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Introduction:

The Tokamak Physics Experiment (TPX) is designed to demonstrate features of an economically attractive steady state tokamak reactor. In this paper we present recent results from numerical studies of the proposed TPX divertor design [1], focusing on particle control and on radiative divertor scenarios for reducing the peak divertor heat flux. The configuration is an up/down symmetric double-null with a deep re-entrant slot geometry for the outer divertor legs as shown in Figure {1}.

Two-dimensional Fluid Simulation Models:

We have used several simulation codes to model a reference operating scenario with 18MW of heating power and an average core plasma density of 5e19/m**3. We assume 8MW of energetic neutral beam injection which defines a minimum particle throughput of 160A. The UEDGE [2,3] and B2.7 [4] codes are two-dimensional fluid models that describe plasma transport in the scrape-off layer and divertor regions. Results from these two codes are generally consistent with each other, but there are important differences which serve to identify uncertainties in the physical model. For the reference scenario, the inboard:outboard power asymmetry is assumed to be 20:800 for purposes of defining the input to the B2.7 simulation (lower outer quadrant only), while the UEDGE code yields an asymmetry of 30:70 from a simulation of the entire lower half of TPX with core-to-SOL heat flux proportional to the local temperature gradient. Peak heat fluxes at the outer divertor plate are 5.5 MW/m**2 (UEDGE) versus 4.6 MW/m**2 (B2.7, projected onto a vertical plate) with peak electron temperatures of 140 eV (UEDGE) versus 32 eV (B2.7). The higher temperature from UEDGE is a consequence of lower recycling on the upper segments of the vertical divertor plate compared to the orthogonal plate used in the B2.7 simulation.

Monte Carlo Neutral Transport Simulations:

The DEGAS Monte Carlo code [7] simulates neutral transport in the outer divertor plasma and pumping plenum under the divertor. The plasma density, temperature, flow velocity and ion current to the divertor plate are given by the B2.7 or UEDGE simulations for the 18 MW reference scenario. The neutral density at the entrance to the pump duct varies over the range 4-9x10**19 /m**3 with small (2 cm) variations in the vertical position of the separatrix strike point on the divertor plate [9]. This indicates that the total particle throughput can be controlled by proper plasma positioning.

Density Control and Divertor Leakage:

For core plasma density control, the leakage of neutrals from the divertor into the core must also be kept to a minimum. Neutral particles that originate at the target plate may escape from the divertor via a charge-exchange random walk and contribute to fueling of the main plasma. This leakage should be minimized to maintain the core plasma density levels required for efficient current drive in steady state. We define a leakage factor, alpha, as the fraction of target plate neutrals that get ionized inside the last closed flux surface (separatrix). This leakage has been assessed within the context of the diffusive fluid neutrals model in the UEDGE code. For the reference 18 MW scenario we find the leakage factor is 7 percent, with the dominant contribution coming from neutrals originating at the inboard target plate. The leakage is reduced to 0.7 percent at higher core plasma density (3.50x10**19 /m**3 versus 1.65x10**19 /m**3 at the separatrix) due to the higher divertor density and lower ion/charge-exchange-neutral temperature.

Comparison of Divertor Leakage from TPX and DIII-D RDP Configurations:

Plasma shaping and current profile control are essential features of the TPX design. This flexibility will produce variations in the divertor and plasma configurations that can have a significant effect on the leakage factor and particle throughput. To illustrate this, we compare TPX with the DIII-D Radiative Divertor Program (RDP) configuration shown in Figure {2}. This DIII-D configuration [8] will be operational in early 1996. The leakage factor for the RDP is only 1 percent (versus 7 percent for TPX) due to the higher separatrix plasma density, with the dominant contribution coming from the inner target plate. If one looks at the outer target contribution only (4.7 percent for TPX versus 0.2 percent for RDP), the longer leg length in TPX (53 cm versus 23 cm for RDP) does not completely compensate for the lower overall density. For the same separatrix density in TPX and RDP, the overall leakage factor is lower for TPX (0.7 percent versus 1.0 percent), but recycling at the inner target plate is mainly responsible for the difference (see Table {1}). The particle pumping in these simulations is spatially localized in the outer divertor leg as indicated in Figures {1} and {2}. The total particle throughput for the RDP (430 A) is higher than for TPX (160 A) because the dominant heating source is neutral beams. The power handling capabilities of the two configurations may also be significantly different. For the deep re-entrant slot in TPX the peak heat flux is only 5.3 MW/m**2 compared to 9.4 MW/m**2 for the shaped baffle in RDP. However, the peak electron temperature is much higher (240 eV in TPX versus 47 eV in RDP), so sputtering is more likely to be a problem.

