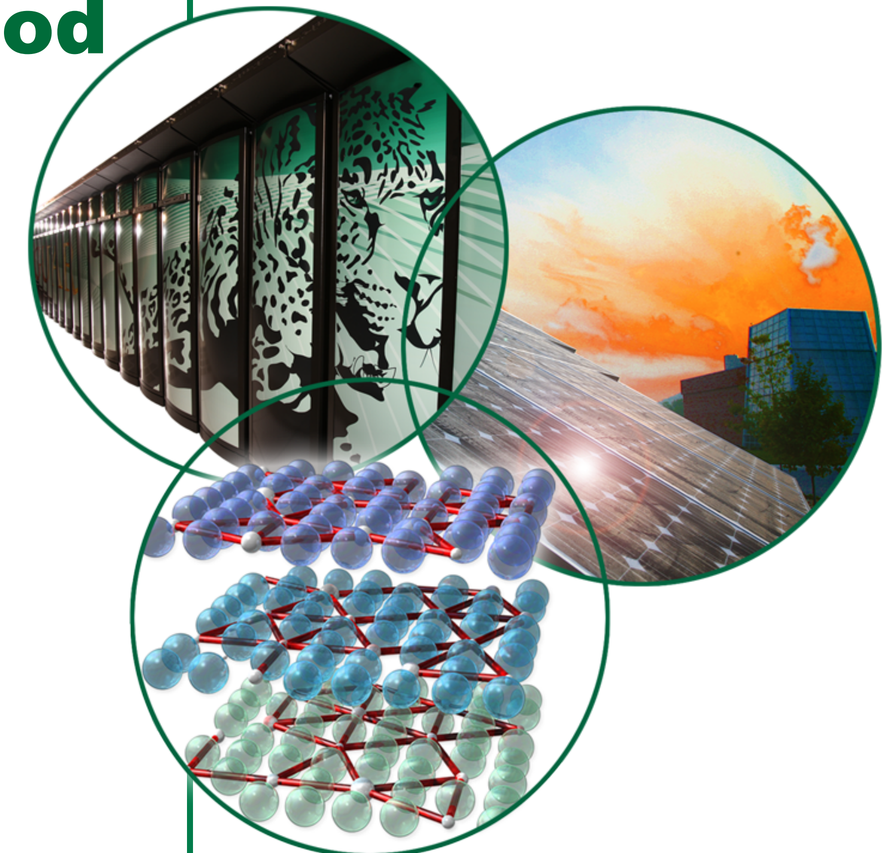
3D modeling of toroidal asymmetry due to localized divertor nitrogen puffing on Alcator C-Mod



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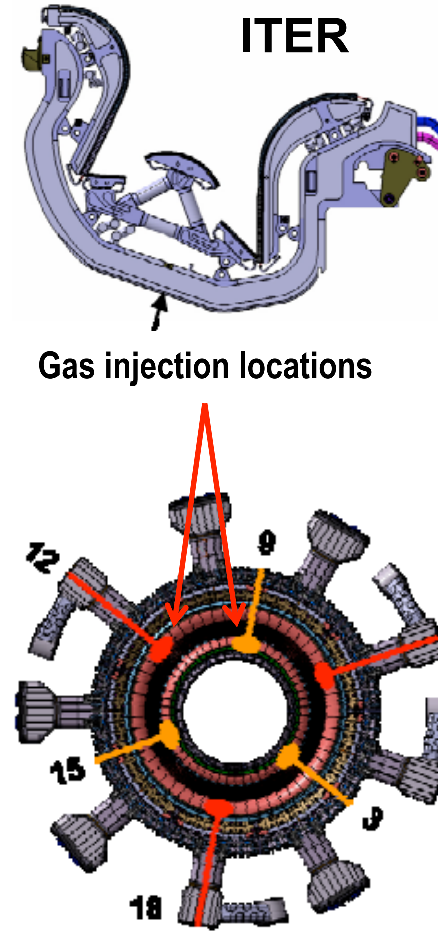
ITER requires partially detached divertor plasmas

