Divertor detachment studies
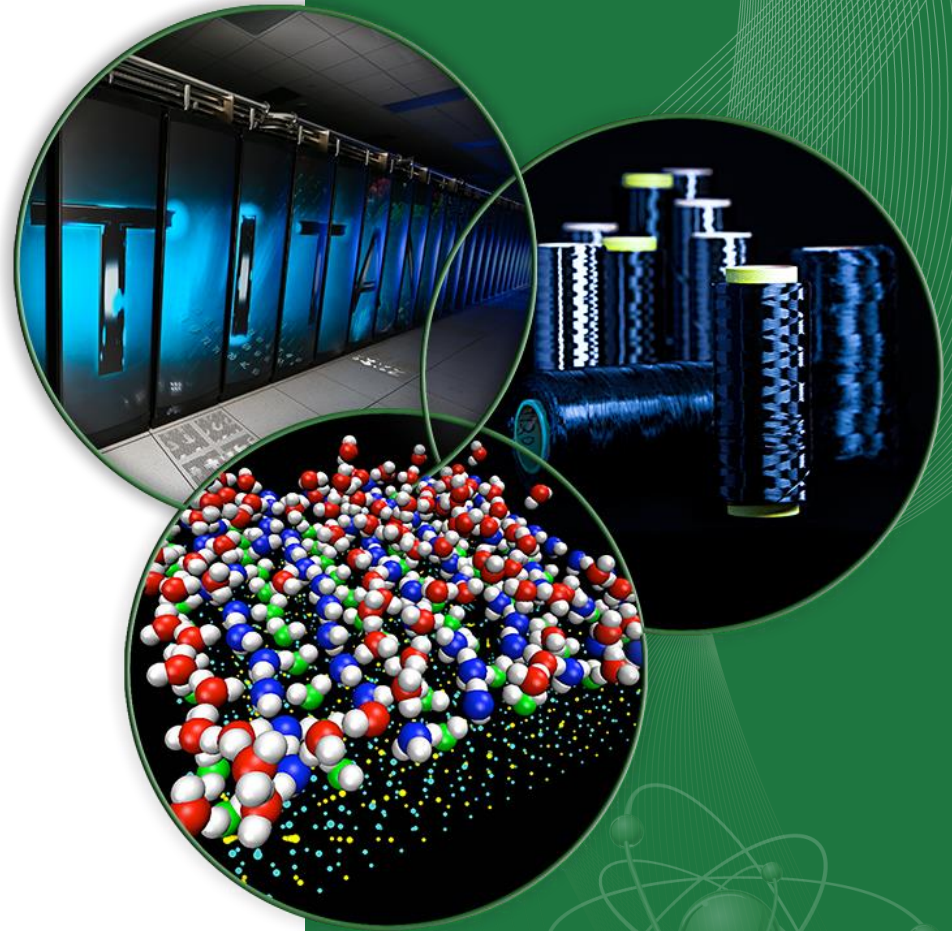
J.M. Canik

Oak Ridge National Lab
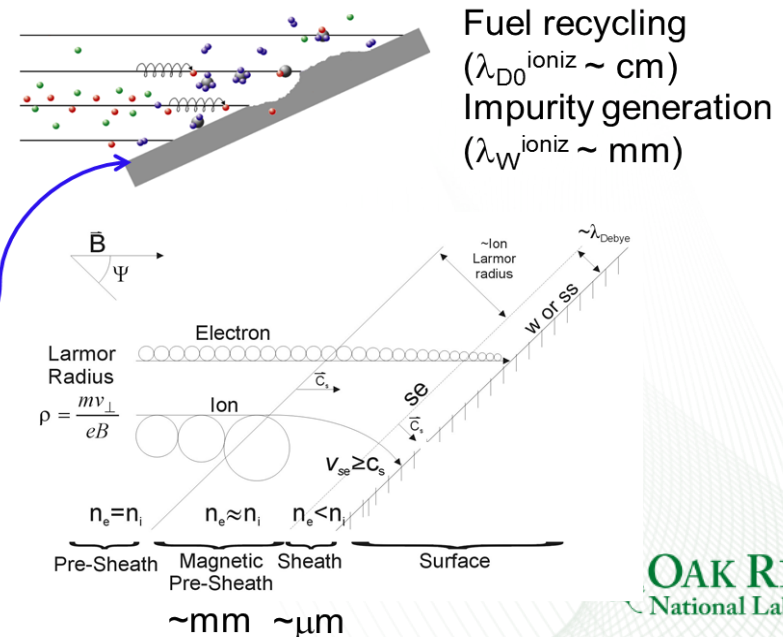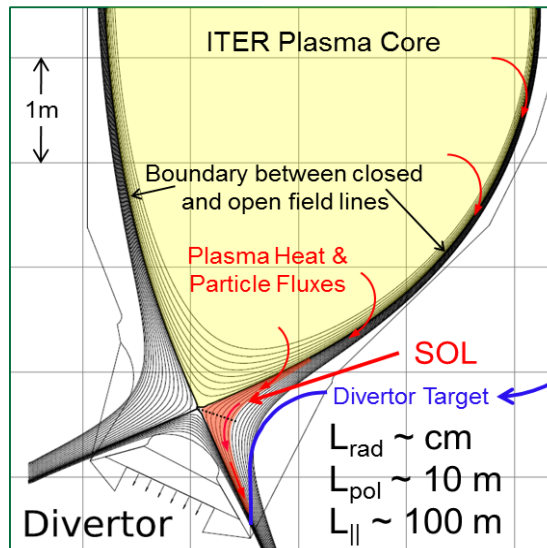
BOUT++ Mini-Workshop

12/17/15

Livermore, CA

Three major questions related to power dissipation

- What is the natural, unmitigated heat flux?

- What is the maximum possible fraction of the parallel heat flux that can be dissipated?

- How much dissipation can be achieved compatible with core (pedestal) performance?

$\Rightarrow$ Will attempt to touch on each & comment on how BOUT++ could contribute

