First nonlinear full-f electromagnetic continuum simulations of turbulence in tokamak scrape-off layer and pedestal

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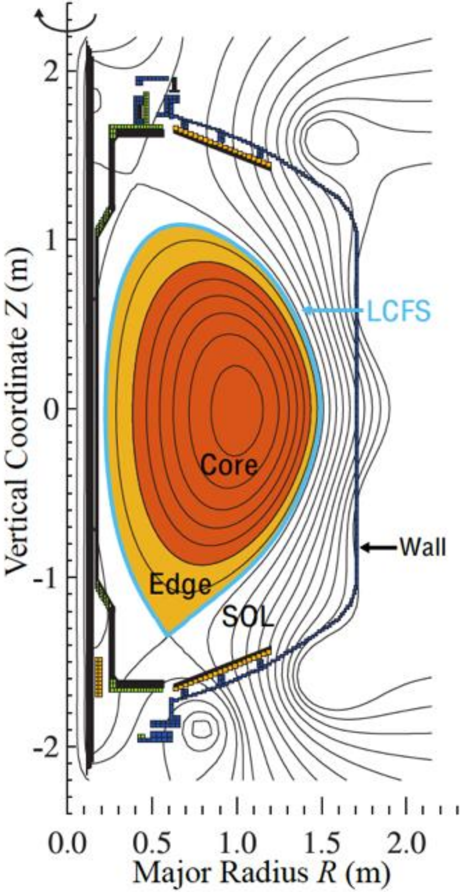
***For full details see N. Mandell Ph.D thesis "Magnetic fluctuations in gyrokinetic simulations of tokamak scrape-off-layer turbulence", arxiv:2103.16062**

Plasma boundary, scrap-off layer and edge physics

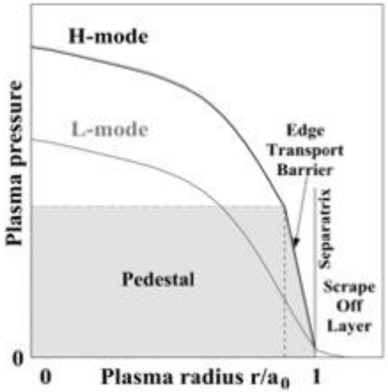
- Edge: narrow region surrounding hot core plasma; steep pressure gradients;
- SOL: open field-lines, plasma material interactions, neutrals
- Inherently multi-scale problem
- In this talk will focus on full-f gyrokinetic simulations of SOL using a continuum approach

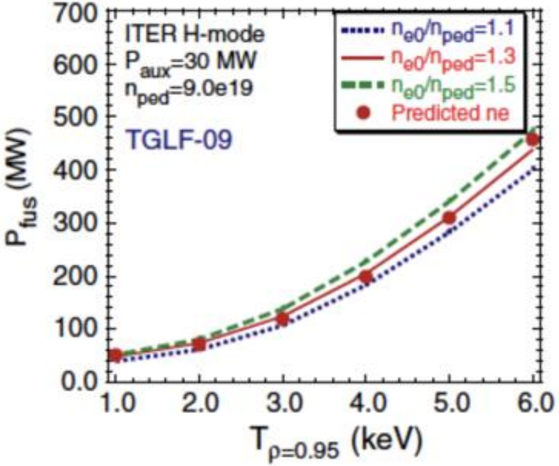


Boundary plasma has strong impact on fusion performance

- Plasma in tokamak edge/SOL constrains performance and component lifetime
  - Sets boundary condition on core profiles (e.g: pedestal in H-mode)
  - Heat exhausted over narrow region can seriously damage divertor plates
- Core transport simulations of ITER strongly depends on pedestal temperature
- Need full nonlinear turbulence simulations to predict and optimize pedestal temperature

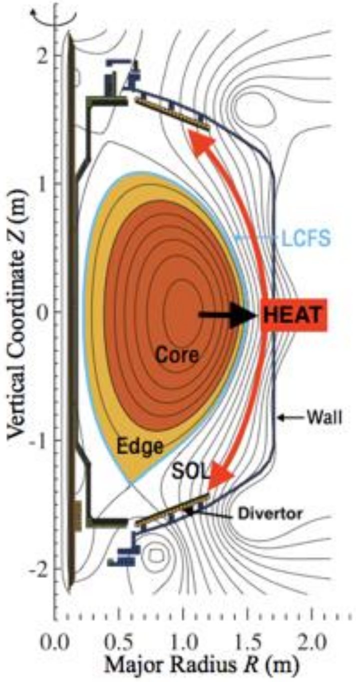
“Pedestal is the tail that wags the dog”

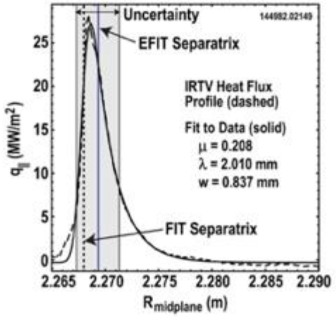




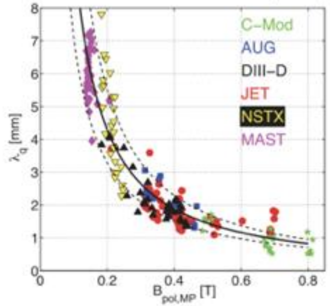
SOL power-exhaust is potential show-stopper

- Most of the power (~ 100 MW on ITER) flows in very narrow layer
  - On ITER, need to dissipate most of this power before it reaches divertor plates
  - Material limits 10 MW/m^2. ITER can easily reach 30 MW/m^2.
- If SOL heat-flux is too narrow, even steady-state power loads can result in material erosion
  - ITER design have assumed 5 mm SOL widths
  - Eich/Goldstone scaling suggests very narrow ~ 1 mm SOL width
- Need simulations to confidently predict scaling towards reactor conditions





DIII-D from Makowski et al. (2012)



Eich et al. (2013)

Gkeyll: full-f nonlinear electromagnetic code for SOL/edge

- Electromagnetic effects are especially important in edge and SOL, where steep gradients can push plasma close to ideal-MHD stability threshold and produce stronger turbulence
- Including EM fluctuations has historically proven challenging in some PIC codes, in part due to well-known Ampere cancellation problem. Significant progress in recent years.
- We use a continuum approach that provably avoids the cancellation problems and can incorporate EM effects in stable and efficient manner. (Mandell et. al. JPP, 2020, Hakim et. al. PoP 2020)

Gkeyll uses symplectic formulation of EM gyrokinetics

EM gyrokinetic equation:

$$\frac{\partial f}{\partial t} = \{H, f\} + \frac{q}{m}\frac{\partial f}{\partial v_\parallel}\frac{\partial A_\parallel}{\partial t} + C[f] + S$$