Private Flux Baffle Shape:

To minimize communication between inner and outer divertor legs, the baffle shape in the private flux region under the x-point should be conformal with magnetic flux surfaces. Since this imposes strong constraints on plasma shaping and positioning, we have assessed the effect of changing the baffle to a flat plate connecting the inner and outer separatrix strike points on the target plates. The non-orthogonal mesh capability in the UEDGE code allows us to accurately model this configuration. The particle throughput was reduced from 440 A for the conformal shape to 380 A for the flat plate and the ion saturation current to the outer divertor plate increased from 10700 A to 12700 A, indicating that more particles escape from the inner divertor leg into the outer divertor leg with the flat plate baffle. The overall leakage factor increased only slightly from 1.5 percent to 1.6 percent. We conclude that a modified conformal shape will provide increased flexibility in plasma configuration without significant penalty for particle control.

Divertor Plate Erosion:

Using the UEDGE plasma solution for the 18 MW reference scenario, the REDEP erosion/redeposition code [5] was used to analyze sputtering at the outer target plate. For the reference carbon surface the analysis shows a stable erosion profile despite self-sputtering coefficients that are locally in excess of unity. Net erosion rates are high, with peak values in the range 1.0-2.5 m/burn-yr, but may be acceptable for low duty factor operation. Details will be presented elsewhere [6].

High Power Radiative Divertor Scenario:

The B2.7 code was used to model the deuterium background plasma plus the 10 charge states of neon in a high power radiative divertor scenario for TPX. For steady state operation with maximum heating power of 45 MW, it will be necessary to radiate a substantial fraction of the power to reduce the peak divertor heat flux to acceptable levels (7.5 MW/m**2). To achieve this, we find that the separatrix plasma density must be at least 4.0x10**19 /m**3 with 1 percent neon concentration at the plasma midplane. For lower plasma density it is not possible to radiate sufficient power without an unacceptably high neon concentration. For example, at 1.65x10**19 /m**3 the neon level would have to be 7 percent, so energy confinement in the core would be significantly degraded. We have not yet explored the option of additional deuterium gas puffing to enhance radiative losses and more efficiently trap impurities in the divertor.

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Table {1}:

Configuration:	TPX reference case	TPX high density	DIII-D 23cm RDP
Inputs:			
separatrix density (x 10**19 /m**3)	1.65	3.50	3.50
power (MW) to SOL:			
electrons	4.75	4.75	3.00
ions	1.50	1.50	1.50
Leakage Factor = core ionization / ion saturation current:			
inner target alpha	.098	.006	.081
core ionization (A)	490	210	400
ion saturation current (A)	5000	34000	5000
outer target alpha	.047	.006	.002
core ionization (A)	270	90	110
ion saturation current (A)	6000	16000	44000
total alpha	.071	.006	.010
core ionization (A)	760	300	510