- **During inductive operation at Q=10, ITER must run with partially detached divertor plasmas**
- **A set of divertor gas valves will be used to maintain the radiated power fraction**
  - **Toroidally localized injection may lead to asymmetry in radiated power, detachment, heat flux**
- **Experiments were run on Alcator C-Mod to investigate potential asymmetry**
  - **Clear toroidal variation in radiated power, impurity line emission, divertor conditions measured with a single divertor puff**
  - **Experiments led to increasing the number of injection locations from 3 to 6 in ITER**
- **3D modeling using the scrape-off-layer transport code EMC3-EIRENE is in progress to model these experiments**
  - **Goal: Validate model on C-Mod, then run predictive simulations for ITER**

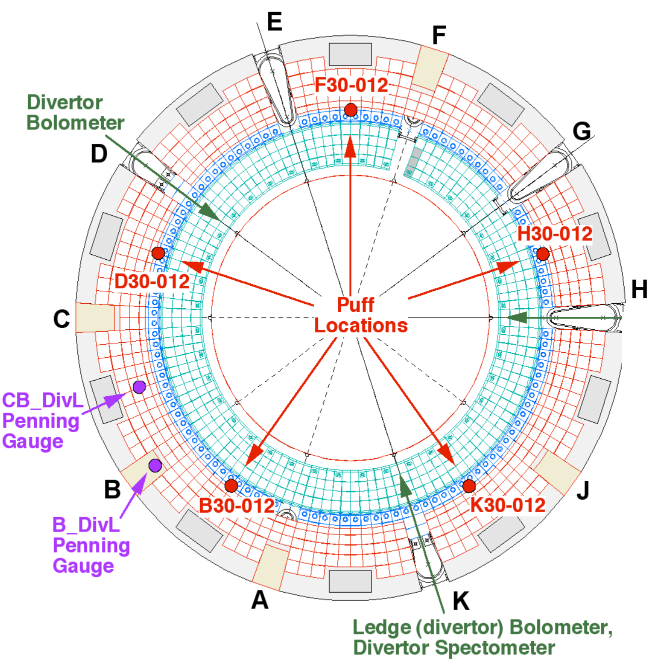


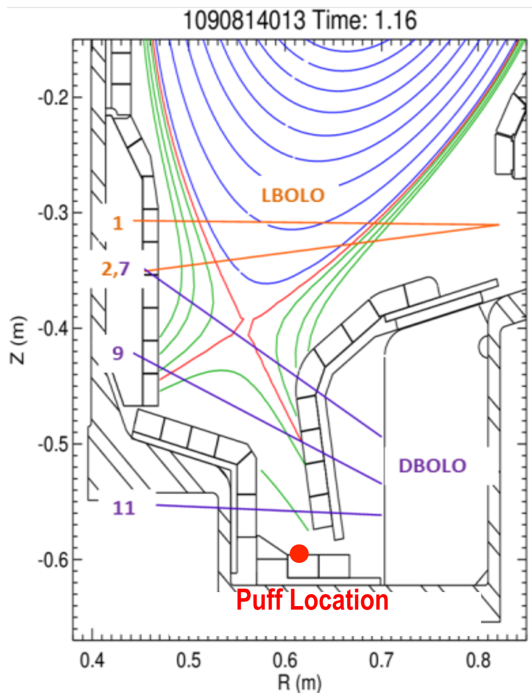
Outline

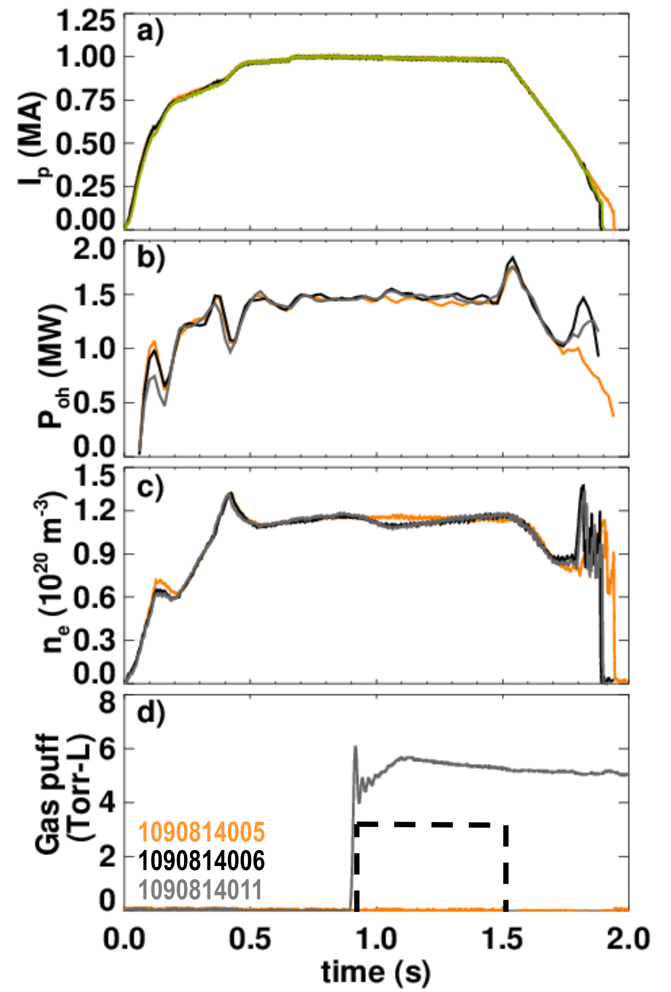
- C-Mod experiments with divertor gas injection
- The EMC3-Eirene Code
- Experimental and simulated trends in divertor pressure, radiated power, and nitrogen line emission
- Predicted asymmetry in divertor heat flux due to a single gas injection location
- Summary

C-Mod Experiments were Performed with Toroidally Localized Divertor Gas Injection

- Set of 10 reproducible discharges: 1090814(006-016)
  - Ohmic L-Mode, I_p=1MA, B_t=5.4T, n_e~1.1e20 m^{-3}, q_{95}~3.75
  - Divertor is in the high recycling regime
- N_2 injected into divertor at ~0.9s through a single valve each shot → gas location shifts relative to diagnostics
  - Gas location analogous to ITER conditions

