Physics Issues for Integrated Modeling of a Fusion Reactor

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Integrated Modeling for Reactors

- OFES: “The mission of the U.S. Fusion Energy Sciences Program is to advance plasma science, fusion science, and fusion technology -- *the knowledge base needed for an economically and environmentally attractive fusion energy source*.” (italics added)
- Integrated modeling mandate should be for more than accurate predictions of burning plasma experiment
- Integrated modeling for reactor parameters should also
  - Identify major physics issues for fusion energy beyond ITER
  - Develop, explore, and validate novel solutions
- Why? Because many reactor physics issues are more severe than ITER-FEAT and innovation beyond is ITER needed

Outline

- Here we discuss reactor issues which are more severe than ITER-FEAT
  - Core plasma physics issues
    - MHD stability of high bootstrap fraction plasma
    - Transport
  - Edge physics and plasma-material interaction issues
    - ELMs
    - Divertor power handling,
    - Ultra-low disruption probability (radiative collapse, detachment stability)
    - First wall heat fluxes
    - First wall impurity generation (Tungsten wall)
- Integrated modeling necessary to evaluate solutions and novel ideas.
  - Why reactor issues are much more severe
  - Some novel solutions where integrated modeling can have an impact

MHD stability of high bootstrap plasma

- ITER much more conservative than *attractive* reactor:
  - Base inductive operating mode β_N~2
  - Advanced: wall stabilized n=1 with feedback
- Reactor studies like ARIES RS, AT use:
  - β_N~ 4.84 to 5.45
  - Require wall stabilization of up to n=4-8
  - High-n eigenfunctions are global, not ELMs - need stabilization
  - Feedback practical at n~1, 2, but not at high n in a reactor
    - Requires close-in coils - incompatible with high neutron fluence and breeding requirements
- How to stabilize such high-n modes in a reactor?

How to stabilize high-n modes?

- Only plasma rotation might stabilize high-n modes
  - Fortunately higher n modes need lower rotation
  - Such low rotations may be feasible without unacceptably high external power input
- IFS is developing kinetic MHD code AEGIS
  - Adaptive, easily parallelizable algorithm to rapidly and accurately calculate n=1-10 modes
  - Benchmarked successfully with GATO for low-n
  - Eigenvalue formulation enables kinetic effects
  - Drift-kinetic pressure response being developed

Transport issues

- For the past few years, we at IFS have been pursuing the idea that the best way to improve core transport is to modify the edge boundary condition via novel divertors
  - To compensate for a low pedestal beta, use a low edge density to maintain high edge temperature
  - Build up plasma density inside the edge transport barrier by pellets, to maintain good confinement despite poor pedestal physics
- Crucial ingredient: novel divertors with acceptable power exhaust at low density (described shortly)
- Thus, novel divertors could compensate for unfavorable pedestal scaling
  - Integrated modeling is needed to show how much improvement in divertor performance is enough

Edge plasma physics issues

- In designing ITER, serious shortfalls in our understanding of edge physics issues were noted
  - Engineering feasibility required the development of new divertor operating modes
  - Disruption concerns are greater on ITER
- In the same way, extrapolating from ITER to reactor further increases the emphasis on edge
  - Issues of the conventional divertor become more severe
    - **Novel divertor concepts may be needed**
  - Ultra-low disruptivity requirement may strongly limit operating modes
  - Main chamber first wall issues become qualitatively more serious

