

Scrape Off Layer Physics for Burning Plasmas and Innovative Divertor Solutions

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Abstract. Two distinct topics concerning SOL physics are examined. First, a novel magnetic divertor geometry is presented: 1) inducing a *second* axi-symmetric x-point downstream of main plasma x-point. For reactor relevant coils, field line lengths from the core x-point to the wall can be increased ~2-3 times, and flux expansion can be increased ~ 5 times. 2) the potential reactor consequences of large SOL convection from "blob-like" transport are examined for the first time. ARIES RS geometries have been simulated using UEDGE, including large convection in the far SOL similar to what is seen in experiments. The hot CX neutral spectrum at the wall is computed using the kinetic neutral code NUT. The high edge plasma temperature plus large recycling from blob like SOL transport give highly enhanced sputtering for a tungsten wall from CX neutrals. Numerical simulations of 2-D nonlinear fluid equations describing blob turbulence from SOL resistive ballooning modes finds that impurities generated at the wall are rapidly convected inward toward the separatrix. Blob turbulence also greatly reduces the impurity screening of the SOL, leading to the potential for core radiation collapse in a tungsten wall reactor.

1. Introduction

As magnetic fusion heads towards ignition experiments and reactor design, the twin issues of heat removal and impurity generation assume serious (even critical) proportions. Power levels rise several-fold as one progresses from the current experiments to an ignition experiment, and rise several fold yet again for a reactor. This natural progression makes it increasingly difficult to meet the engineering limits on heat removal. The impurity problem originates in our being "forced" to use high Z facing materials to insure the required lifetime of the main chamber solid wall in a reactor. At the prevalent high edge temperatures, serious plasma contamination, especially in view of the recently discovered far SOL transport, is likely to result.

We shall critically examine both these issues; we will also propose some possible solutions.

The power exhaust characteristics of the SOL (while maintaining good core performance) may be vastly improved through a novel magnetic divertor geometry with a *second* x-point downstream. MHD equilibrium calculations with realistic ITER-like coils show that the proposed geometry can increase the SOL field line length (from the x point to the wall) by a factor of two to three, and the flux expansion by a factor of five or more. These characteristics enable greater radiative dissipation, and also lower heat fluxes for the plasma power which remains. The extra coils could be accommodated in a reactor with a modest increase in the complexity of the magnetic design.

The contamination of the core plasma with tungsten from the main chamber wall due to SOL interaction with a tungsten wall is also considered, in light of recently discovered SOL blob convection. We use the comprehensive simulation code EDGE [1] and the kinetic neutral code

NUT [2] along with an empirical model of SOL convection. Possible contamination is so severe that SOL convection could be a feasibility issue.

2. Novel divertor - heat flux problems

The new magnetic configurations require localized modifications of the divertor magnetic fields which, in turn, require coils that are spaced closer than the conventional PF reactor coils. For superconducting TF coils, the placement of linked PF coils inside TF coils is highly undesirable. A possible solution to this difficulty is examined here: the use of non-axisymmetric rings that fit in between TF coils to generate the required fields. These coils are not linked, and small non-axisymmetric ripple appears acceptable ($< 0.3\%$ for the cases here). These coils can be attached outside of the vacuum vessel and the neutron shield, and could be removed along with the blanket segments. Possible ways to retrofit such coils onto ITER are being examined. But first, we motivate our discussion by describing the severe requirements imposed on a reactor divertor - imposed by the search for engineering solutions without degrading "physics" of the machine.