Hamiltonian: $H = \frac{1}{2} m v_\parallel^2 + \mu B + q\phi$. Fields determined by quasineutrality:

$$-\nabla \cdot \sum_s \frac{m n_0}{B^2} \nabla_\perp \phi = \sum_s q \int d^3v f$$

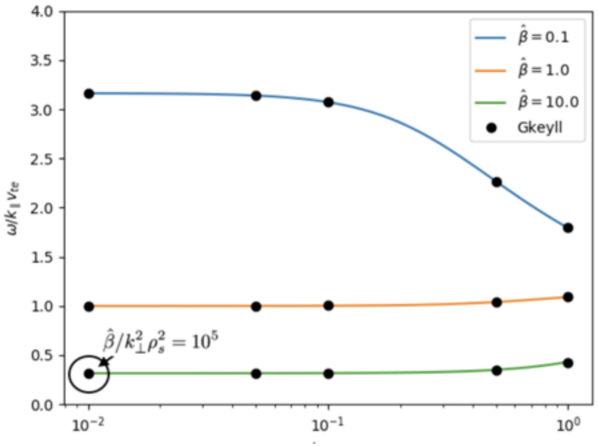
and Ampere's law:

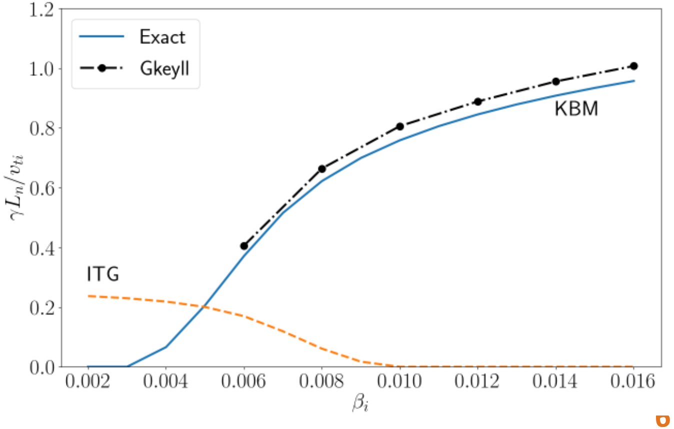
$$-\nabla_\perp^2 A_\parallel = \mu_0 \sum_s q \int d^3v v_\parallel f$$

In code we instead evolve time-derivative of this equation:

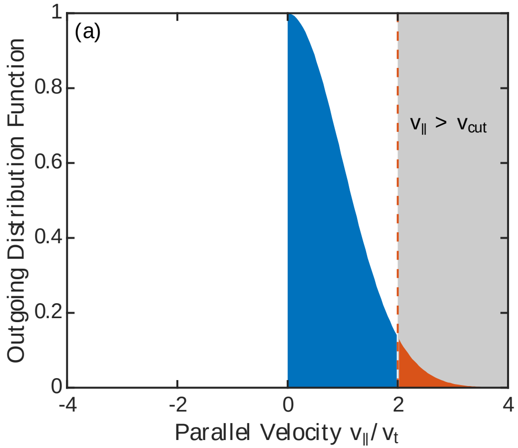
$$\left(-\nabla_\perp^2 + \sum_s \frac{\mu_0 q^2}{m} \int d^3v f\right) \frac{\partial A_\parallel}{\partial t} = \mu_0 \sum_s q \int d^3v v_\parallel \frac{\partial f}{\partial t}$$

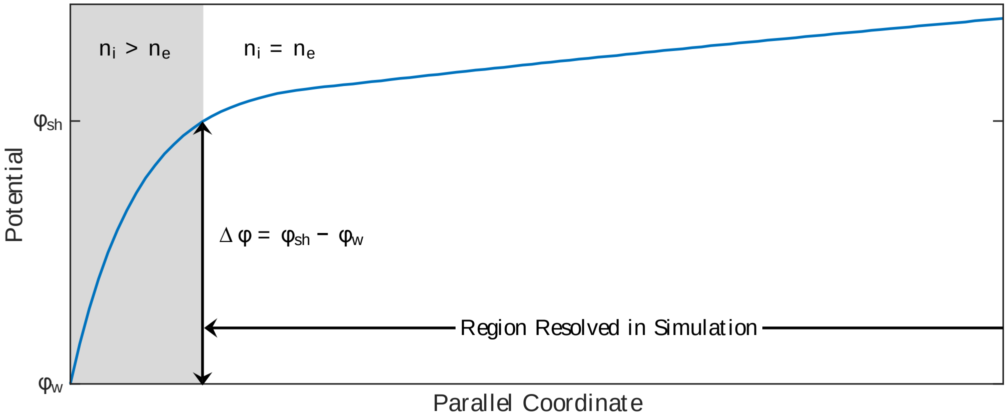
See Mandell et. al. J. Plasma Physics (2020) for details.





