major radius. Consequently the scrape off region constitutes a magnetic mirror, with a magnetic field ratio of about three.

The reactor design specifies that the hot plasma flow will deliver about 120 MW to each arm of the divertor. If we imagine a plasma collecting surface stretching from 6 meters to 12 meters in major radius in each of the divertor arms, this energy flow amounts to about 35 watts/cm^2 , a rather modest figure. To help visualize how such a collection of plasma might be accomplished, a cartoon of one arm of the divertor is shown in fig. (3). The magnetic flux surfaces have been spread apart somewhat in the collecting region to facilitate collecting the plasma over a large surface.

We imagine the following processes to take place under steady state conditions. The ion impact on the collecting surface will cause an equivalent number of neutrals to be emitted by the surface. These neutrals may escape into regions which are

shielded from plasma by other collecting surfaces-whence they may find their way to the pumps - or, more likely, the neutrals will find themselves ionized in the plasma near the emitting surface. Thus a cold plasma will be built up deep in the divertor. This cold plasma provides a partial energy dump for the incoming hot plasma as well as a dangerous source of enhanced sputtering of the collector surfaces. We may estimate the temperature and density of this cold plasma by consideration of particle flow balance and energy flow balance. To analyze the particle flow we imagine the entire collecting structure to be represented by a single surface with an effective sticking fraction. The throughput of ions must then be equal to the total ion flow to the collectors multiplied by this sticking fraction. In regard to the energy flow, we consider the major loss of energy from the cold plasma to be via the flow of ions from the cold plasma to the collectors. The ions will obtain the bulk of their energy by falling through the plasma sheath potential, which we take at four times the plasma temperature. Thus the plasma temperature is known in terms of the energy input and the effective sticking fraction of the collecting structure. We can compute the ion density from knowledge of the ion current density, which is just the total ion flow divided by the projected collecting surface, together with knowledge of the average speed of the ions. The average speed can be computed if we assume an ion velocity distribution, such as half a maxwellian, to hold at the edge of the plasma sheath.

In the end, one must have a consistent calculation of energy input and cold plasma parameters. If one assumes the cold plasma to be confined to the last 100 m of hot ion path, one can calculate the energy lost via coulomb collisions by the hot incoming electrons and ions in a given plasma. It is soon evident numerically that the hot electrons lose very little energy in passing through the plasma. A self consistent set of numbers is as follows: a sticking fraction of $1/20$, (our most optimistic estimate, assuming conventional pumps); an energy of 2 KeV deposited in the cold plasma by each hot ion; a plasma temperature of 25 eV and a density of 10^{13} cm^{-3} .

Unfortunately the cold plasma pressure exceeds the rate of momentum carried into the divertor by the hot plasma ions. Therefore, it is impossible to prevent the cold plasma from leaking out of the divertor and filling the entire scrape off region. Since the path length over which the hot ions can lose their energy is thus quadrupled, it suggests that perhaps the hot ions can dissipate their entire energy in the cold plasma. Under such an assumption the plasma temperature rises to 190 eV. There are several implications that can be drawn from this example.

Firstly, a competition will ensue between diffusion of the cold plasma across the magnetic field to the walls bounding the scrape off region and flow along the field to the collectors. As a result, the scrape off region occupied by the cold plasma will be substantially thicker than the region occupied by the hot electrons which simply make one pass through the cold plasma on their way to the collectors. The collectors must therefore span a greater amount of magnetic flux in order to catch the cold plasma. The material walls bounding the scrape off region may have to be further away from the separatrix surface than otherwise. However, the hot electrons, which may carry about half the input energy, will still deposit their energy over a relatively narrow region on the collectors. Hence some means must be found to spread out the flux tubes adjacent to the separatrix.

Secondly, a plasma temperature of 190 eV is too high. To see this consider the following. Using a sputtering yield of 0.01, the sputtering of the collecting surface due to a primary flux of hot ions alone amounts to about 0.3 mm/year. This may be an acceptable rate of erosion. However, if the cold plasma ions, striking the collector with some 750 eV, are presumed to have the same sputtering yield, then the total sputtering of the cold plasma ions will be twenty times the above rate, or 6 mm/year, which is unacceptable. Furthermore, atoms of wall material which become ionized in the cold plasma will also strike the collector surface at 750 eV, which may be energetic enough to produce sputtering yields in excess of unity. Such circumstance will produce avalanches of wall material which

would be disastrous.

The conclusion is that the cold plasma temperature must be reduced below something like 25 eV in order to avoid excessive sputtering. This reduction in temperature can be brought about by reducing the pumping speed of the divertor to a value where the sticking fraction is about $1/150$. The total flux of ions would then increase to some 150 times the primary flux of hot ions, but the sputtering yield at 100 eV is expected to be several orders of magnitude less than 0.01. Therefore, one might expect the total sputtering will be acceptable. Furthermore, owing to the low plasma temperature charge exchange effects will not substantially modify these results.

The direction in which our considerations are pointing is, of course, a neutral gas blanket around the reacting plasma; in which case what is the need for a divertor? The effectiveness of a gas blanket to act as a limiter or the relative merits of the magnetic limiter action of a separatrix cannot be argued here. What does appear from simple considerations of energy and particle balance and sputtering yields is that a feasible poloidal field divertor on a steady state 5000 MW(th) tokamak reactor will necessitate a cold plasma blanket around the reactor at a temperature not higher than 25 eV.

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FIG. 1. TOKAMAK REACTOR

FIG. 2. POLOIDAL DIVERTOR

FIG. 3 TOKAMAK DIVERTOR CONCEPT