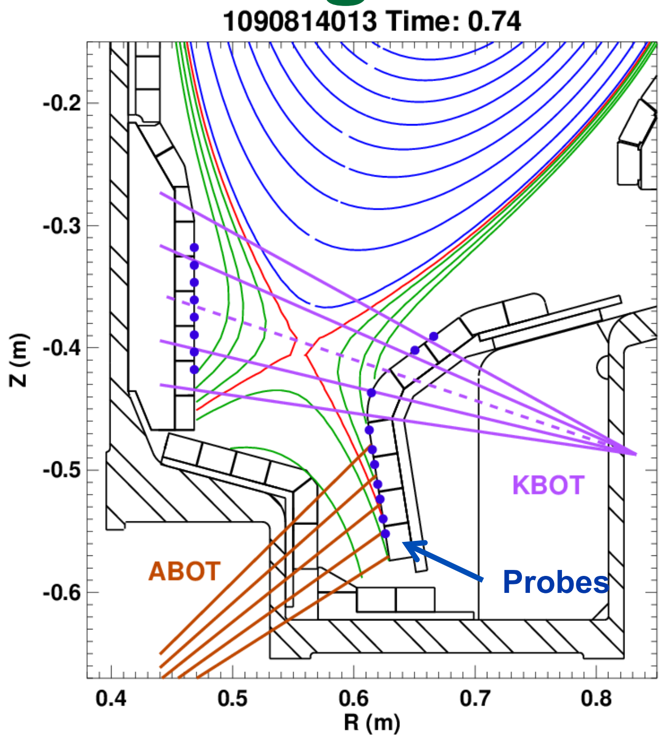


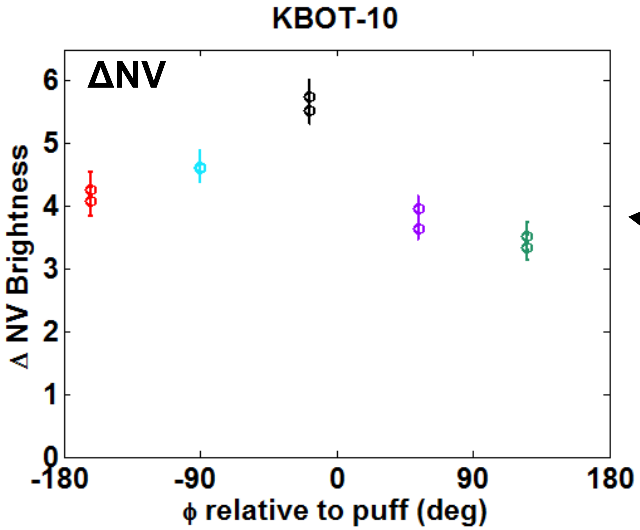


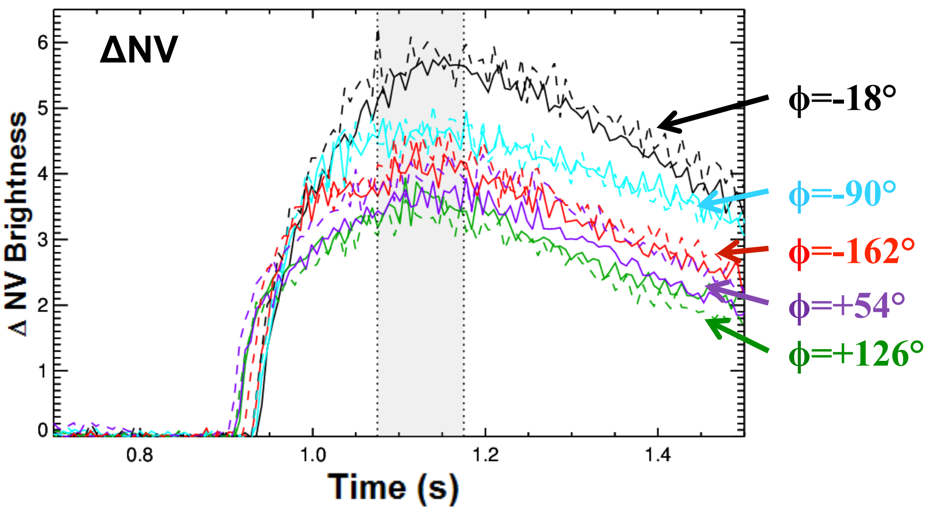


Reproducible toroidal asymmetry is measured in edge and divertor diagnostics

- Experiments are well diagnosed, with many divertor and SOL views to constrain and validate modeling
- Toroidal modulation measured in nitrogen line emission, P_{rad}, and divertor electron pressure