SOL simulations require careful handling of plasma-sheaths

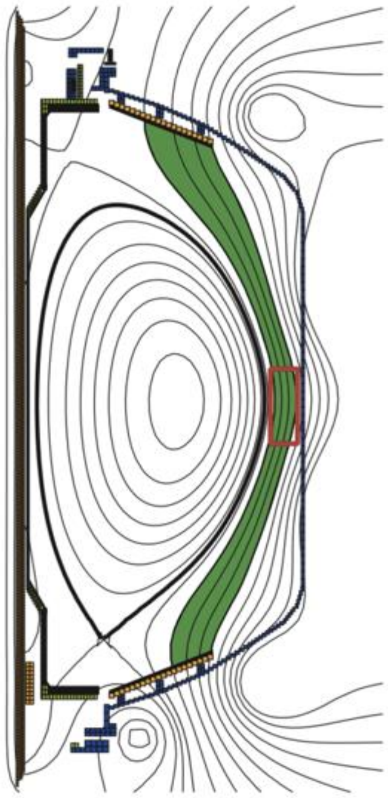


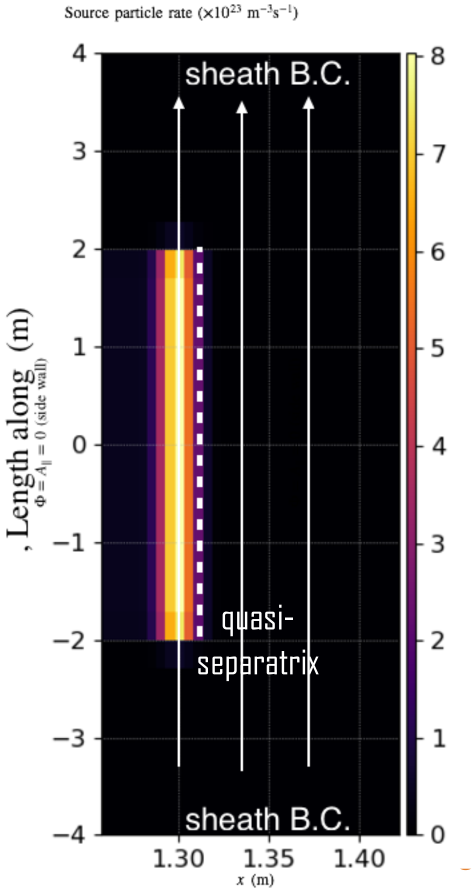


- GK is a quasi-neutral model: need to handle sheaths using BCs
- Get $\phi_{sh}(x,y)$ by solving GK Poisson equation, then use $\Delta\phi = \phi_{sh} - \phi_w$ to reflect low-energy electrons entering sheath
  - Kinetic version of sheath-BCs used in some fluid codes
- Potential self-consistently relaxes to ambipolar-parallel-outflow state
- Allows local currents in/out of the wall

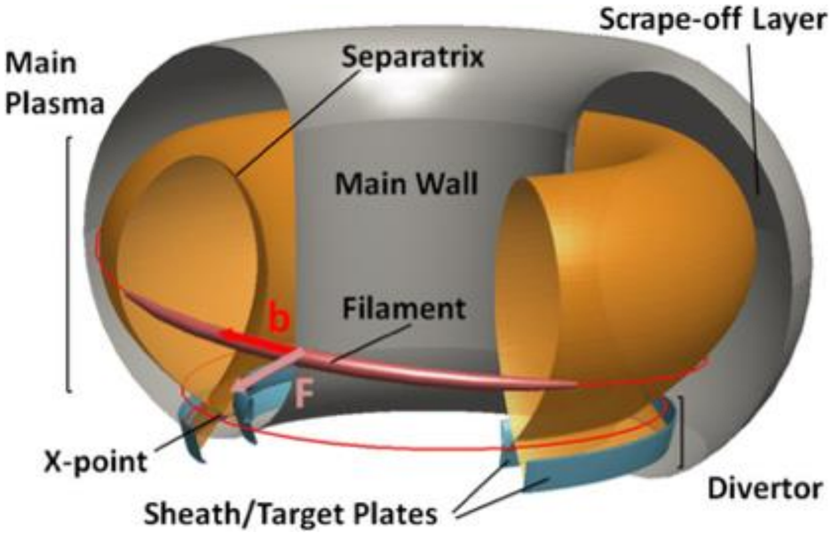
Modeling NSTX-SOL with Gkeyll

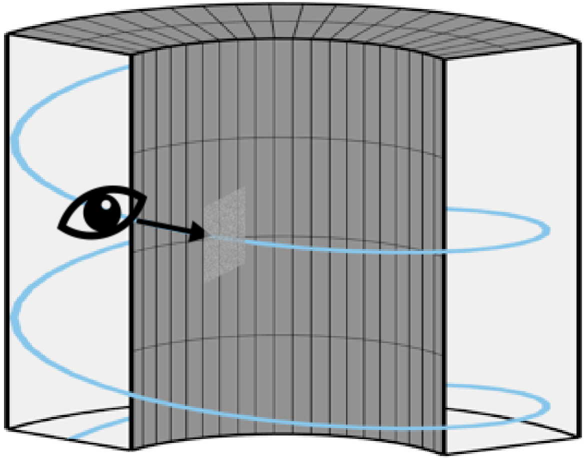
- Modeling open field-line regions only
- Simplified helical geometry: all bad curvature, no X-point at present
- Model flux of heat- and particle-flux as sourcing from core
- Boundary conditions: perfectly conducting walls; sheaths on divertor plates