Divertor power handling problems

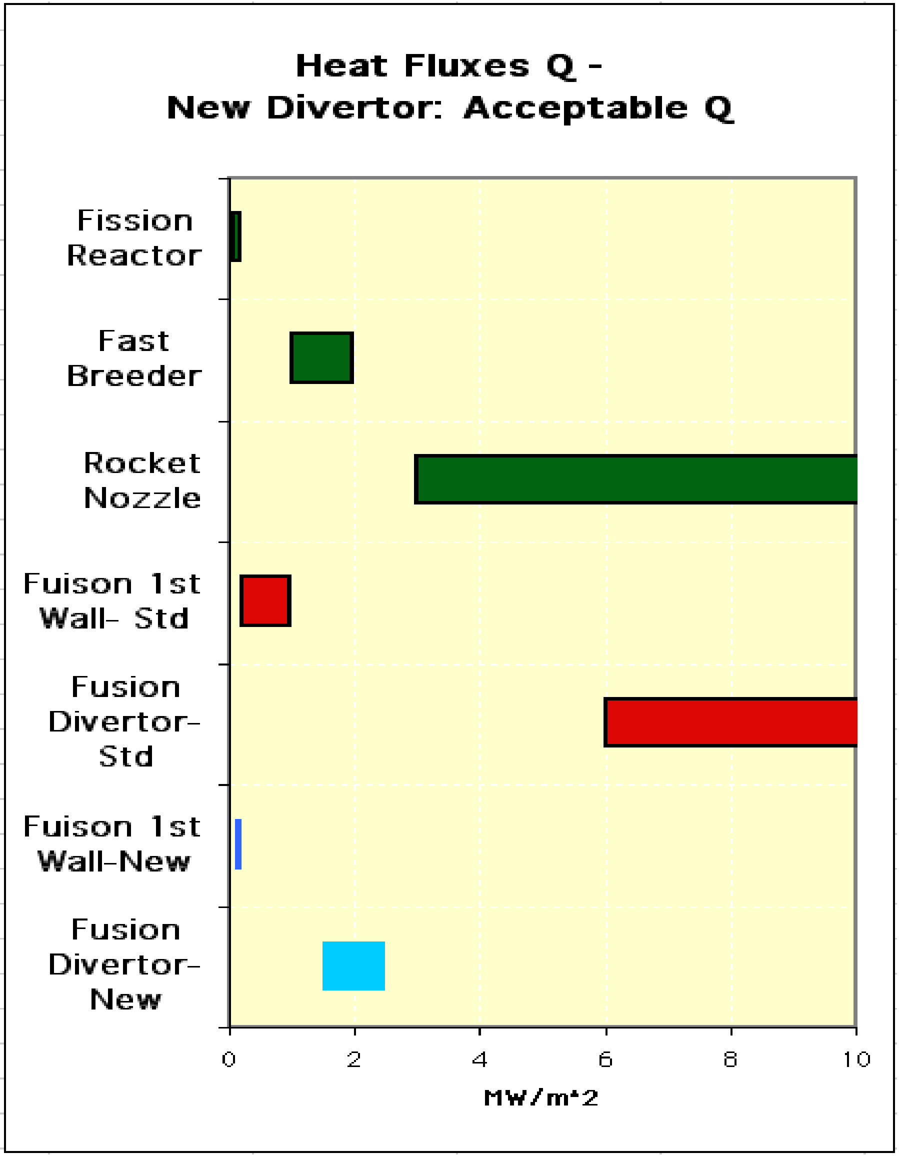
- ITER-FEAT: already close to limit of physics and engineering feasibility (?)
- Reactor heating power ~ 5 x ITER-FEAT (much higher α power) *and* acceptable heat flux is probably lower
  - Why is tolerable heat flux probably lower?
    - Divertor lifetime ~ 10^2 times longer
    - Neutron fluence ~ 10^2 times higher
    - Much larger material degradation concerns
- => higher radiation fraction than ITER
  - Detachment stability problematic: X-point MARFE gives poor confinement & disruptivity
  - Are very high radiation fractions consistent with ultra-low disruption probability (< 10^5 lower than ITER) constraint?

Divertor: Integrated Modeling Issues

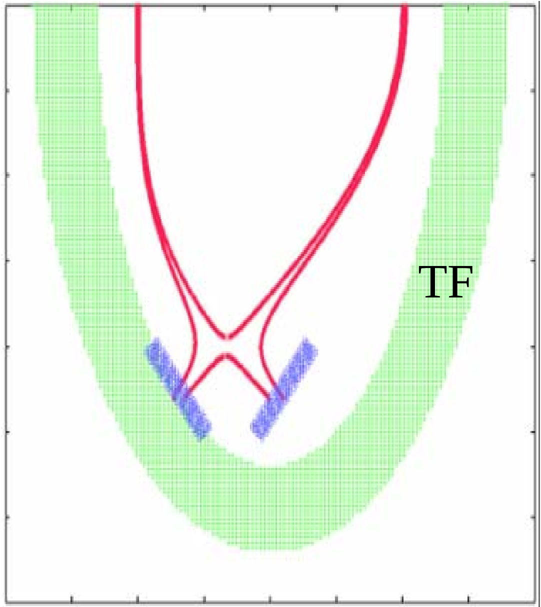
- Adequate power handling forces operation at high density (near limit) to radiate divertor power.
- Near density limit:
  - Disruption probability goes up
  - H-mode confinement goes down
  - ITB’s become more challenging
- High radiation fraction in plasma
  - Peaks plasma pressure =>lowers ideal β limit => unattractive economics
  - Leads to high main chamber heat fluxes => engineering limit on wall laoding => unattractive economics
- A novel divertor to operate at lower density and lower core radiation would help many areas