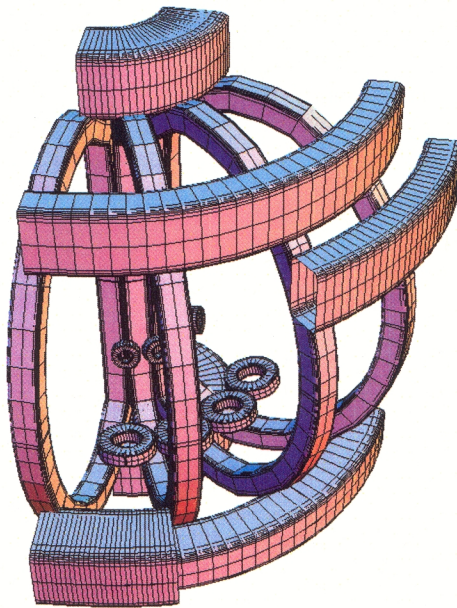


Fig 1. Coils for the CREST reactor. The small new divertor ring coils are seen near the bottom and on the center post. Note that they can be removed between the TF coils (like blanket modules). Coil cross sectional area is proportional to the coil current.

2.1 Reactor divertor issues: heat flux and physics compatibility

The divertor requirements for a tokamak power plant are *much* more demanding than in a burning plasma experiment such as ITER. A 1-2 GW electric utility reactor (with 3000-5000