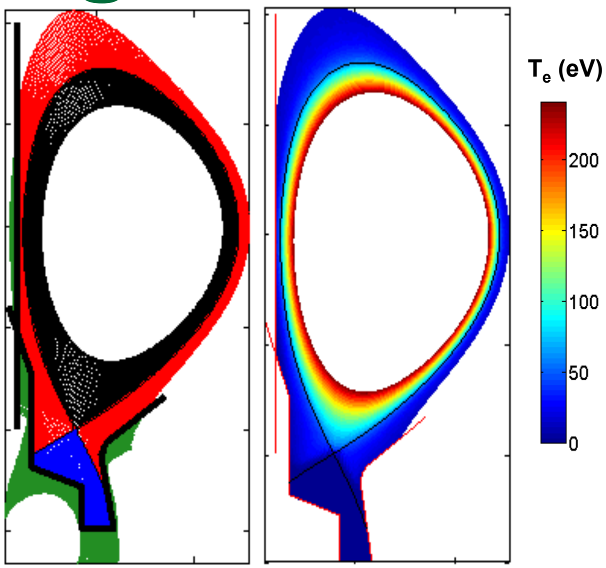


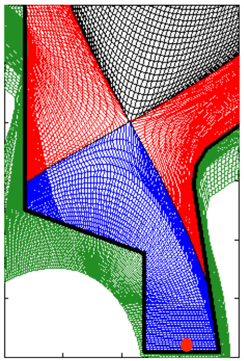




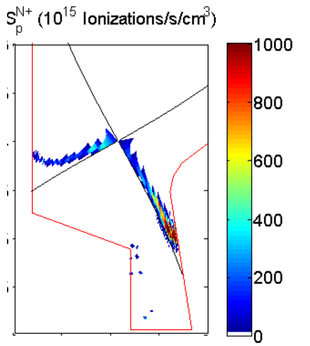
Experiments are modeled using the 3D EMC3-Eirene code

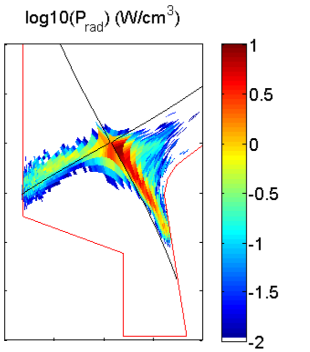
- The EMC3-Eirene code[1]
  - 3D fluid plasma model (EMC3) coupled to kinetic neutral transport and PSI (EIRENE)
  - Classical parallel transport with prescribed anomalous cross-field diffusivities
  - Trace fluid impurity model ($T_a=T_i, n_a Z_a << n_i$) with feedback to main plasma through electron energy loss
  - Outputs: 3D neutral and fluid plasma quantities, surface loads on to PFCs
  - No cross-field drifts or kinetic corrections
- Simulation of N puff experiments
  - High resolution, full toroidal grid with single N^0 puff in divertor
  - Inputs: P_{core}=1.25MW, n_{core}=1e20m^{-3}, constant cross-field diffusivities, N^0 strength from puff calibration, R_{imp}=0.5
  - PFR is largely transparent to N^0, ionization occurs near separatrix
  - Impurity radiation largest in flux tubes connecting to the divertor near the outer strike point