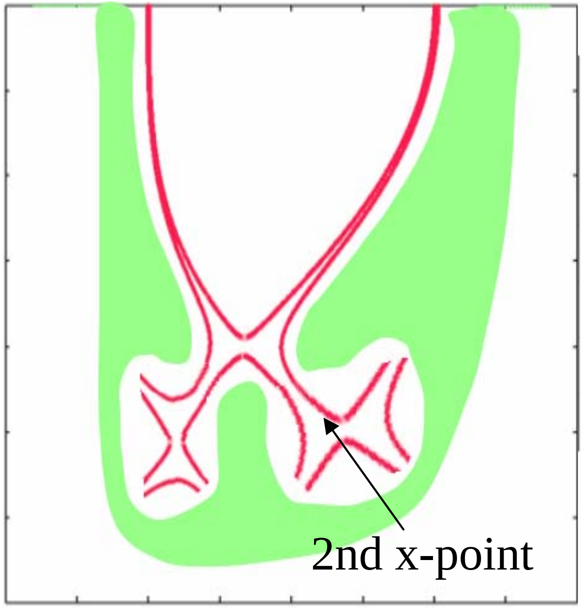
High Heat Flux: Engineering Consequences

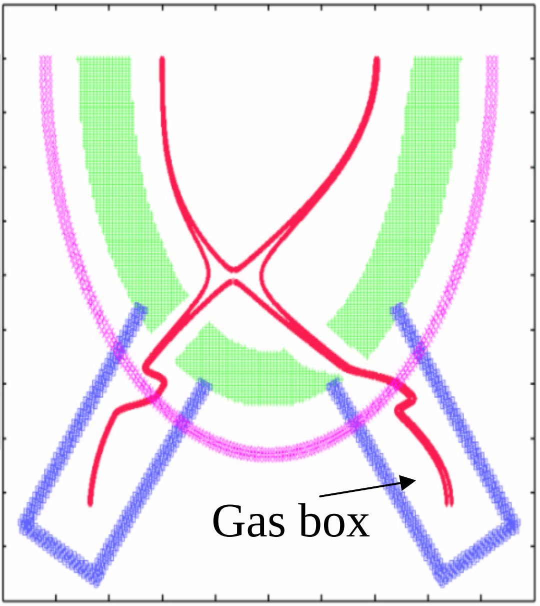
- **ALL** industries: Higher power density lowers costs
- **BUT**: too high flux => unacceptable failure rate
- **FUSION**: high flux AND high reliability => many testing iterations
- **FUSION**: full fluence test ~ 5-10 years
- **MANY DECADES** of engineering development?



Novel Divertors to Solve Reactor Problems







Conventional

- Concentrates heat flux
- Detachment limited by collapse to x-point

(Disruption & low τ_E)

Extra X-point

- Spreads heat flux
- Complete detachment stable?

(Locks at 2nd x-pt)