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Predictive capability to answer these questions crosses scales, disciplines
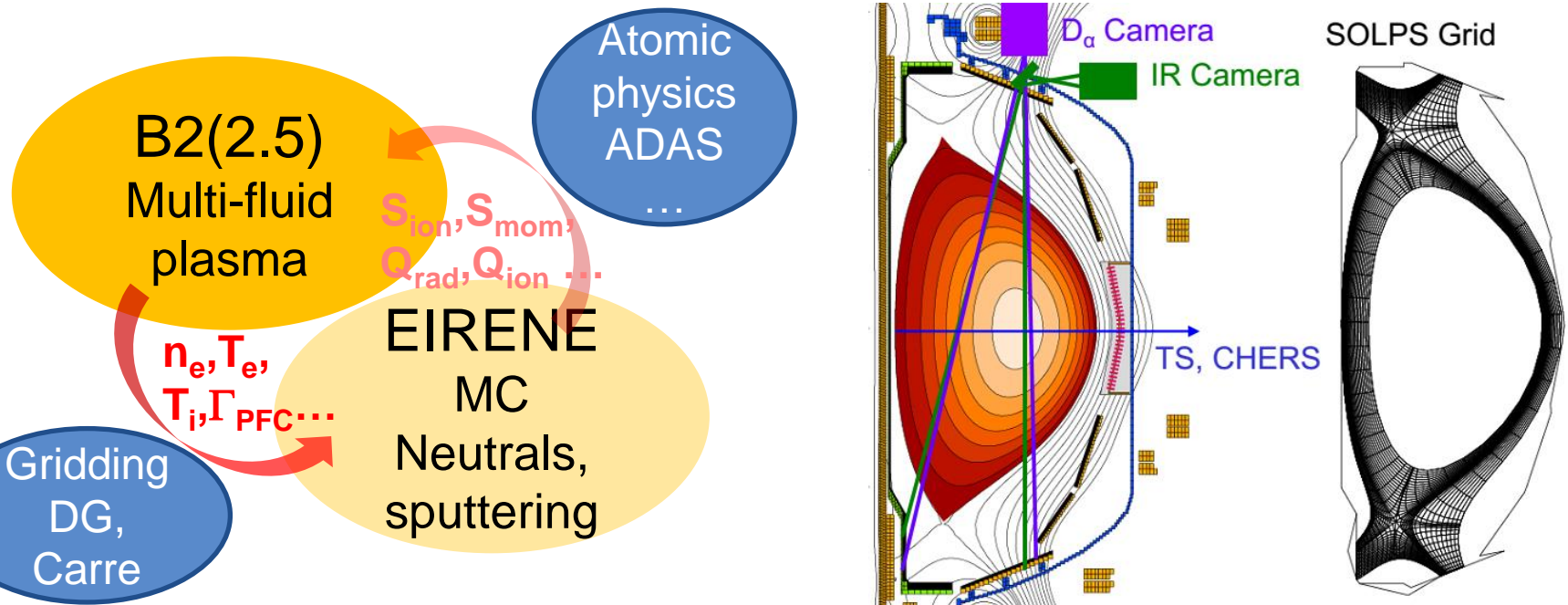
- Plasma transport
  - Parallel
  - Cross-field

- Neutrals/impurities
  - Source (erosion/recycling)
  - Transport in plasma
  - Atomic physics (e.g., ionization, radiation)

- **Near-surface sheath**
  - Spectrum of ions striking surface
  - Boundary conditions on heat flux, potential, flow

- **Evolving surface**
  - Surface morphology
  - Changes to erosion/recycling
  - Nonlinear feedback on plasma

ITER Plasma Core

1m

Boundary between closed and open field lines

Plasma Heat & Particle Fluxes

SOL

Divertor Target

Divertor

$L_{rad} \sim$ cm
$L_{pol} \sim$ 10 m
$L_{\parallel} \sim$ 100 m

Fuel recycling
$(\lambda_{D0}^{ioniz} \sim$ cm$)$
Impurity generation
$(\lambda_{W}^{ioniz} \sim$ mm$)$

$\bar{B}$

Ψ

$\sim$Ion Larmor radius

$\sim\lambda_{Debye}$

Electron

Larmor Radius

$\bar{C}_s$

w or ss

se

Ion

$\rho = \dfrac{mv_\perp}{eB}$

$\bar{C}_s$

$V_{se} \geq c_s$

$n_e = n_i$ $n_e \approx n_i$ $n_e < n_i$

Pre-Sheath   Magnetic Pre-Sheath   Sheath   Surface

$\sim$mm $\sim\mu$m

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Answering these questions requires a range of tools

- What is the natural, unmitigated heat flux?
  - Primarily an issue of cross-field transport (|| plays role as well): neoclassical+turbulence
  - Tools: BOUT++, XGC/COGENT-class GK codes

- What is the maximum possible fraction of the parallel heat flux that can be dissipated?
  - Requires model for parallel transport (inc. imp's)
  - Atomic physics key
  - 2D fluid codes current standard: SOLPS/UEDGE/EDGE2D-EIRENE…

- How much dissipation can be achieved compatible with core (pedestal) performance?
  - How do pedestal and core react to high n_e, high P_{rad}?
  - EPED current pedestal model, need more (BOUT++?)

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'Predictive' edge transport simulations are performed with SOLPS and UEDGE

- Plasma fluid equations solved, including multiple ions and charge states
  - Classical transport assumed parallel to magnetic field (+kinetic corrections)
  - Ad-hoc transport coefficients in the cross-field direction

- Monte Carlo code EIRENE (SOLPS) or fluid model (UEDGE) simulates neutral transport

- Comprehensive atomic and PMI processes included via databases, boundary conditions

Schneider, CPP 2006   www.eirene.de

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What is the natural, unmitigated heat flux? Need cross-field transport model

- Significant and ongoing effort to improve neutral and atomic physics in codes like SOLPS and UEDGE

- Radial transport remains an assumption without much physics basis
  - Nature (usually diffusive, sometimes w/ convection, intermittency)
  - Magnitude (D, χ informed by current experiments, fixed to project next)
  - 2D structure (often assume D poloidally constant, but expts show fluxes more ballooning-like)
  - Should improve with Theory target

- Moving towards physics based model important just from psychological perspective
  - 'You can get any answer fiddling inputs parameters'

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Empirical projections of heat flux channel width (i.e., $q_\parallel$) in ITER have varied wildly

- Loarte scaling; IPB '99: $\lambda_q \sim$ 2-3 cm

Table 9. Heat flux power deposition width and peak heat flux extrapolation for ITER in H-mode

P_{div} (MW)	λ_q (cm)	$q_\parallel$ (MW·m^{-2})	$q_\perp$ (MW·m^{-2})
50	2.2	270	5
100	2.8	430	7.5

- JET scaling; IPB '07: ~5 mm
  - Also recognized that some parameter dependencies (esp P) varied strongly study-by-study, including sign

- ITPA scaling; '10-present: Down to 1mm
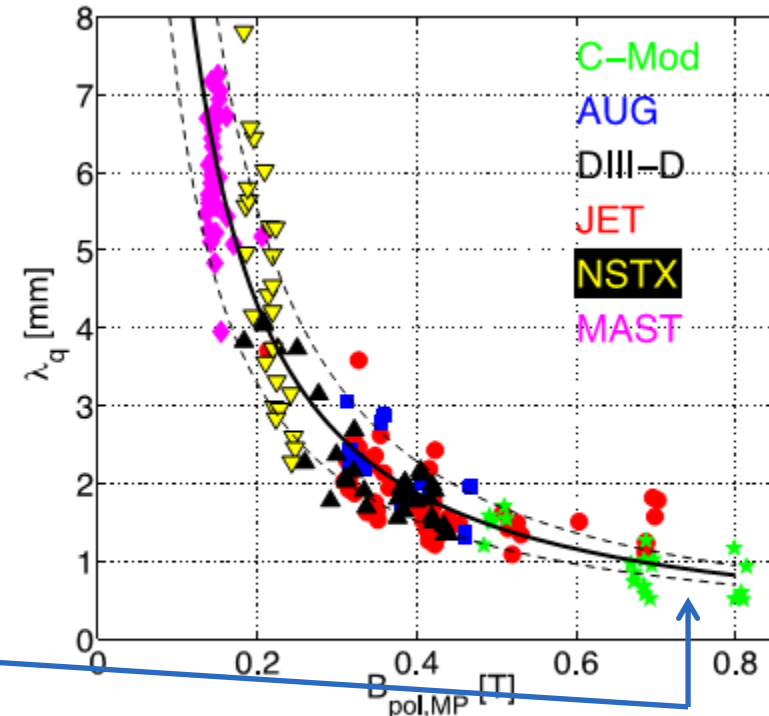
Figure II-2: Power scrape-off width vs. poloidal magnetic field from international database[1].