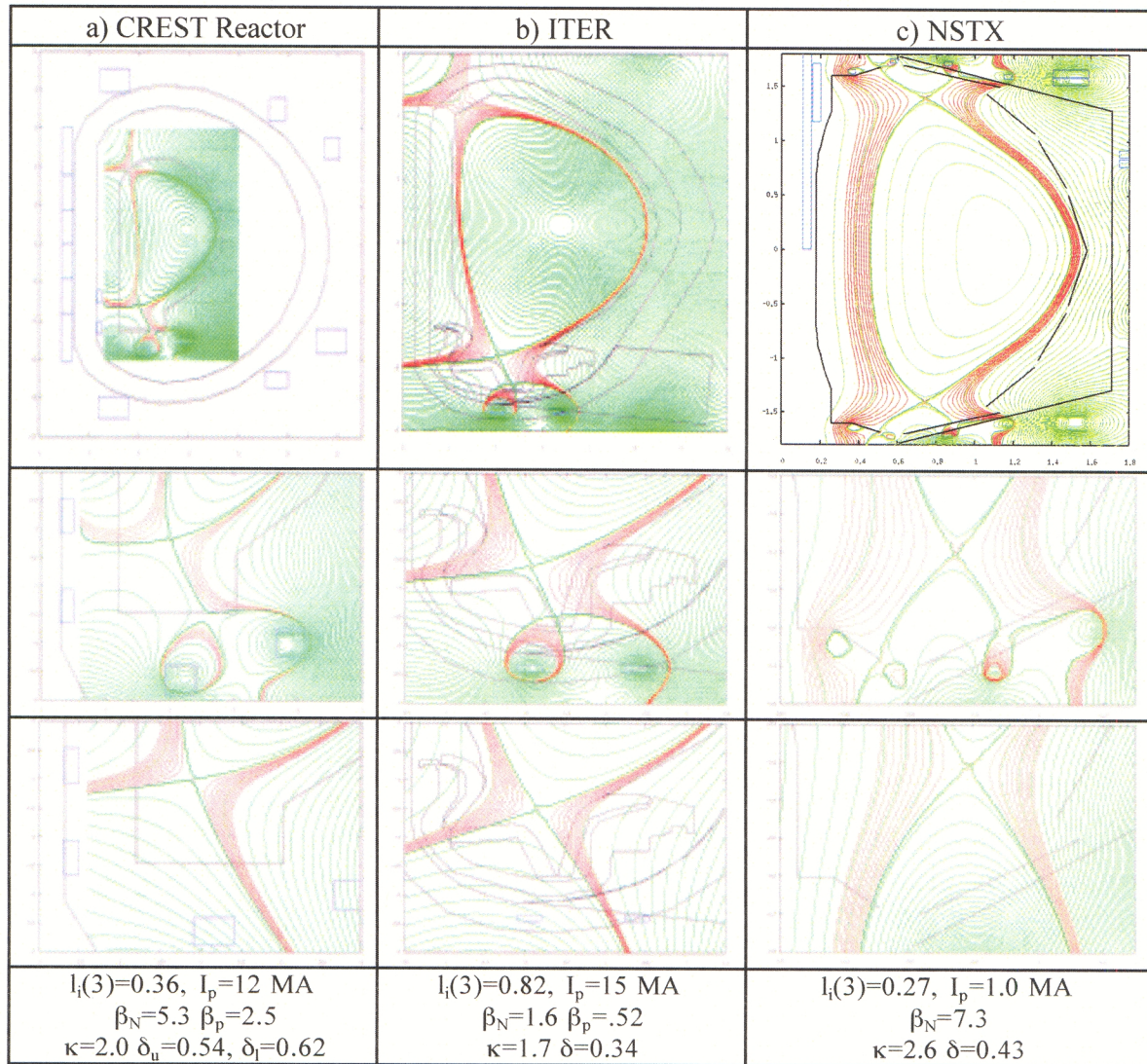


FIG. 2. New divertor solutions for NSTX, ITER, and REACTOR.

MW of fusion power) has 700-1400 MW of plasma heating power from alphas and current drive, as compared to about 120 MW for ITER. The empirical indicator of divertor heat flux, P/R , is similarly larger. Unless the radiated fraction is increased from about 50% to above 90%, the surface heat loading on the divertor would be ~ 5 -10 times higher than ITER. Despite such high radiation fractions, and operation near the density limit, the confinement must be slightly better than the predictions of H-mode scaling laws (by $\sim 20\%$ in several reactor studies). Disruptions and unplanned shutdowns must be extremely rare. Furthermore, these heat fluxes must be sustained continuously (rather than in low duty cycle operation) at values one to two orders of magnitude higher faced by the present continuous industrial applications such as fission reactors and steam generators; reliability also must be much. Whereas some slight cracking and leaking often occurs and are tolerated in current applications, these will be show-stoppers in a high vacuum environment. Studies find that maintenance and down time are crucial economic factors in electrical power plants. It is frequently suspected that the divertor may require the most frequent maintenance of the in vessel components, but replacement (both planned and unplanned) requires months.

Furthermore, this very high level of reliability under high stress must be achieved in an environment with an expected level of neutron damage that is unprecedented. The lifetime neutron fluence is about two orders of magnitude higher than in burning plasma experiments, and the 14 Mev neutrons lead to new and serious material damage beyond that found in fission reactors.

These engineering requirements are unprecedented; they are so severe that full detachment (rather than the partial detachment regimes planned for ITER) may be a necessity to reduce the heat fluxes to acceptable levels. The fully detached discharges are, however, quite prone to disruptions, and with conventional divertors they adversely impact the core energy confinement. For a self heated reactor, a 20% degradation in confinement results in a fusion power reduction of > 50%; the economic fallout is grave. Increased disruptivity may be significant since an acceptable disruption probability for a reactor (on a per second basis) is roughly five orders of magnitude lower than an acceptable value for ITER. Finally, note that operation with highly radiating mantles to reduce divertor power loading leads to peaked pressure profiles in the core, which have relatively low beta values due to ideal MHD instability. Low beta is inadequate for reactor economics.

The staggering and simultaneous physics and engineering requirements surely justify (perhaps force) an exploration of alternative divertor concepts.

2.2 Magnetic geometry of novel divertor

The concept of adding a new x-point is shown in fig.2 for the reactor study CREST [3] (an advanced tokamak reactor with very similar geometry to ITER), ITER (Ohmic) and for the spherical torus experiment NSTX. These free boundary MHD equilibrium calculations were made with the code FBEQ (a version of TEQ, which has been used to design CIT, NSTX and other machines). The axisymmetric component of the current in the ring coils is included via equivalent axisymmetric coils. It can be shown that this accurately reproduces the axisymmetric magnetic field.