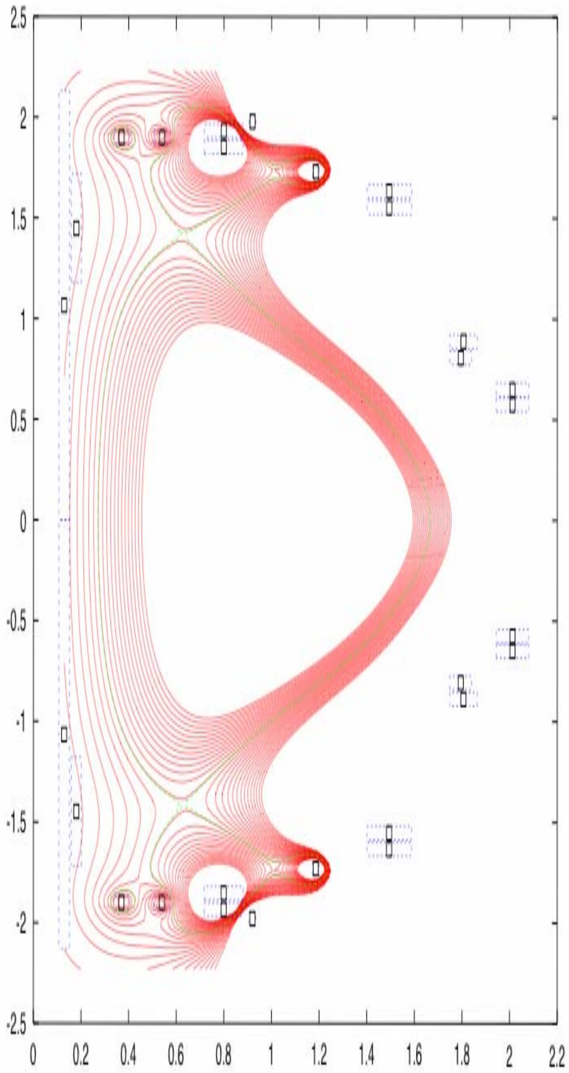
- Allows high T_{edge}

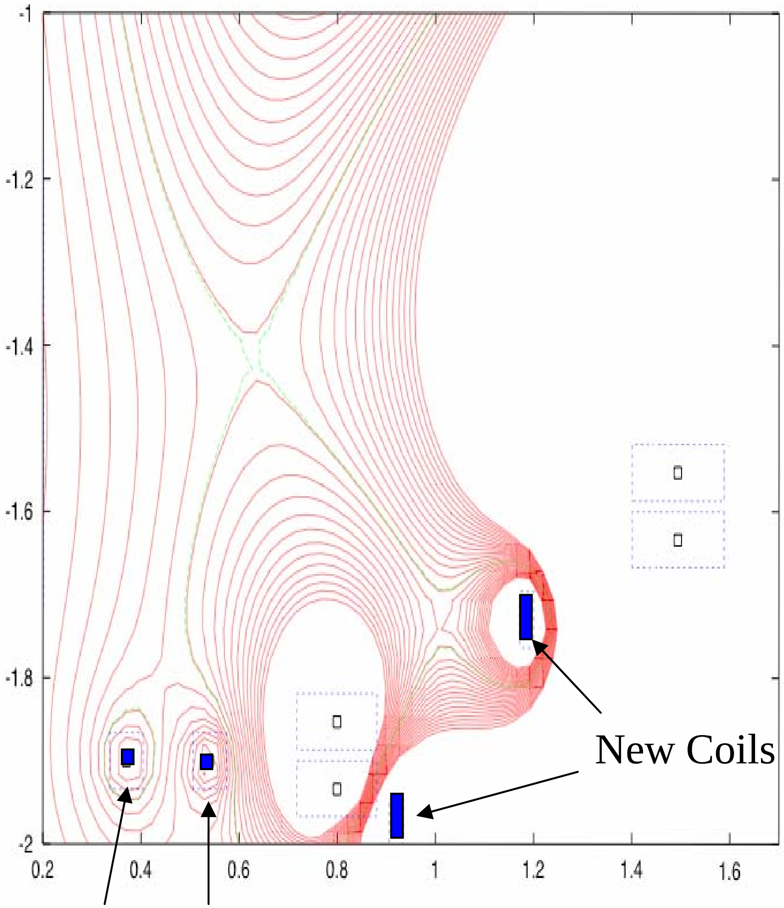
Extracted Outside TF

- Possible with low main plasma ripple
- Huge area outside TF for heat spread
- Complete, stable detachment likely
- Also allows high T_{edge}

Divertor bottleneck is a mission- critical reactor issue

Double X-point Divertor Equilibrium





New Coils

New Coils

Coil Optimization for Divertors

- IFS is using PPPL-NCSX & ORNL tools to develop and optimize 2-D and 3-D coils for novel divertors including engineering constraints
  - Extra x-point
  - Field line extraction outside TF (low ripple)
- Coil inclusion is a new level of integrated modeling
  - We are developing a fast 1.5D divertor analyzer for optimizer
  - Verify stable detachment with second x-point or field-line extraction “isolated gas box” outside TF coils

Novel Divertor- Plasma Modeling

- We are currently modeling these novel divertors to show
  - Much lower heat fluxes on divertor surfaces
  - Stable, fully detached divertor without plasma x-point MARFE
    - Highly radiating, detached region stays confined away from main plasma x-point
    - Stays near 2nd x-point or in the gas box
- Modeling methods
  - Starting with 1.5D divertor model
    - Novel geometry is included
  - 2-D divertor simulations will require unusual divertor geometries
  - Ultimately, divertor simulation inside the magnetic optimization