Lack of radial transport model can be bypassed by relying on experiment

1. Focus on the outer divertor

2. Adjust $D_\perp, \chi_\perp$ to match fitted upstream profiles

3. Adjust upstream parallel heat flux so that divertor heat flux in model matches IRTV measurement

Iterative transport coefficient updating scheme described in Canik JNM '11, '15
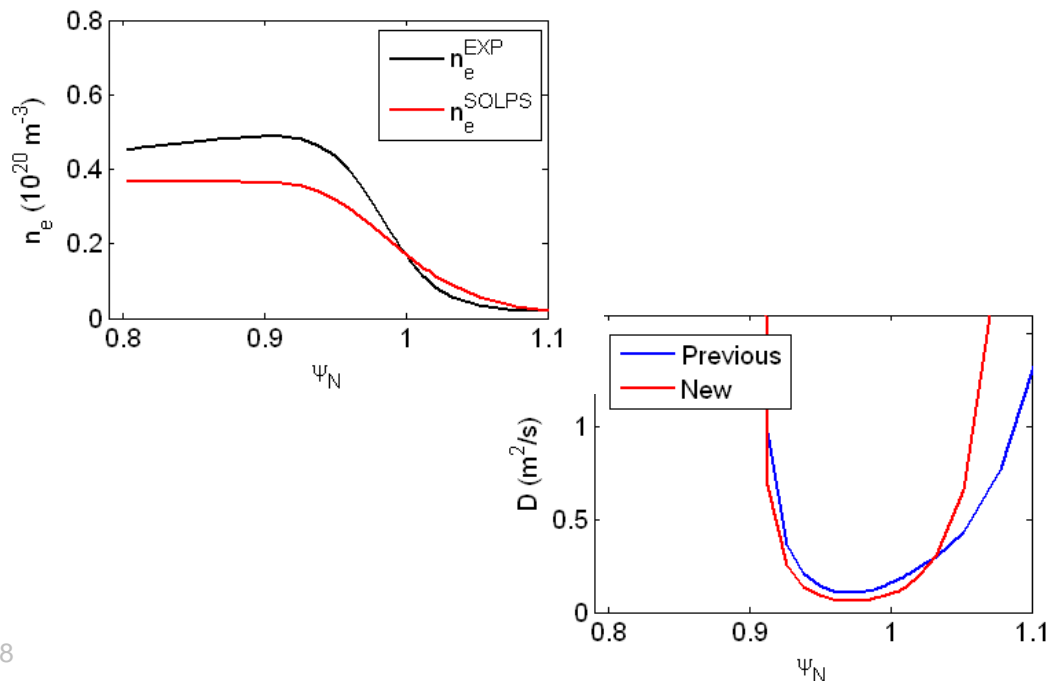
Parameters adjusted to fit data	Measurements used to constrain code
Radial transport coefficients $D_\perp$, χ_e, χ_i	Midplane n_e, T_e, T_i profiles (TS, CER)
Separatrix position/T_e^{sep}	Peak divertor heat flux (IRTV)
Scale factor multiplying carbon radiation	Total radiation in outer divertor (bolometers)

Model results to be compared to measurements	Diagnostics
n_e, T_e, Γ profiles along divertor floor	Langmuir probes, DTS
Poloidal/2D n_e, T_e profile above floor	DTS
Deuterium, carbon line emission	Filterscopes, multichord spectrometer

Promising (parallel) code-experiment comparisons with measured radial profiles

$\psi_N = 1.001-1.005$

SOLPS

DTS courtesy of LLNL

Canik, JNM '15
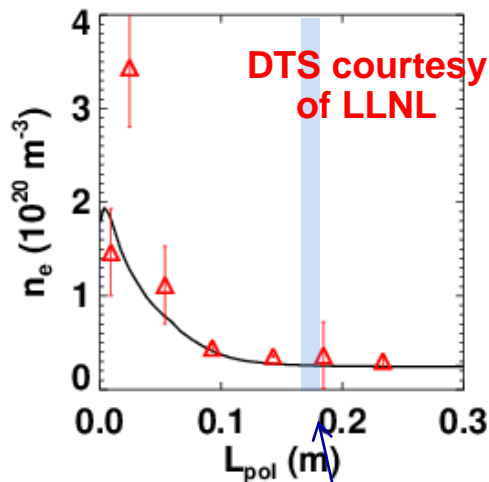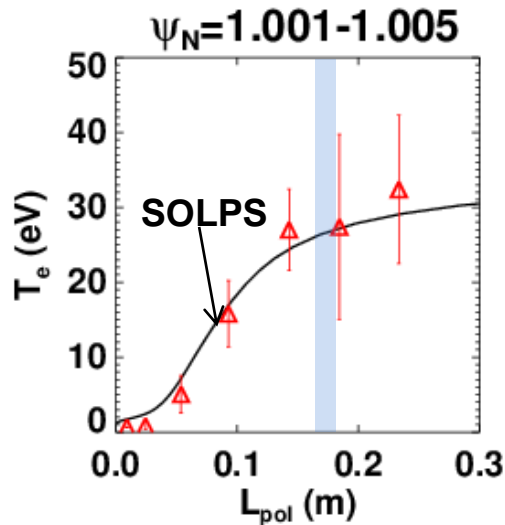
Target

X-pt

- Code-experiment comparisons made, but tend to be case-by-case

- Example from DIII-D
  - Parallel heat flux is matched as best possible to experiment
  - Parallel T_e profile in agreement with DTS for high density L-mode case

- Much further to go for validation

- Adding a predictive model for radial transport should give reasonable predictive capability
  - Couple BOUT++ to SOLPS/UEDGE
  - This has been done before, what is the status?

9

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Question 2: what is the maximum $q_{\parallel}$ that can be dissipated?

- Assuming the answer to 'what is the natural $q_{\parallel}$' isn't a good one, this becomes central to determining actual heat flux
  - Have to reduce many GW/m^2 to <100 MW/m^2

- Several mechanisms can provide volumetric losses that spread heat over first wall
  - Radiation, CX, cross-field transport, …

- Estimates of upper limit on dissipation limited
  - ~600 MW/m^2 from coronal radiation, others?