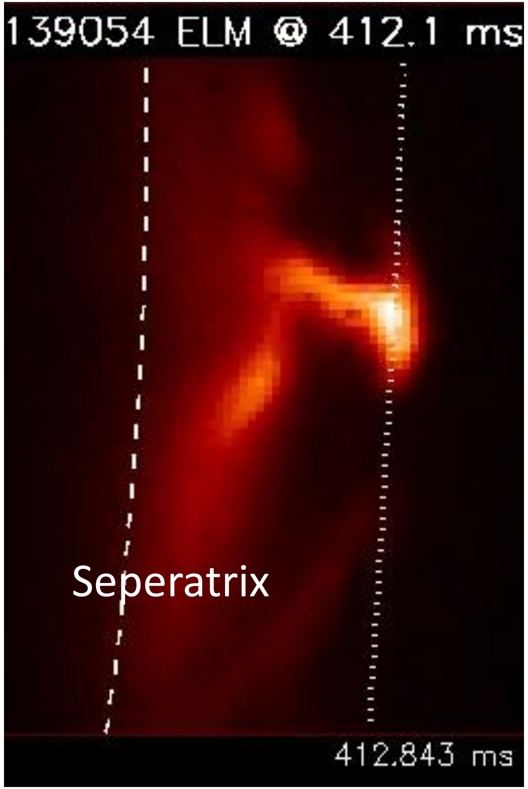
Modeling NSTX-SOL with Gkeyll

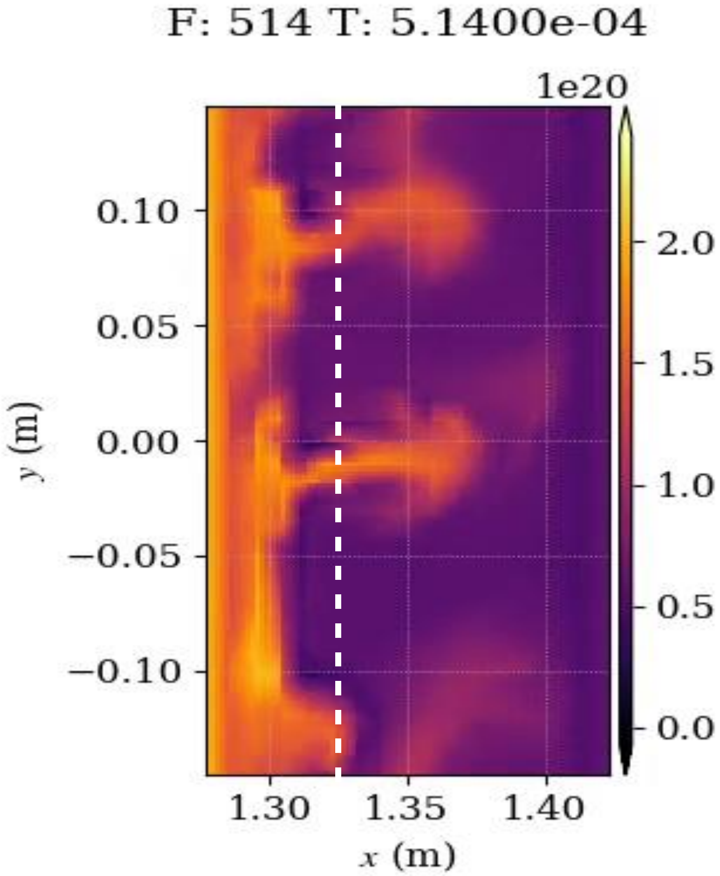


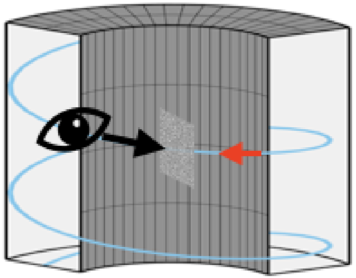


- Field-line following coordinates that start at bottom divertor plate and end on top divertor plate
- All bad curvature, interchange instability driven turbulence. Strong blob dyamics
- Parameters from NSTX H-mode SOL plasmas

Modeling NSTX-SOL with Gkeyll



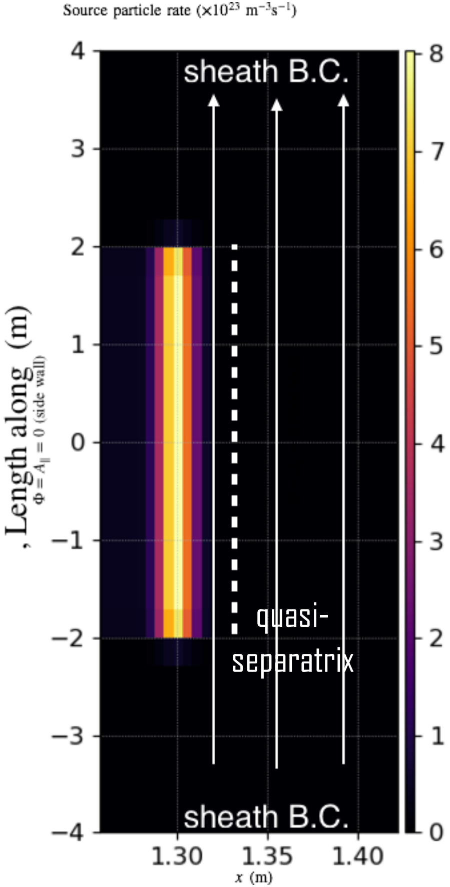




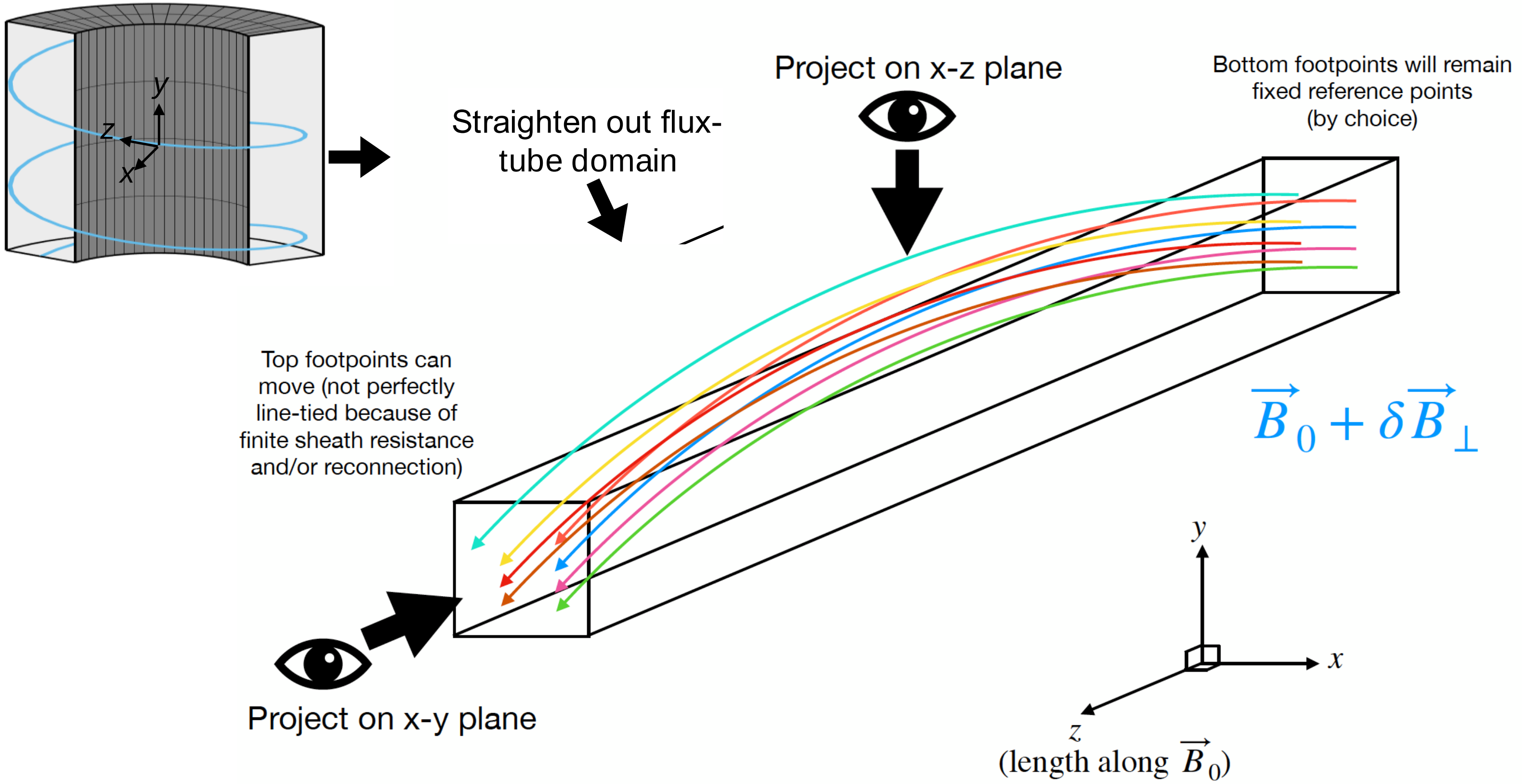
Formation and propagation of blobs & turbulent structure