ELMs

- Much more significant issue for reactor divertor
  - Reactor stored energy >> than ITER stored energy
  - Fractional energy loss for ELMs must be lower
  - Type 1 ELMs unacceptable, type 2 marginal
- Reactor engineering constraints more sever than ITER
  - Required divertor lifetime ~ 10^2 higher
  - Reactor divertor must withstand ~ 10^8 ELMs
  - Fatigue stress limits more stringent than ablation limits - further reducing tolerable fractional energy loss
- Tungsten main chamber wall => ELMs to purge impurities may be more necessary
- IFS is developing novel divertors for ELM problems
  - Heat flux spreading of impulsive and steady state heat loads

Ultra-low probability of disruption

- Reactor disruption rate/sec *must be* 10^5 less than that of ITER
- Reactor requires conservative operating modes that are resistant to disruptions
- Factors that increase disruptivity:
  - High radiation fraction
  - High edge density
  - Wall flakes (~1 mm^3 W) falling in plasma
- Conventional reactor concepts face these simultaneously

Possible Solutions

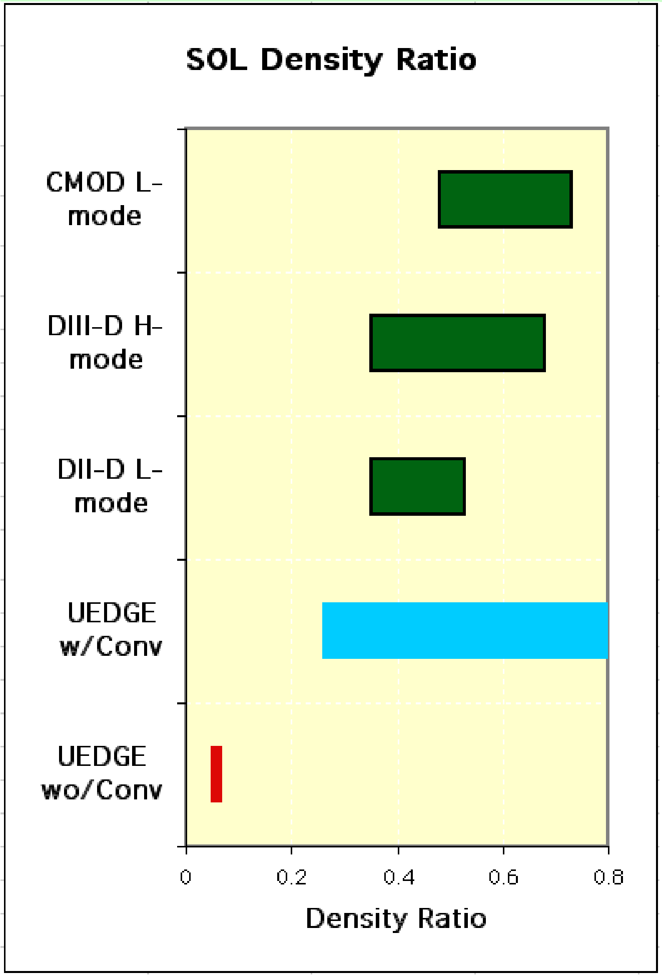
- Operate with less radiated power in the plasma
  - Less sensitive to impurity fluctuations
  - Less heat flux on first wall => lower flake probability?
  - Liquid film on first wall (APEX)
- Roles for integrated modeling:
  - Evaluate plasma response to impurity pulse (Flake dropping in SOL/pedestal/core)
  - Determine which operating modes are most resilient

First wall impurity generation (Tungsten wall)

- ITER has Be wall (low Z)
- Reactor *must* have W, Mo wall, (or liquid wall)
  - Due to structural erosion over multi-year *continuous* operation
- Previous estimates of wall sputtering (impurity generation) do not include recently discovered blob effects
- We calculate that SOL blob convection greatly increases Tungsten sputtering (FED paper accepted)
  - Reactor edge Ti >> present => higher CX energy
  - Enhanced impurities can lead to radiation collapse
  - Confinement requirements can increase substantially

Erosion Estimates Without Convection: Likely to be Low

- Standard SOL transport model: constant diffusivity
- Probably under-estimates plasma-wall interaction by ~ 10 - 20