Ion Saturation Current (A)	11000	50000	49000
Particle Throughput (A)	160	940	430

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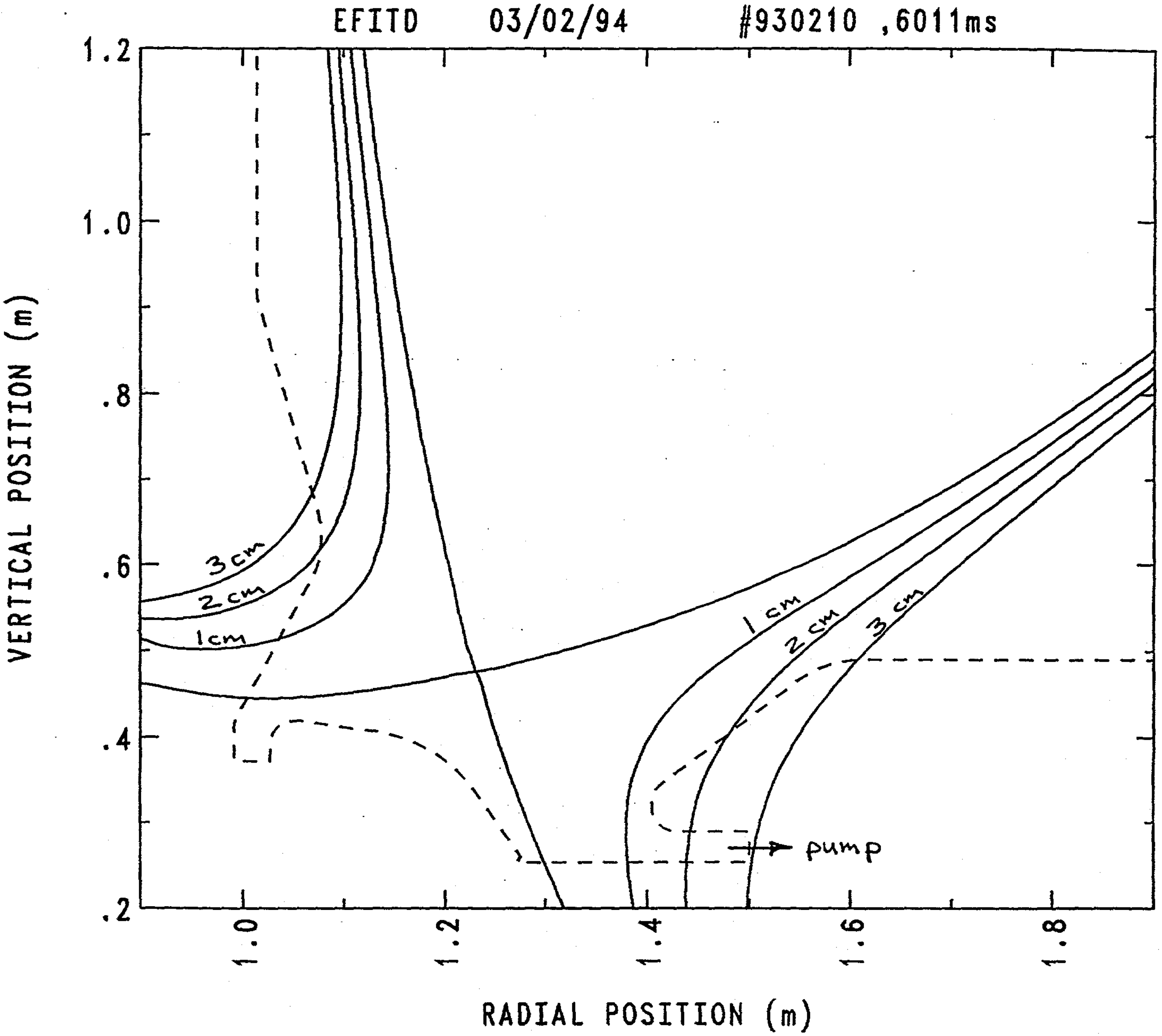
{Figure 1 - TPX lower divertor configuration. SOL flux surfaces displayed here pass through the outboard midplane at 1 and 2 cm from the separatrix.}