Transport as important as atomic physics in setting radiations levels
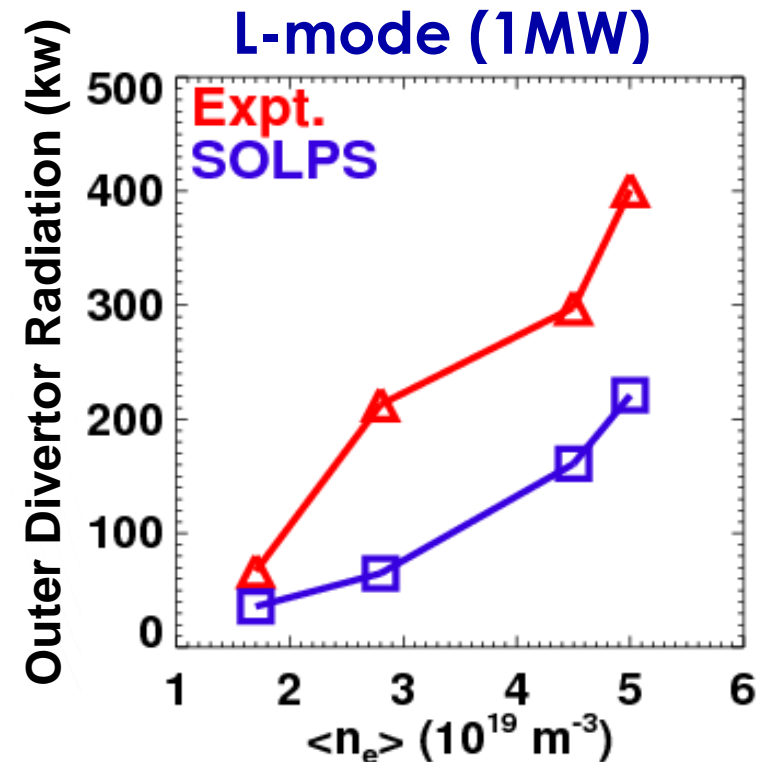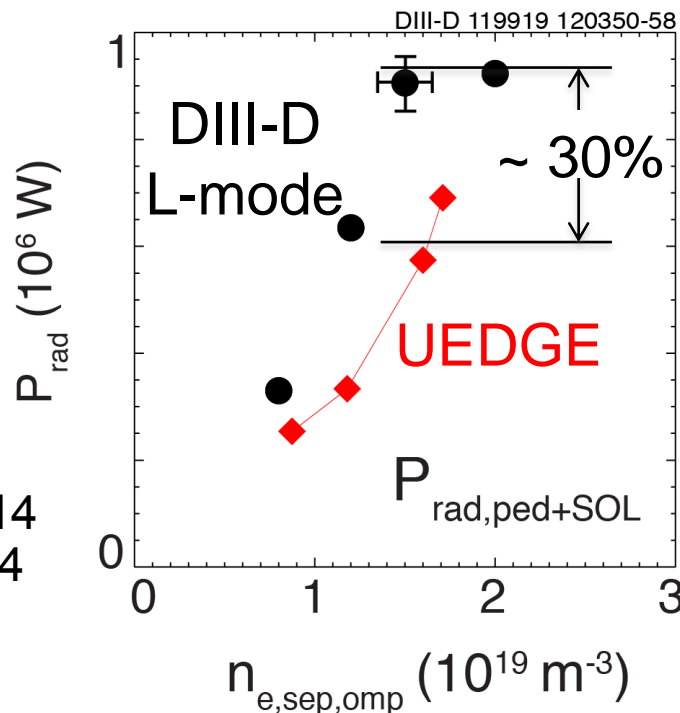
- Long-recognized that charge state distribution more than just balance between ionization and recombination

- Transport assumption can dominate radiative loss curves, especially at high temperature

- 2D edge codes (SOLPS/UEDGE) *should* capture this aspect of impurity transport

Allen, JNM '92

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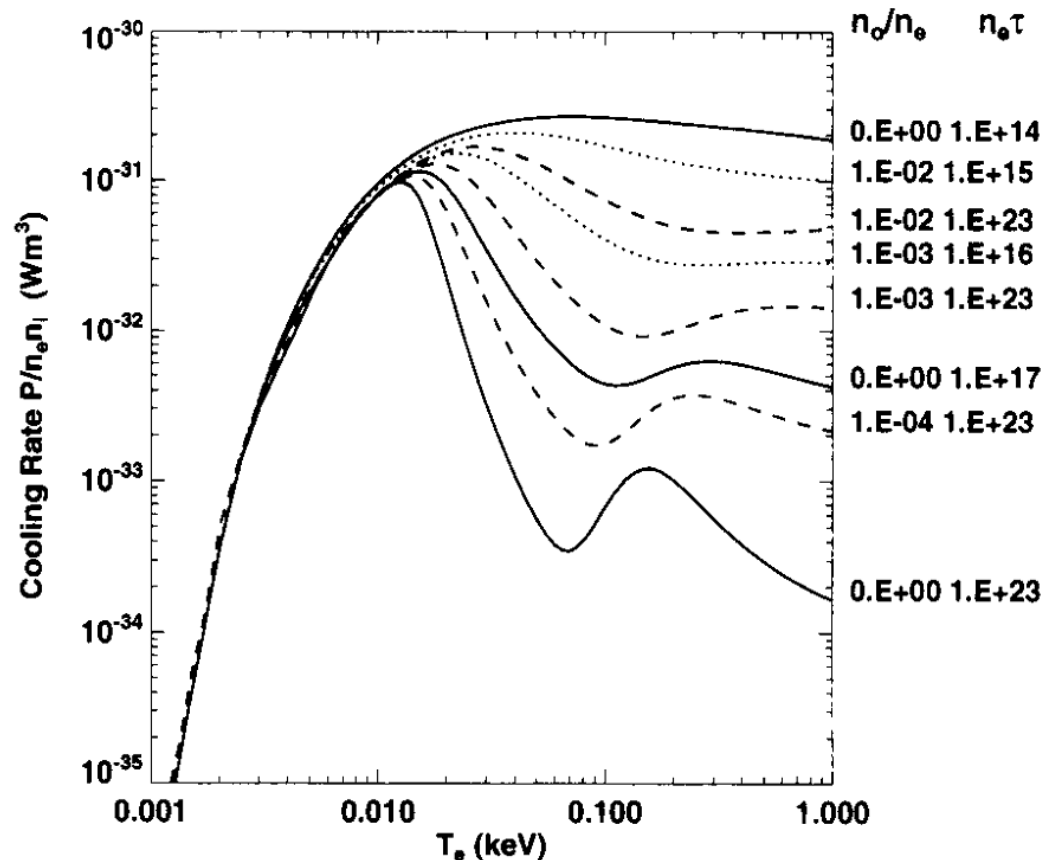
'Radiation shortfall' has emerged as common observation across codes/expts

- Divertor radiation in consistently lower than experiment
  - Stronger in SOLPS and UEDGE, but seen with OEDGE using DTS n_e, T_e
  - Also observed in modeling efforts at other tokamaks (JET; PSI '14)
  - Critical to predictive capability (and correcting improved predictions of T_e in divertor[1,2]…)

- Indirect evidence that this is not just error in C sputtering[1,2]
  - Increasing C radiation inconsistent with spectroscopic data in L-mode
  - Observed in all-metal machines + low modeled D_α suggests D problem (molecules?)
  - Other possible culprits make it hard to pin down (background n_e/T_e? Bad atomic physics? Non-thermal e's? Impurity transport?)