TABLE I: SOL FIELD LINE PARAMETERS OF EQUILIBRIA

Machine	Divertor	Flux Expansion	L_{XT} (X to Target)	Ratio L_{XT}/L_{XM}
NSTX	Standard	1.3	0.8 m	0.29
	New	6.9	1.1 m	0.32
ITER	Standard	4.3	23 m	0.45
	New	22.7	65 m	1.12
CREST	Standard	3.3	37 m	0.74
	New	23	75 m	1.19

As can be seen in fig.1 and Table 1, adding new coils in the region of the divertor can greatly expand the flux. Quantitative comparisons for field line length and flux expansion for equilibria with and without the new coils are shown in Table 1.

For ST reactors, axisymmetric coils can be placed inside of the TF coils, and axisymmetric copper PF coils could be used near the divertor instead of non-axisymmetric ring coils.

3. SOL simulation of blobs and impurity generation

Here, we present the first calculations of the potential impacts of large transport in the far SOL on a reactor with a tungsten wall. The 2-D SOL code UEDGE is used together with the kinetic neutral code NUT. Sputtering is predominantly from the high energy C-X neutrals for Tungsten. The inclusion of convection increases sputtering rates by factors of ~ 4 - 10 above cases without convection.

Analysis using UEDGE of ELMy H₋ modes with a highly radiative divertor on DIII-D required SOL convection which strongly increased away from the separatrix in order to match far SOL plasma density profiles, D_a recycling light and neutral pressure [6]. The best fit was obtained with a convection profile which increases from 10 m/s at the separatrix to 137 m/s in the far SOL (at the midplane) with a roughly exponential profile. C-mod [7] finds similar SOL convection, which is also roughly consistent with results from ASDEX [8]. Data from C-mod and DIII-D also indicate a roughly exponential increase of convection with distance [9].

It is reasonable to conjecture that similar convection could be present in a reactor. We use UEDGE with ARIES RS geometry, adding convection to a constant diffusivity of 0.3 m²/sec. Parameters are varied to produce density profiles similar to present experiments. Three cases with convection (A,B and C) are considered, and a case (D) without convection.

TABLE II: CONVECTION PROFILE PARAMETERS FOR UEDGE CASES

Case	Convection at $d/a = -.01$	Convection at $d/a = .045$ (wall)	W erosion (mm/yr)
A	10.	100.	0.6
B	10.	50.	0.27
C	5.	100.	0.56
D	0.	0.	0.07

Experimental data from SOL density profiles on C-mod, ASDEX and DIII-D [7,8,10] is shown in fig. 4. Comparisons at distances normalized to the minor radius produces the clearest trend. The reactor is taken to operate at $n_G=1$. Case A matches the data trends best, case D (with no convection) is well outside the data, and case B and C are intermediate. We have also considered the SOL density scale lengths normalized to minor radius. Similar to figure 4, case A is closest to the empirical results, and case D is well outside the data.

Using the plasma profiles and wall recycling source from UEDGE, the energy spectrum of the charge exchange neutral flux on the wall is computed using the kinetic neutral transport code NUT [2]. This code solves the full non-local, kinetic integral equations using a rapid solution algorithm and has been benchmarked with experiments [11,12]. The hot CX spectrum is

integrated over the Bohdanski formula for tungsten sputtering to obtain the erosion, with results shown in table 1. (Prompt redeposition is estimated to be small in the main chamber).

