Divertor Solution for MITcostcode

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1 Heat load Entering the SOL

The heat load that the divertor must ultimately be able to handle is provided by the power leaving the core. We know that in a fusion reactor the power balance is:

$$P_\alpha + P_{heating} = P_{Diffusion} + P_{Brem} \tag{1}$$

In this equation the heat load that the Divertor has to deal with is $P_{Diffusion}$.

2 Heat Flux

Knowing the heat load alone is not enough, we must also know the area over which the power is distributed. This will determine what kind of active cooling we need in order to keep the divertor from melting. In doing this calculation we will assume that the entire heat load is deposited in the outer midplane. The heat radiates out from the core radially and is quickly caught by the poloidal field lines that make up the scrape off layer and are carried out of the core region and into the divertor leg. Therefor the area over which the heat is distributed is the washer shaped area that is:

$$Area \approx 2\pi R\lambda \tag{2}$$

Where λ is the distance that the plasma diffuses into the scrape off layer before being trapped. Naturally this distance will not be well defined theoretically, however its value has been empirically determined by Thomas Eich and has the value:

$$\lambda \approx \frac{2}{3} B_\theta^{-1.2} [mm] \tag{3}$$

therefore the heat flux at the outer midplane is:

$$H_{||} = \frac{3 P_{Diffusion} B_\theta^{1.2}}{4\pi R} \tag{4}$$

This is the full form of the referenced PB/R parameter disscused by Labombard et all......

3 Traveling down the leg

There are two major tricks that can be employed in order to reduce the heat flux that actually impacts the divertor: Detatchment and Flux Expansion.

Detatchment is an extreamly complicated and not well understood phenomina, esspecially in long leg divertor desigens. It is characterized by a sharp ion density and temperature drop prior to the divertor targets. It is caused by large amounts of volumetric power removal from the plasma in the divertor leg. These losses take the form of raidation due to recombination and dissipation on neutral and impurity ions. It is impossible at this time to calculate the fraction of volumetric power loss with any certainty. Therfore we will include it by ignoring the physics and assume some volumetric power loss fraction, ρ_{vol}, that we will sweep over in our designs.

Flux expansion is much better understood and comes from the fact that the plasma is locked onto field lines and as those field lines spread out so does the heat flux. There are three flux expansion factors to take into account

$$FX_{Toroidal} = \frac{R_{target}}{R_{Outermiplane}} \tag{5}$$

$$FX_{Poloidal} = \frac{B_{target} B_\theta^{OuterMidplane}}{B_{Outermiplane} B_\theta^{Target}} \tag{6}$$

$$FX_{Tilt} = \frac{1}{\sin\beta} \tag{7}$$

Where β is the angle between the magnetic field lines and the target plate. We then divide the heat plane at the outer midplane by the flux expansion and multiply by $(1 - \rho_{vol})$.

4 Divertor Equation

The divertor equations can be solved to give the below equation that contains explicit dependence on B and R as well as given plasma parameters. The maximum heat flux a divertor can handle at the target plate is considered to be $10MW/m^2$.

$$h_{||}^{target} = (P_\alpha + P_{heating} - P_{radcore}) \left(1 - \rho_{loss}^{vol}\right) \left(\frac{3}{2} B_{\theta up}^{1.2} \left(2\pi \left(R + a\right)\right)^{-1}\right) \frac{B_\theta^{target}}{B_\theta^{up}} \sin\beta \tag{8}$$

The term on the left had side is the power loading limit (in this case $10MW/m^2$). The factors in the first term on the right are supplied by the fusion energy and RF groups and can depend on B and R. The second term is a free parameter and will be varied over during the economic analysis. The next term is the effective area of the outer midplane where the power is distributed $B_{\theta up}$ is specified in the reactor design paper and should be taken at $\rho = 1$, R and a are the major and minor radius respectively. The final term is the magnetic flux expansion. $B_{tor}^{up,target}$ is the toroidal magnetic field at the outer midplane and target plates respectively, these values will be provided by the magnet group. $B_\theta^{up,target}$ is the poloidal magnetic field at the outer midplane and target plates, this value will either be provided by the magnet group or the divertor group pending a discussion between the groups. β is the angle between the target plate and the flux lines, due to realistic constraints its minimum value is 1 degree, however for compact designs it will be closer to 45 degrees as we will use here.

The Poloidal magnetic feild at the target is given by

$$B_\theta = \frac{\mu_0 I_p}{2\pi a \kappa} \left(0.040387, 0.0324895\right) \cdot \left(\sin(\theta), \cos(\theta)\right) \tag{9}$$

where

$$\theta = \arctan\left(\frac{1.397\kappa}{0.48\kappa - \delta}\right) \tag{10}$$

note that the direction is wrong, however we are only interested in the magnitude so we ignore the specifics of the coordinates and their transform.

5 Test Case

Following the paper we get

$$h_{||} = 0.00111249\mu_0 \frac{\left(0.00294864 T^{.5} - (\sigma\nu)\right) T}{\left((\sigma\nu) - 1.11995\right)^3 R^3} \left(\frac{\mu_0 T}{R \left(1 - 0.8929 \left(\sigma\nu\right)\right)}\right)^{.2} \tag{11}$$