[1]Groth, APS '14
[2]Canik, PSI '14

DIII-D 119919 120350-58

DIII-D L-mode

~ 30%

UEDGE

P_{rad} (10^6 W)

$P_{rad,ped+SOL}$

$n_{e,sep,omp}$ (10^{19} m^{-3})

L-mode (1MW)

Expt.
SOLPS

Outer Divertor Radiation (kw)
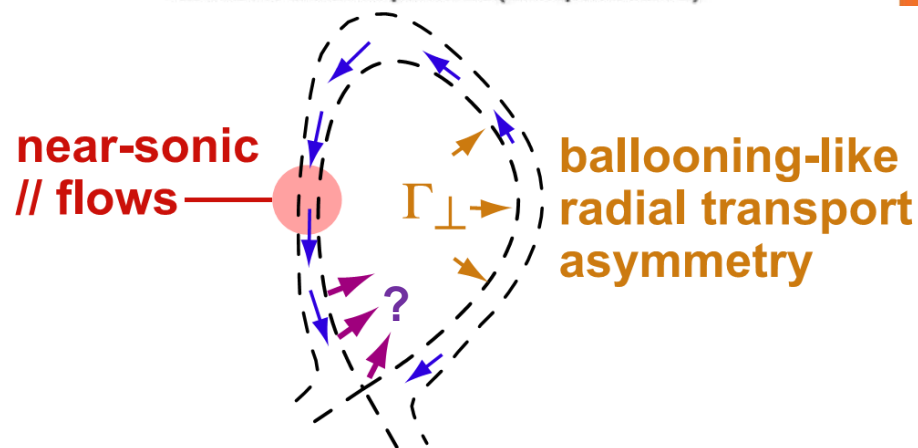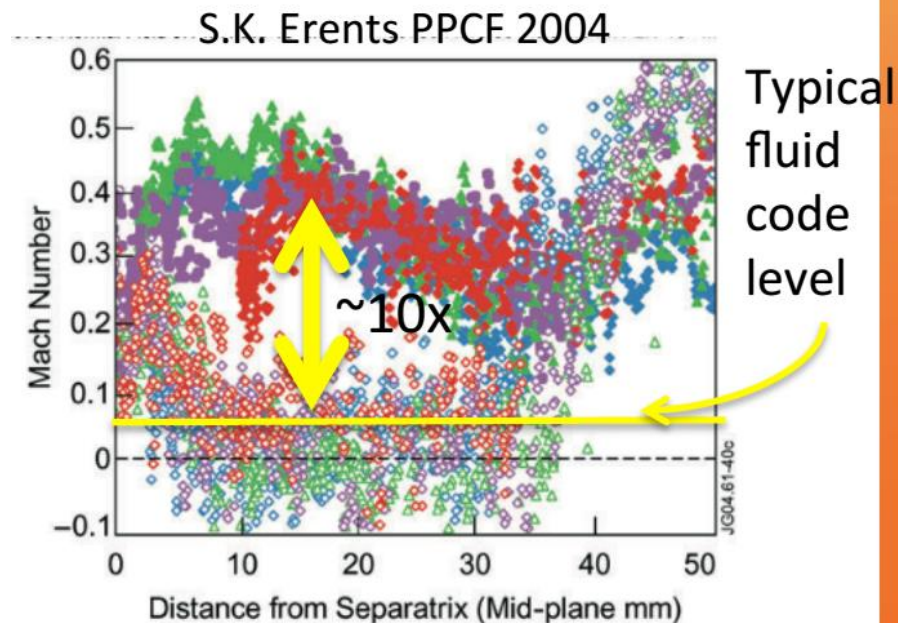
$<n_e>$ (10^{19} m^{-3})

Impact of intermittency not (normally) captured in SOLPS/UEDGE

- Typically only deal in time-averaged quantities

- But nonlinearities in atomic physics mean that $\langle F(E)\rangle \neq F(\langle E\rangle)$

- Can check using models such as the macroblob model implemented in UEDGE
  - Assumes features of blobs
  - Should do this to check how important these effects could be on radiation

- Could BOUT++ simulate time-dependent transport (inc. atomic physics, impurities) more directly?

Krashenennikov, PoP '09

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Could general SOL flow patterns and impurity transport be playing role?

- Well-known that 2D fluid codes don't reproduce flow patterns measured
  - Predict low flows away from divertor, measure substantial fraction of sonic ~everywhere

- Implies impurity transport isn't right (strong influence of background flow)
  - Impact on radiation?

- Can BOUT++ simulation close the loop on SOL flow understanding?
  - Expt evidence points to transport driven flow, except all piles up at inner divertor
  - Can transport into PFR solve this (Harrison meas.)
  - Will this improve impurity/radiation predictions?

S.K. Erents PPCF 2004

~10x

Typical fluid code level

near-sonic // flows

$\Gamma_\perp$

ballooning-like radial transport asymmetry

?

LaBombard, TTF '08

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Turbulence in divertor could contribute to heat flux spreading (esp w/ novel div)

- Cross-field transport could in principle contribute to heat flux spreading, $q_{||}$ reduction
  - Inference from heat flux measurements suggest q_{pk} reduced by factor of 2 due to transport into PFR
  - Recent MAST measurements confirm turbulence in div, role of curvature?

- Especially interesting aspect for novel divertors
  - Large high βp region near X-pt postulated to drive strong mixing
  - Addtl' control for reducting $q_{||}$

- Needs exploration via simulation to test strength of effect

b) Confinement zone

d)