β-dependence of SOL dynamics

- Parameter scan of β at fixed temperature (70 eV) by scaling source rate by factor $\hat{n}$
- Base case ($\hat{n}$=1) corresponds to “nominal” experimental heating power of $P_{\mathrm{SOL}} = 5.4\mathrm{MW}$
- Electromagnetic (EM) and electrostatic (ES) cases
- All other parameters (including sources) same for all cases
- We will look at highest β case first



Electromagnetic terms allow magnetic field-lines to “dance”



Straighten out flux-tube domain

Project on x-z plane

Bottom footpoints will remain fixed reference points (by choice)

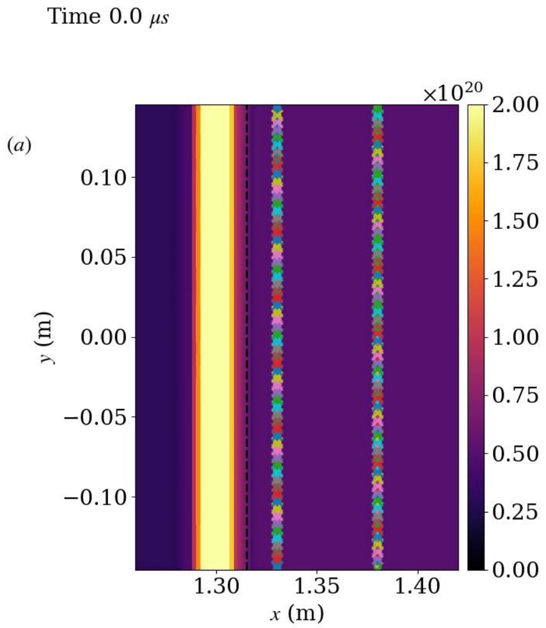
Top footpoints can move (not perfectly line-tied because of finite sheath resistance and/or reconnection)

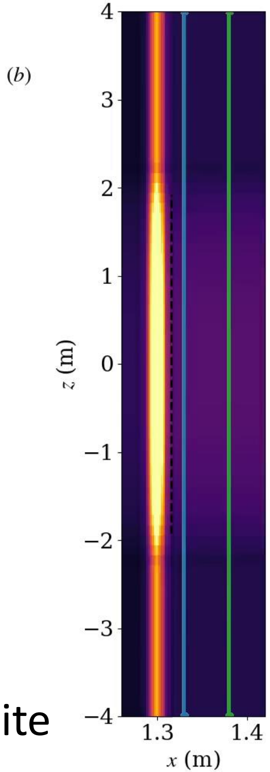
$\vec{B}_0 + \delta\vec{B}_\perp$

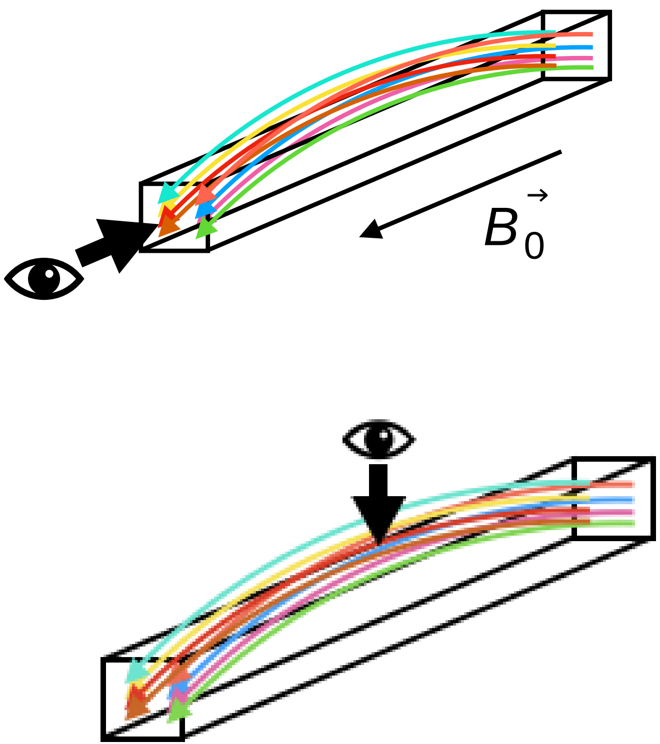
Project on x-y plane

z
(length along $\vec{B}_0$)

Electromagnetic terms allow magnetic field-lines to “dance”

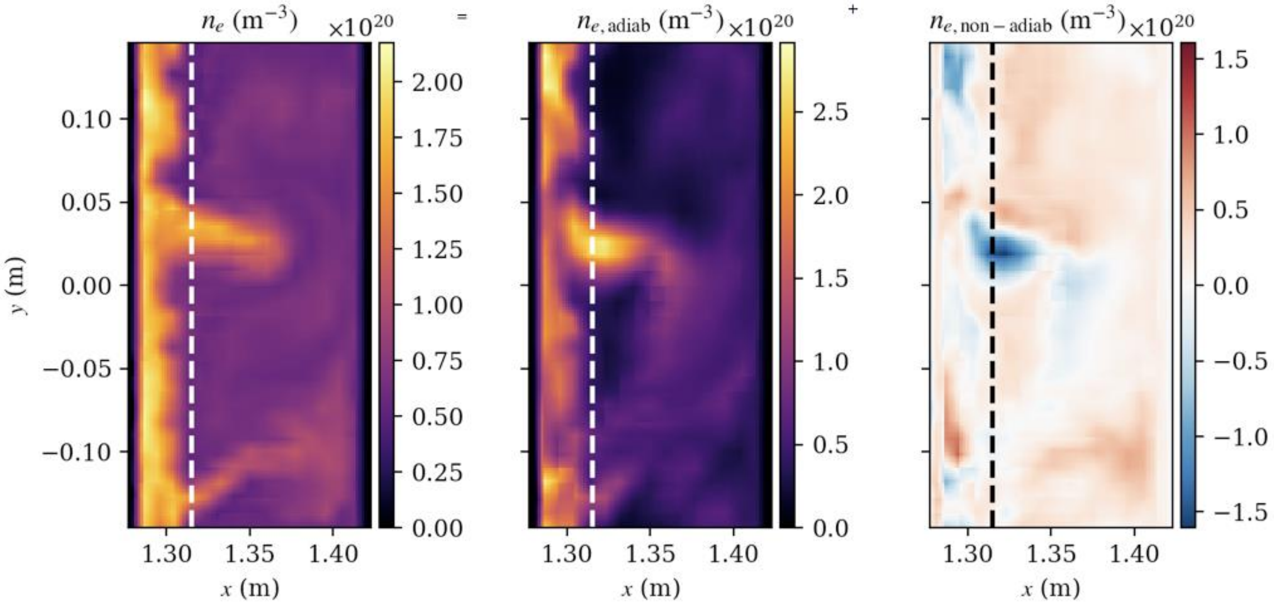






Field-lines dance from EM effects; slippage on divertor plate due to finite sheath-resistance.