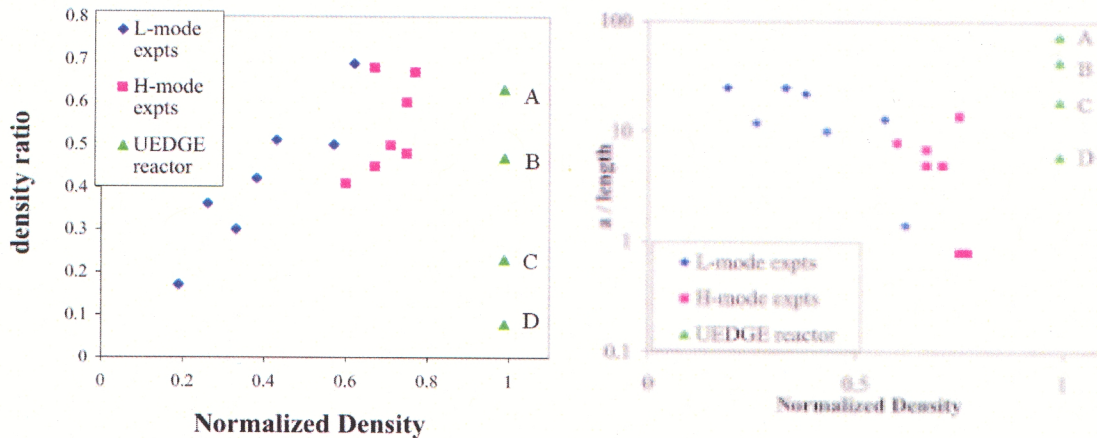


Fig 3. The ratio of the SOL density at $d/a = .04$ to the separatrix density from experiments and UEDGE versus plasma density normalized to n_G

Blob-like turbulence will also increase impurity transport from the wall to the plasma. This process, outlined by Krashennikov et. al.[13], has been confirmed by our numerical simulations of blob turbulence using the equations of reference [13]. With a density source, the simulations produce continuous, intermittent turbulence. Trace impurities originating near the wall are transported to the main plasma predominantly by inward convection in the regions of low plasma density between blobs, whereas plasma convection to the wall is dominated by outward convection in the high plasma density regions inside blobs (see Fig. 4).

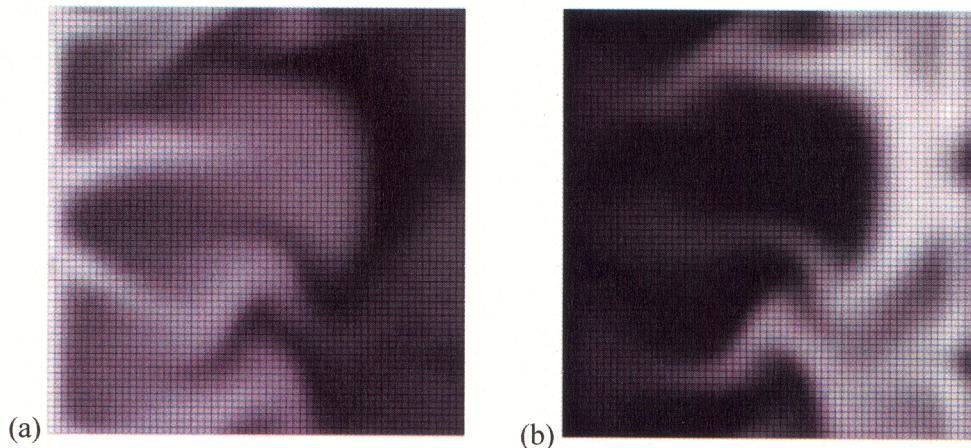


Fig.4. Density plots of (a) plasma and (b) impurities. The separatrix is on the left edge, and the wall is the right edge. The impurities from the wall can be seen to slip inward between the outward convecting plasma blob fingers.

Converting the normalized units of the simulation to a reactor, the net inward impurity transport is much more rapid than in a model with only a plasma diffusion coefficient of roughly $0.5 \text{ m}^2/\text{sec}$. Thus, the simulations show that blob transport increases both the plasma

flux to the wall and the impurity flux to the plasma above the standard model which neglects blob transport.

We have estimated the impurity content of ARIES RS based on the impurity generation rates found by UEDGE and NUT, and using the impurity screening factors found on C-mod and ASDEX. These tokamaks show strong signs of blob-like transport in the far SOL. Clearly one cannot directly extrapolate screening factors to ITER, but for H-mode like profiles, the resulting tungsten impurity density would lead to a radiative collapse for a reactor. Though clearly preliminary, these results indicate that SOL transport might be a very serious issue for a reactor.

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