Ryutov, Phys. Scr. '14

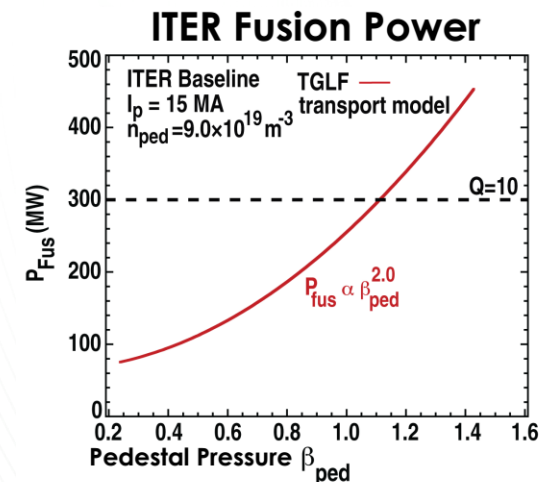OAK RIDGE
National Laboratory
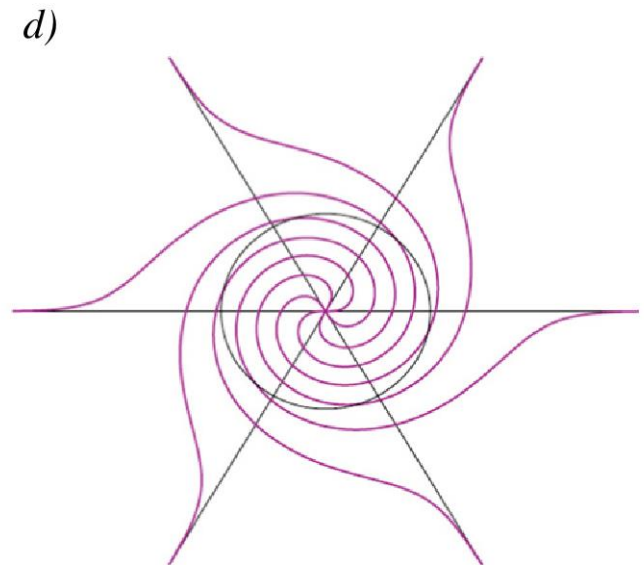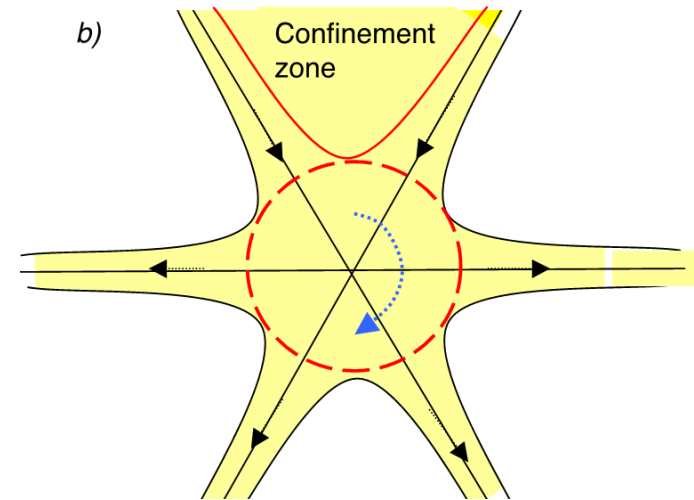
Question 3: can dissipative divertor be compatible with core performance?

- Arguably the major outstanding question in the field related to detachment/heat flux control
  – Empirically we know we can essentially turn heat flux off
  – But can we do that without killing confinement?

- Linked to pedestal performance
  – Core confinement largely driven by pedestal height
  – Degradation with dissipative divertor can be correlated with reduced pedestal

- Significant opportunity for BOUT++ impact
  – Leading pedestal model (EPED) based on physics that can be accessed within BOUT (I think?)
  – Major need to moving beyond pressure limits, understanding channel-resolved transport

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Widely reported that high density edge correlated with loss of confinement

- High density or impurity seeding to mitigate heat fluxes results in poor confinement
  - Linked to pedestal height
  - Good confinement sometimes observed if core profiles peak

- Not well understood
  - Too little power for good H-mode?
  - Excessive cooling at sep?

- More generally, mitigating heat flux means raising density, adding impurities
  - Sets n_e, n_{imp} at sep ($+\Gamma_0$)
  - Have to compatible with core (current drive, ok radiation, etc)
  - Need to propagate those to pedestal top

Reinke, APS '15
C-Mod EDA H-mode

ITER Fusion Power

ITER Baseline
I_p = 15 MA   TGLF
n_{ped} =9.0×10^{19} m^{-3} transport model

Q=10

$P_{fus} \propto \beta_{ped}^{2.0}$

P_{Fus} (MW)

Pedestal Pressure β_{ped}

State-of-the-art pedestal model can address some of the issues

- Great progress in predicting pedestal pressure
  - EPED: peeling-ballooning combined with kinetic-ballooning constraints
  - Successful multi-machine validation of resulting height and width

- Can access stability-limit-related contributions to core-edge combatibility
  - E.g., reduced pressure limit at high collisionality

- Significant assumption remained built in
  - Separatrix temperature
 - Ped/SOL n_e ratio

Snyder, NF '11
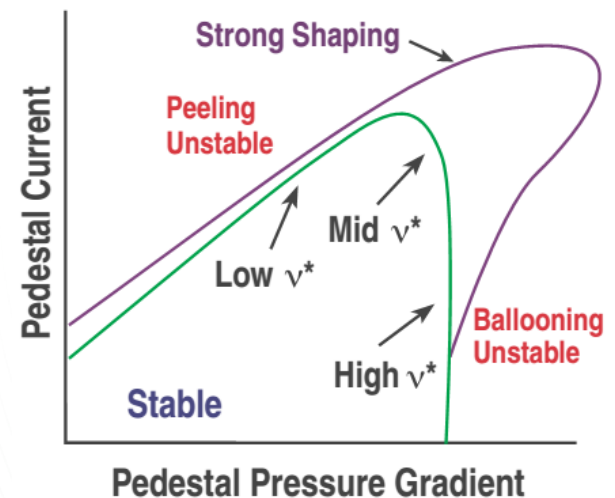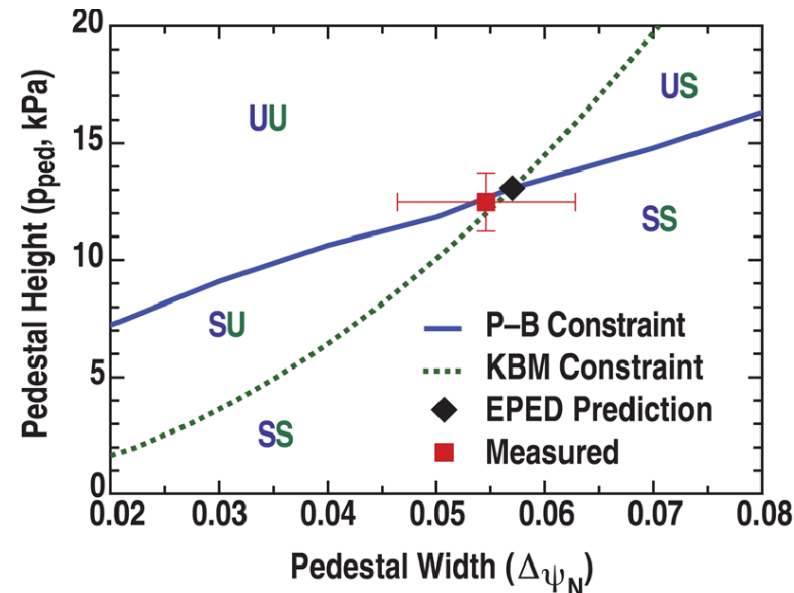
Significant advances needed to improve predictions of core-edge compatibility

- General issue of needing transport-channel-resolved predictions
  - Extension of KBM-critical model
  - Especially important for density, since this is often source of tension between core and divertor needs

- Edge (incl pedestal) becomes (at least) 2D when we push the limits of dissipative operation
  - Strong radiation near X-pt->impact on pedestal transport?
  - Just T_e reduction? Or net P_{SOL} loss? More fundamental change?
  - Can BOUT++ provide self-consistent turbulence assessment accounting for, e.g., non-flux surface constant T_e?