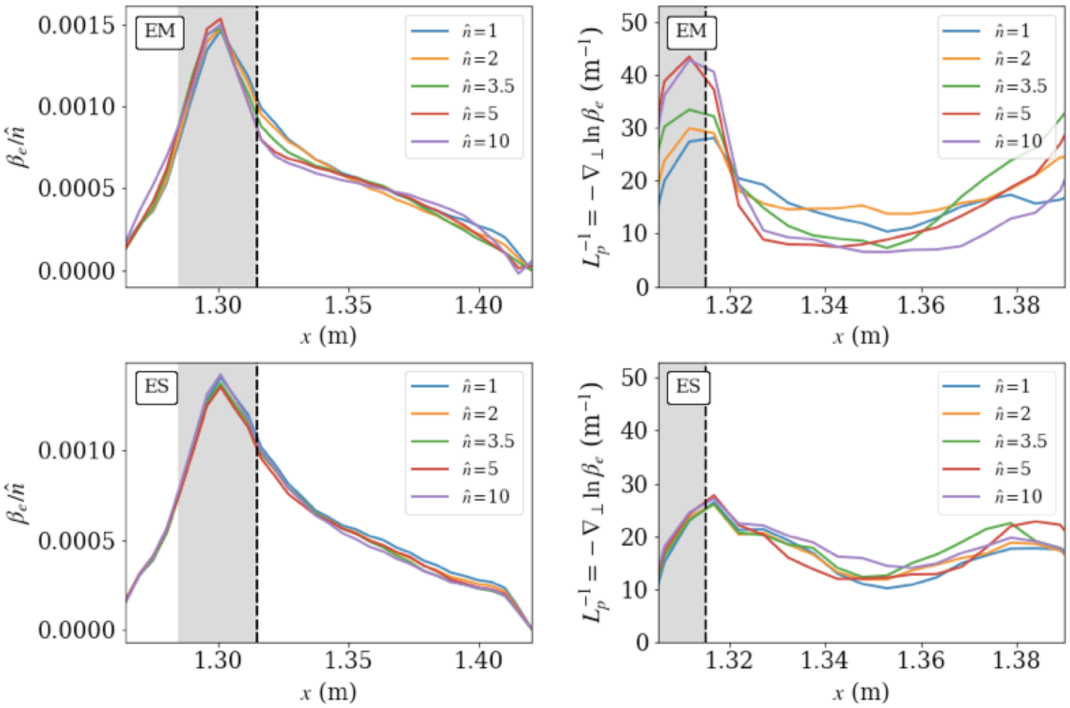
EM non-adiabatic electron response



- Electron density response is non-adiabatic in the EM case (not strong enough to give an MHD-like response)
- Non-adiabatic electrons allow energy exchange between particle internal-energy and field-line bending via induction

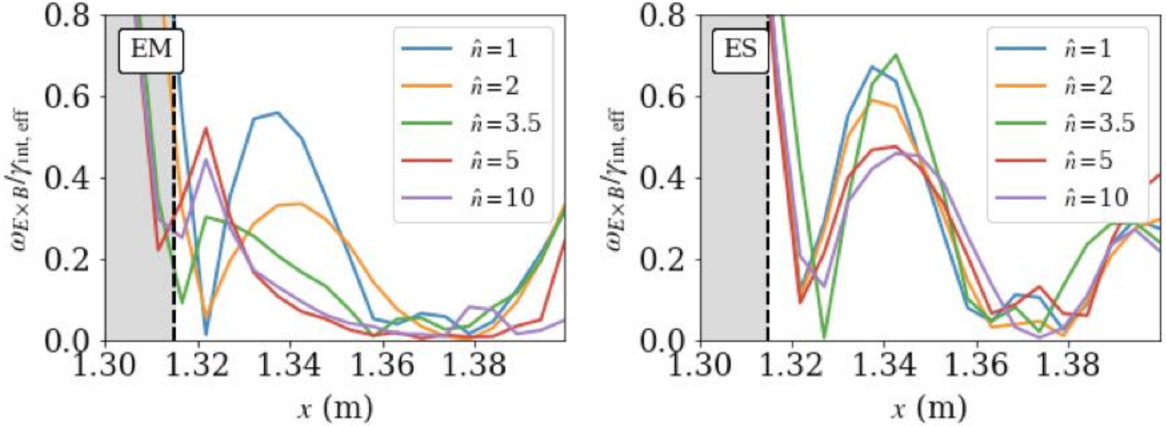
Midplane radial pressure profiles and gradients

- Full $\hat{n}$ scans to study impact of plasma β
- Profiles and gradients vary with increasing β.
- Electrostatic cases do not change with $\hat{n}$, indicating collisions not critical in these calculations
- 60% increase in steepness in gradient length-scales in EM case



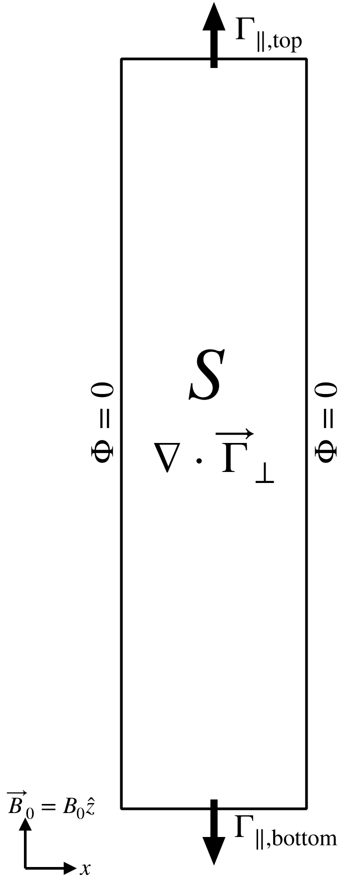
ExB shear responsible for interchange stabilization?