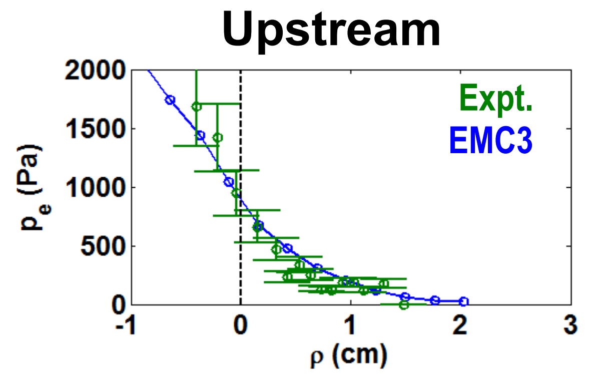
Puff Location

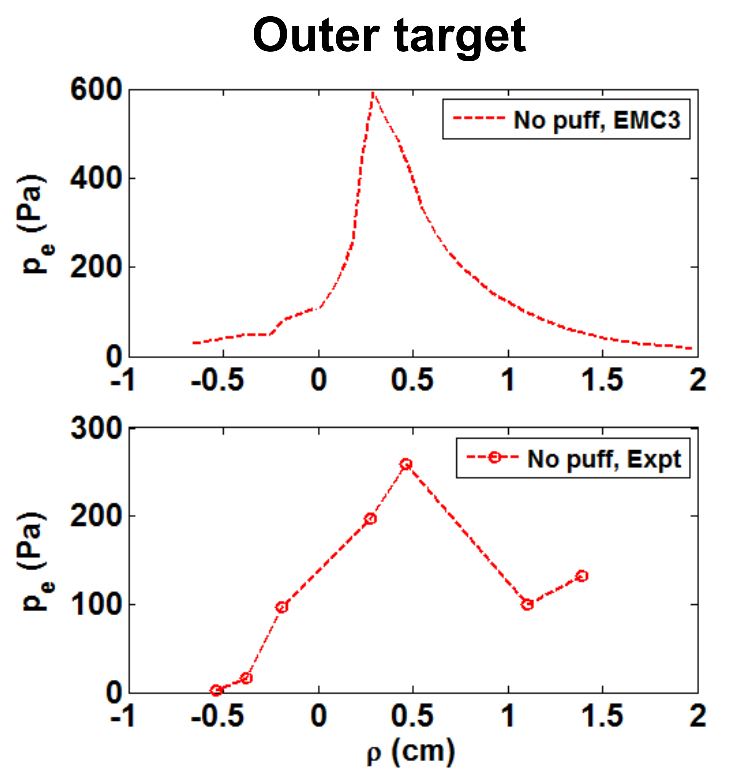




Impurity puff results in net pressure drop with toroidal modulation

- Upstream pressure approximately matched with constant cross-field coefficients
  - Downstream pressure within ~2x, radially varying coefficients could be used to better match





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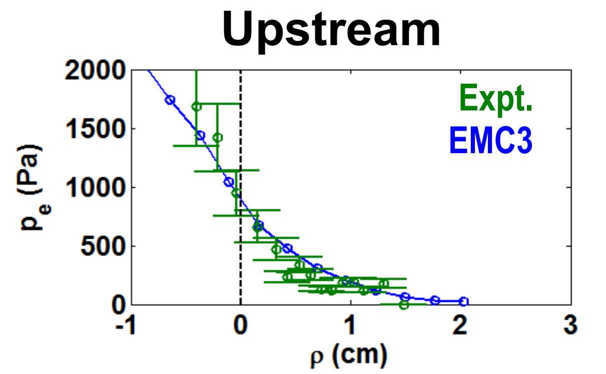
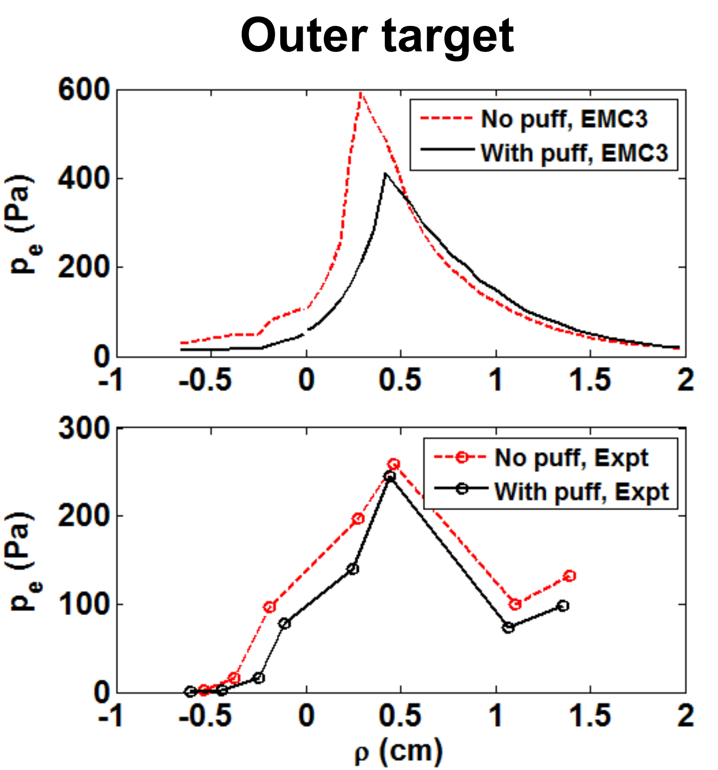
- Toroidally averaged divertor profiles:
  - Net (n=0) pressure drop in experiment and model