Reimold, NF '14
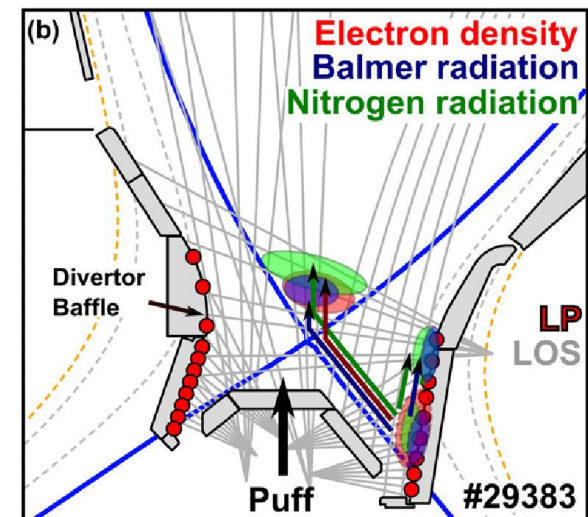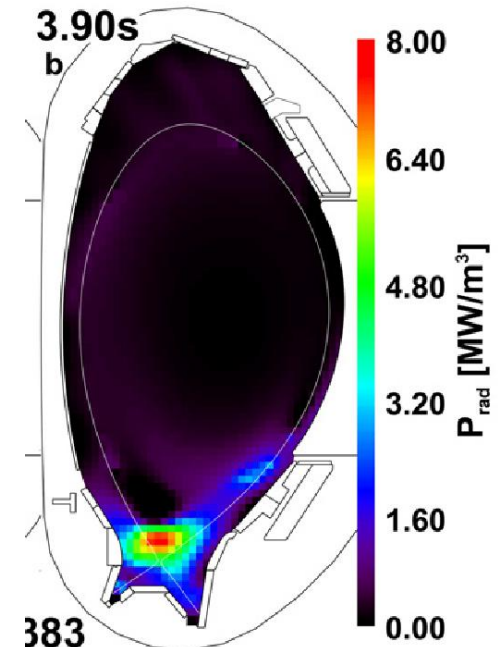
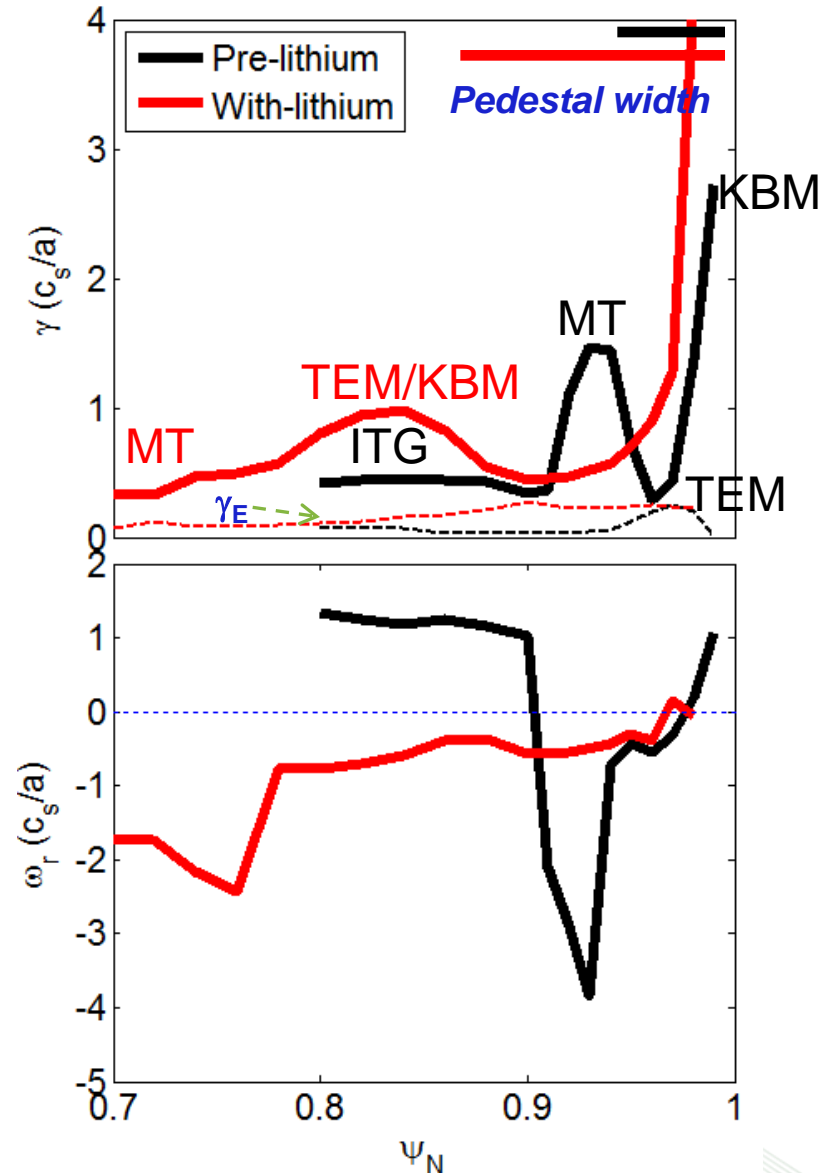# Experiments show sensitivity of core confinement to recycling/fueling

- Example from NSTX: lithium reduces divertor recycling, increases core confinement
  - Major changes to pedestal profiles

- Not necessarily linked to detachment studies as yet, but indicative of need to understand better how edge influences core
  - Becomes even more important for ITER, where recycling and pedetsal fueling characteristics are very different

- Physics behind these changes remains poorly understood
  - In part because appropriate toolset very limited
  - BOUT++ to the rescue?