- The interchange mode can be strongly stabilized by flow-shear with estimates that short-wavelength modes stabilized at $\omega_{E\times B}/\gamma_{int} \gtrsim 0.4$, with $\omega_{E\times B} = v_E'$.
- With EM cases this ratio peaks just outside source region; ES peak is much farther away
- May indicate feedback mechanism between steeping gradients and ExB shear-stabilization in EM case
- Could be important in pedestal formation and L-H transition (see recent R Goldston proposals)

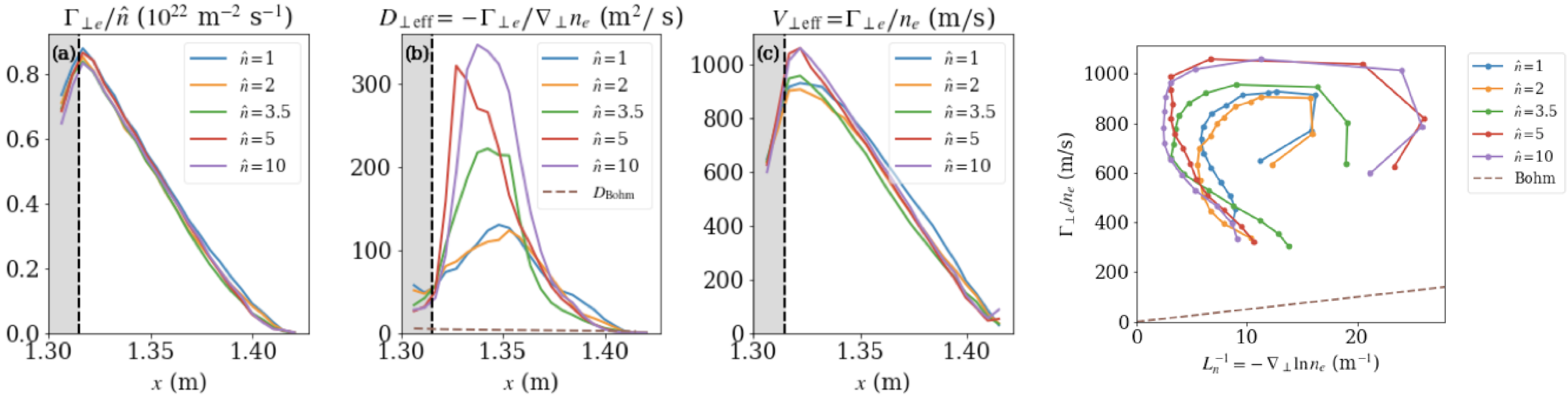


Particle balance and transport

- Profiles in SOL set by balance between sources, cross-field (perpendicular) transport, and parallel transport, including parallel end losses to the walls
- In our simulations, a quasi-steady state is reached with sources balanced by end losses to sheath, so that $\nabla \cdot \vec{\Gamma} = \nabla_\perp \cdot \vec{\Gamma}_\perp + \nabla_\parallel \Gamma_\parallel = S$
- Radial BCs do not allow particles to leave side-walls of domain



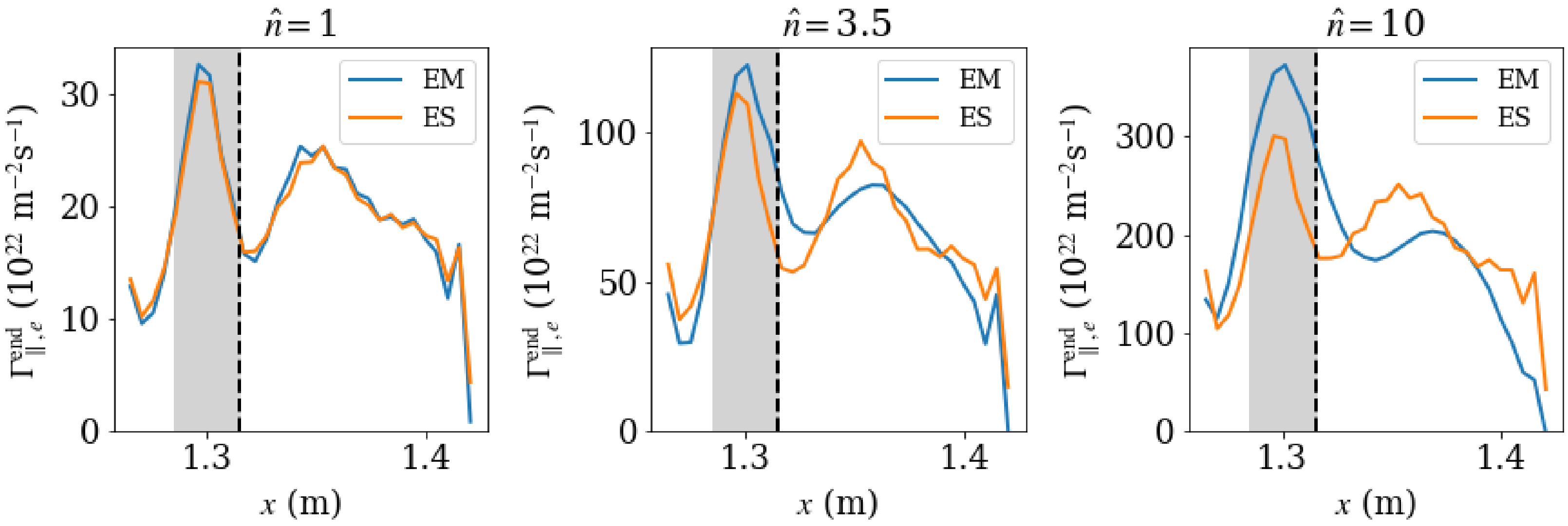
Cross-field electron transport at mid-plane



- Particle flux scales linearly with $\hat{n}$, profile does not change much
- If there is clear scale separation between background and fluctuations, the transport can usually be parametrized by an effective diffusivity and convective velocity $\Gamma_\perp = nV_\perp - D_\perp \nabla_\perp n$
- No such separation in SOL! Transport is non-local and non-diffusive, with large fluctuations and intermittency