{Figure 2 - RDP lower divertor configuration. SOL flux surfaces displayed here pass through the inboard and outboard midplanes at 1, 2 and 3 cm from the separatrix.}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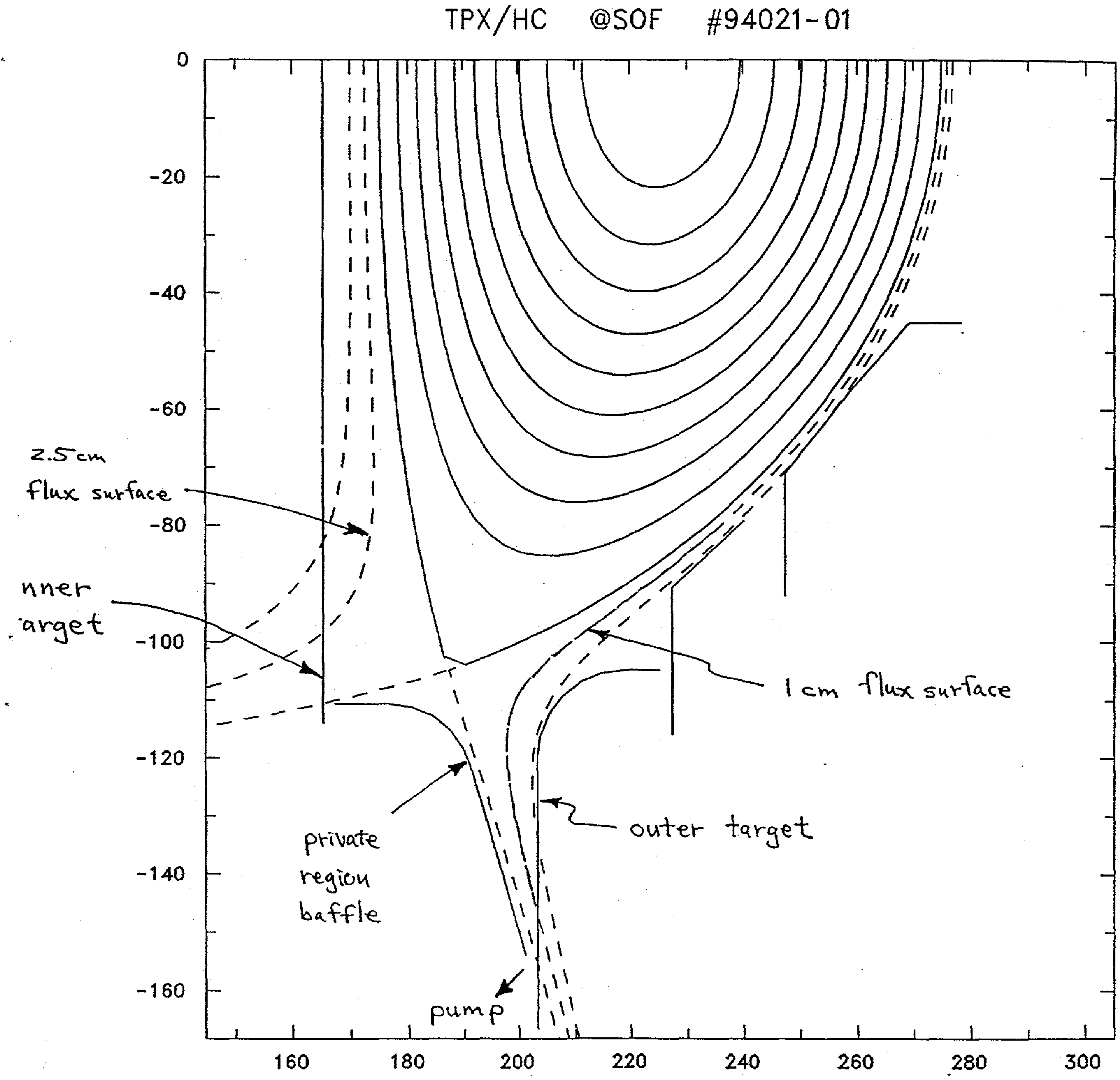

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