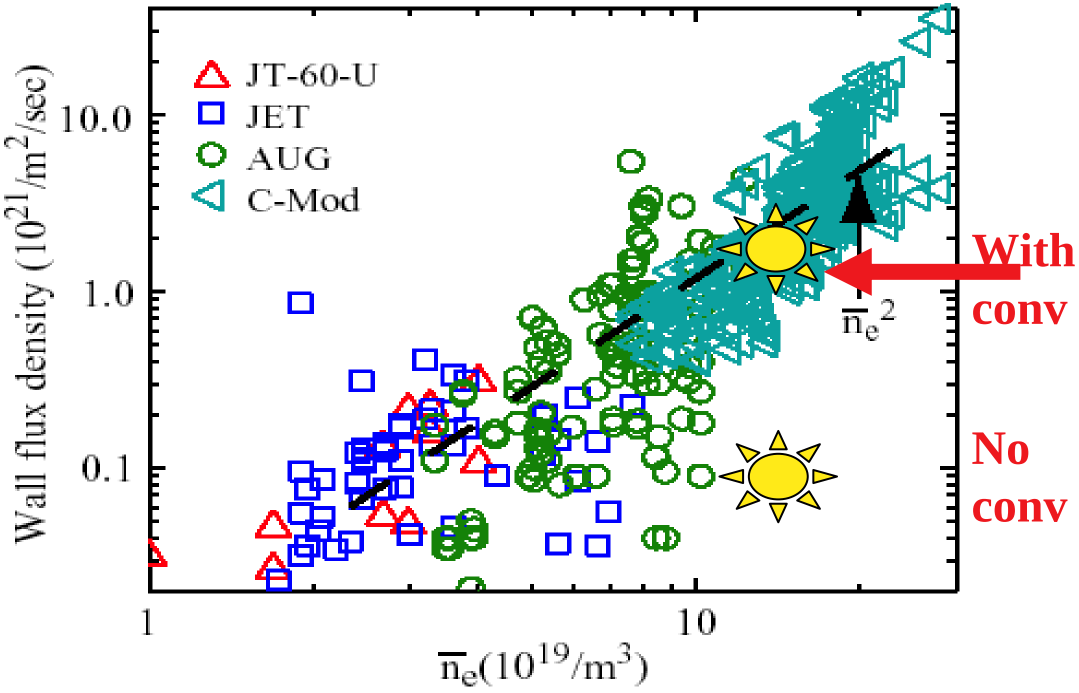


Fig. from Labombard

Integrated modeling aspects of SOL

- IFS is pursuing fast 2.5-D SOL simulation of blob transport coupled to kinetic neutrals
  - We find that blobs increase inward convection of impurities as well as outward plasma convection

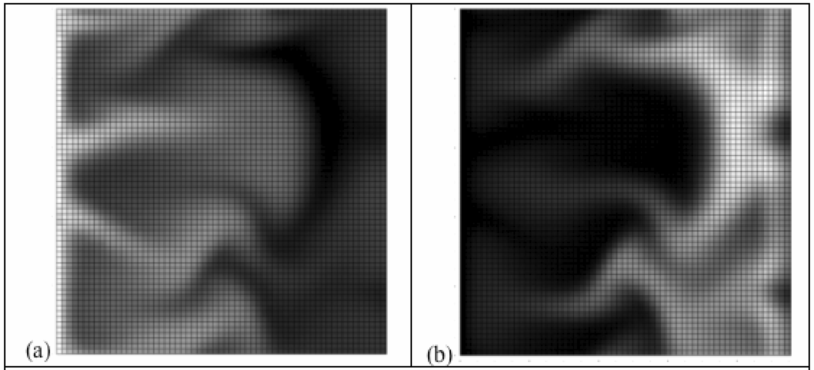


Fig.8. Density plots of (a) plasma and (b) impurities. The separatrix is on the left edge, and the wall is the right edge. The impurities from the wall can be seen to slip inward between the outward convecting plasma blob fingers.

- We are worried that plasma impurity influx may be serious
- Possible solution: ExB stabilization of SOL turbulence
  - Is it possible to design a novel divertor with electrodes in a fusion compatible place?
- Integrated modeling is needed to simulate impurity transport through pedestal and core

Conclusions

- Integrated modeling can play important role in
  - Quantifying difficulties beyond ITER-FEAT
  - Supporting innovative solutions
- IFS is actively involved in this effort. IFS groups are developing novel ideas and codes
  - Kinetic MHD codes: high-n, adaptive, parallelized, fast
  - Divertor concepts may solve many problems
    - fast analysis code for optimizer
  - SOL simulations: fast 2-D blob simulation
  - Core transport / divertor integrated scenarios