Canik, PoP '11

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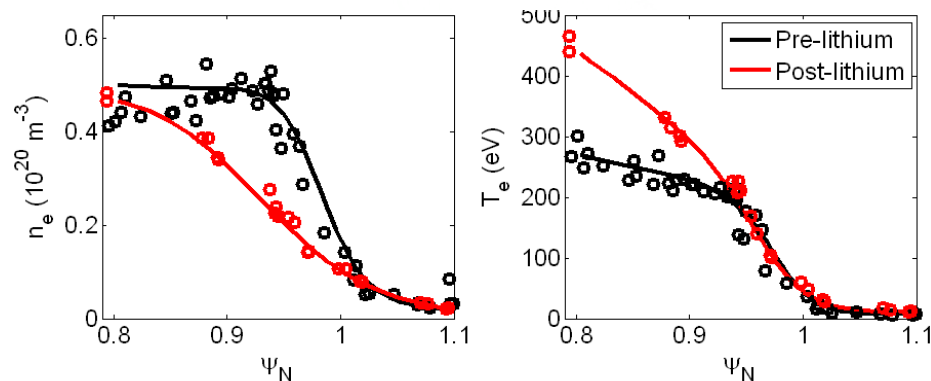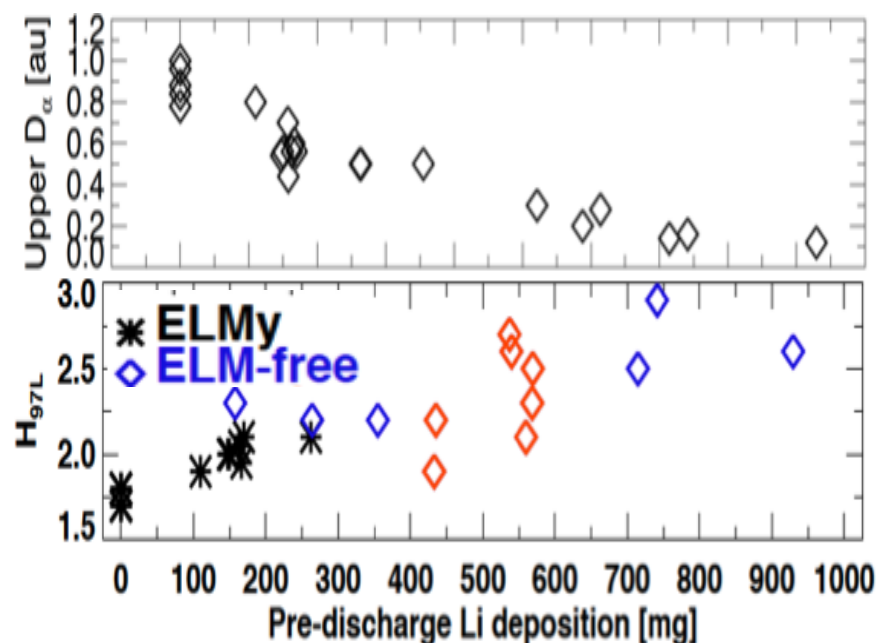
Zoo of modes identified in pedestal via GK stability analysis

- GS2 code used (linear, local)
  - GK applicability limited (ρ/L)

- Overall takeaway: density profile is key, how do we predict it?

- Microtearing is dominant at pedestal-top without lithium, is stabilized by the increased density gradient with lithium
  - Dominant mode becomes TEM/KBM hybrid, with growth rate on order of ExB shear rate over wider region->need nonlinear simulations

- ETG is destabilized near separatrix with lithium
  - Could play a role in observed T_e stiffness
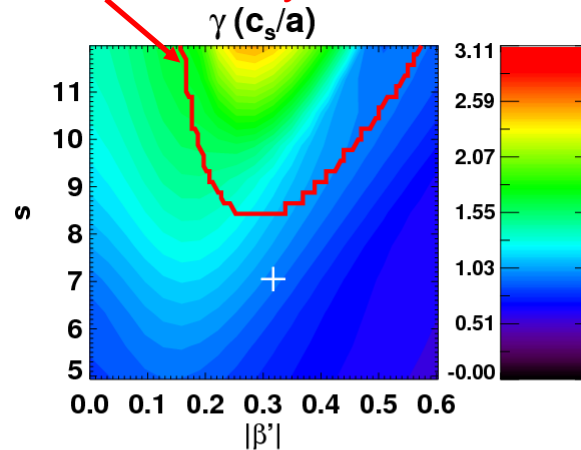 - Nonlinear simulations suggest plausibility

Canik, NF '13

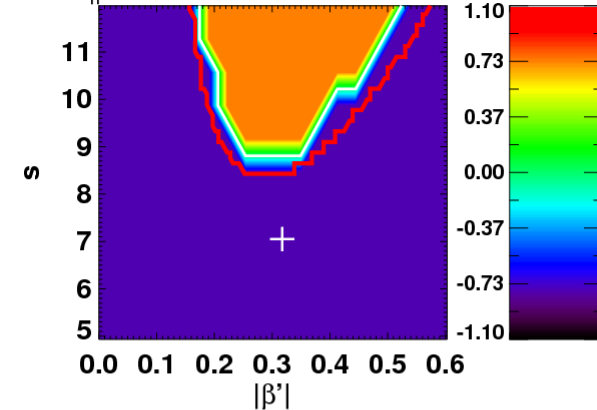# Global KBM analysis would be extremely interesting

- Local GK calculations show KBM-unstable space very similar to ideal

129038 (post-lithium)
$\psi_N=0.94$
$k_\theta\rho_s=0.2$

- Hybrid TEM/KBM throughout

- At experimental pressure gradient, further increase in, ∇P is stabilizing

  – Regardless of shear
  – On second stable side
  – Can KBM clamp p'?
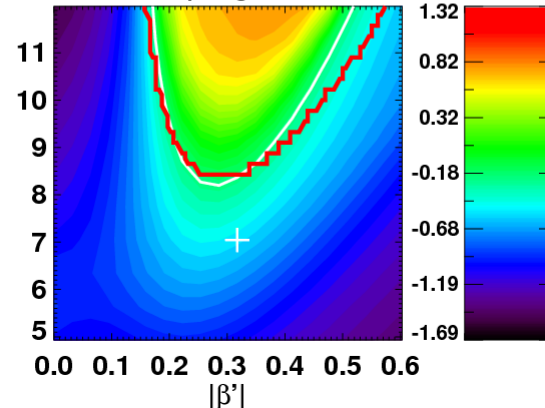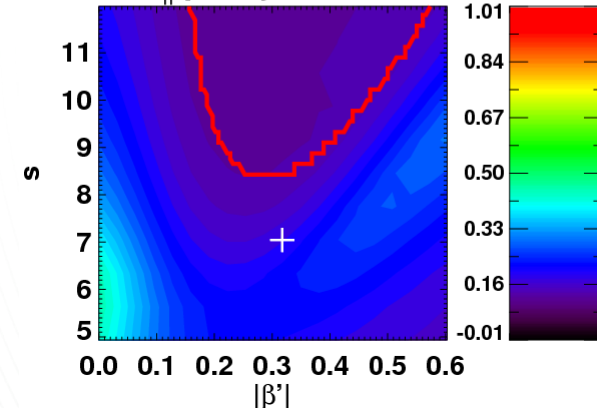
⇒ Non-local effects are likely important

  – May close off second stability, similar to finite-n ideal MHD

Ideal boundary

Canik, NF '13

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Summary: many areas where BOUT++ could contribute

- Two main interesting applications
  - SOL turbulence/profile/λ_q model
  - Pedestal turbulence (beyond EPED KBM)

- Need to couple edge turbulence simulation with divertor modeling
  - Do this literally (UEDGE/SOLPS+BOUT)? What is status?
  - Develop more reduced model based on BOUT++ for use in 2D fluid codes?
  - Do this all directly within BOUT++?

- Major contributions to the frontier of divertor research may be possible
  - Outstanding issue is compatibility with the core
  - Multi-channel pedestal model will be key component

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