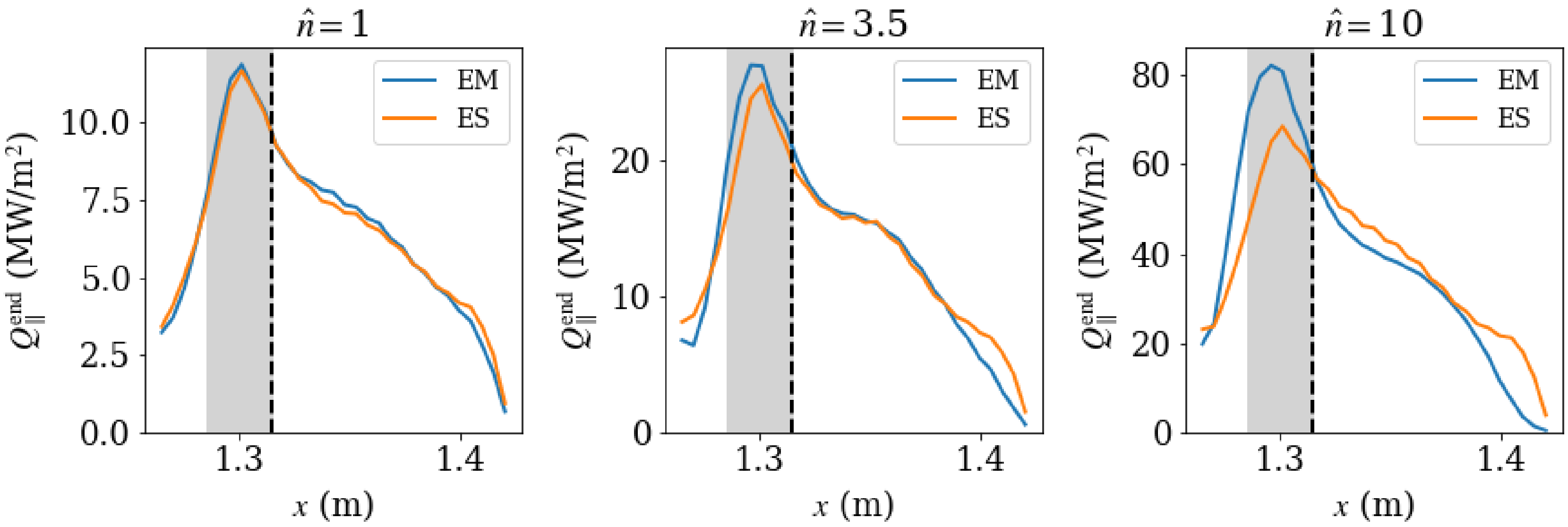
Parallel transport: particle flux to end-plates

- Particle flux profiles on endplates show end result of competition between perp. and parallel transport in SOL, with turbulence widening the flux width
- Reduced radial transport upstream due to magnetic flutter results in ~10% higher peak electron particle fluxes than in ES case



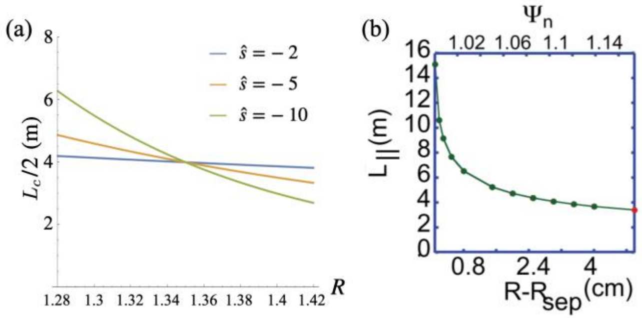
Parallel transport: heat-flux to end plates

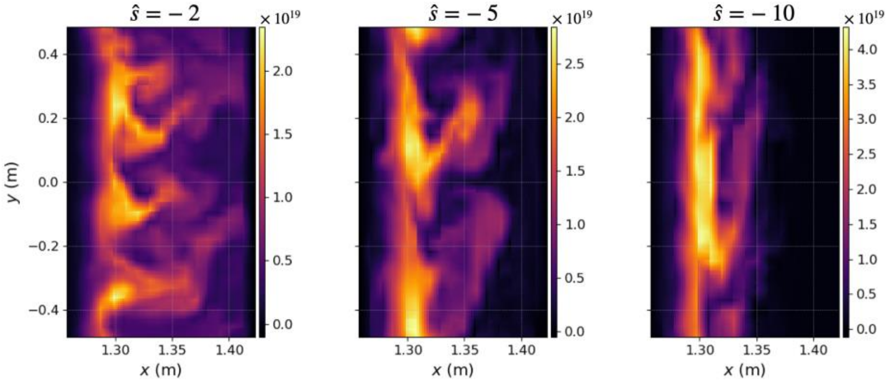
- Peak (ion+electron) heat flux increases with in EM cases, with 20% increase over ES in $\hat{n} = 10$ case
- Heat flux widths are still much too wide compared to experiment (with SOL widths centimeters), but interesting that EM effects increase peak heat flux for our parameters/setup
- In experiment, narrow grazing angle of field lines on divertor plates reduces component of heat flux perpendicular to wall $Q_{\parallel,\perp} = Q_{\parallel}\cos\theta$. Not included here.

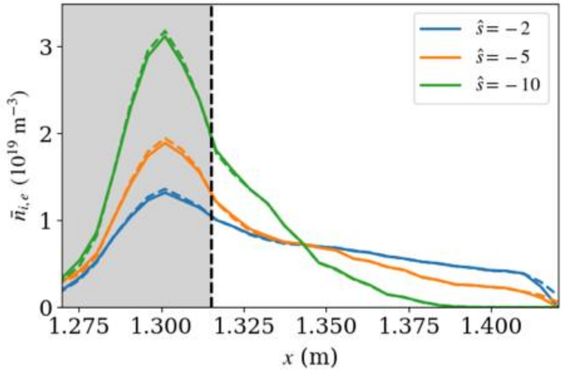


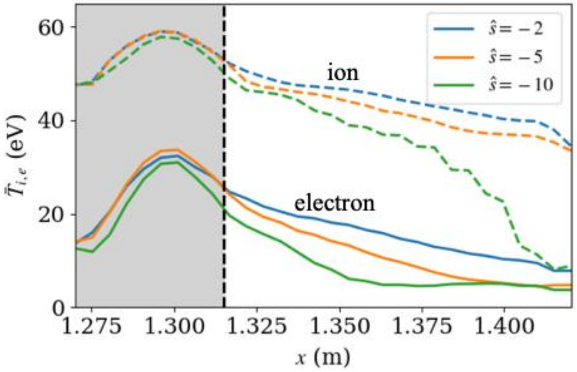
Including magnetic shear leads to steeper profiles

- Magnetic shear reduces perpendicular transport leading to steeper profiles









Summary and future outlook

- We now have unique capabilities to simulate electromagnetic turbulence and transport dynamics in the tokamak edge/SOL
  - Electromagnetic effects are critical to understanding phenomena such as the pedestal and ELMs
  - First electromagnetic gyrokinetic simulations on open field lines
  - Electromagnetic fluctuations handled stably and efficiently
- We showed how electromagnetic effects can affect blob dynamics and transport, resulting in line-tied ballooning structure, gradient steepening, and more peaked fluxes to the endplates
  - Could have implications for pedestal formation, transport of high β blobs and ELMs
- Future steps, such as coupled pedestal/SOL modeling and X-point geometry, will build on this work and allow detailed comparisons with experiments and predictions