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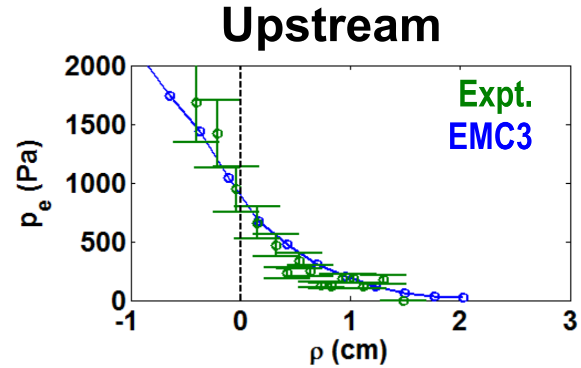

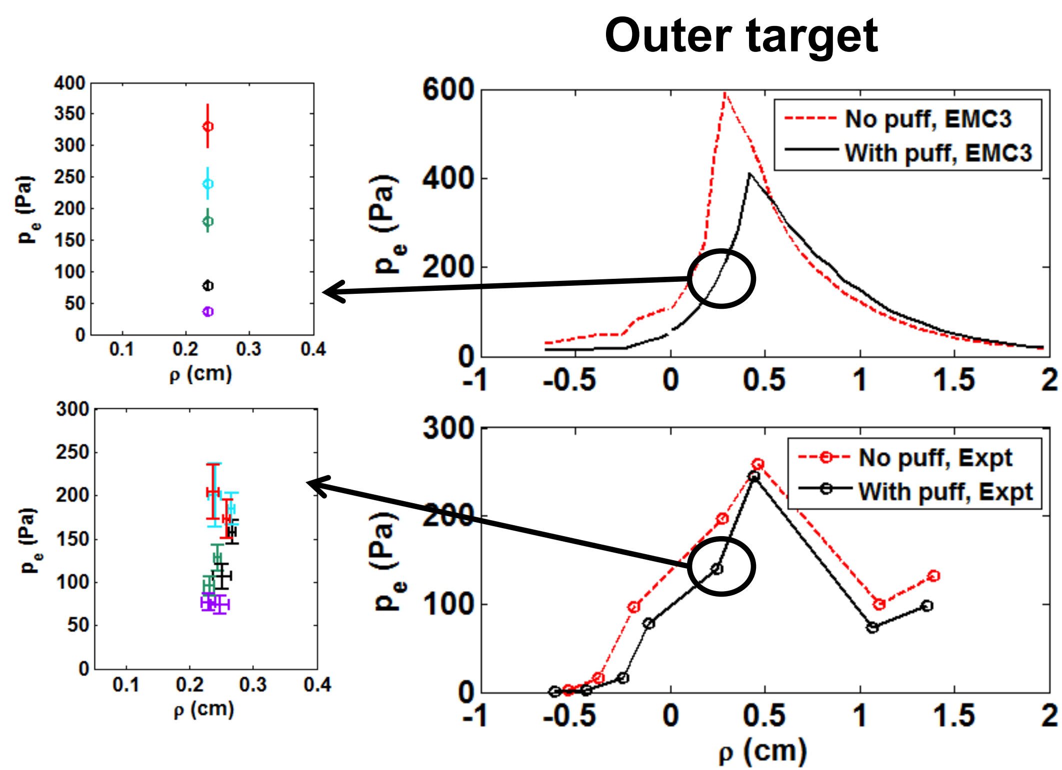

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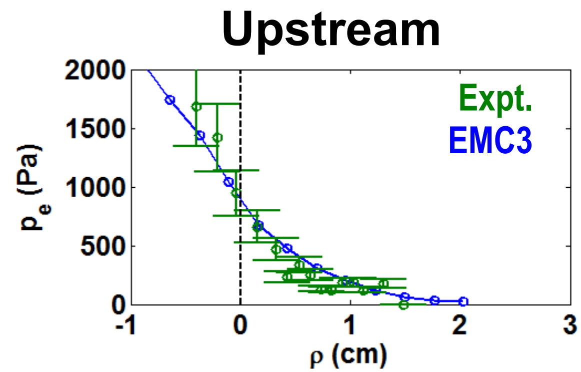
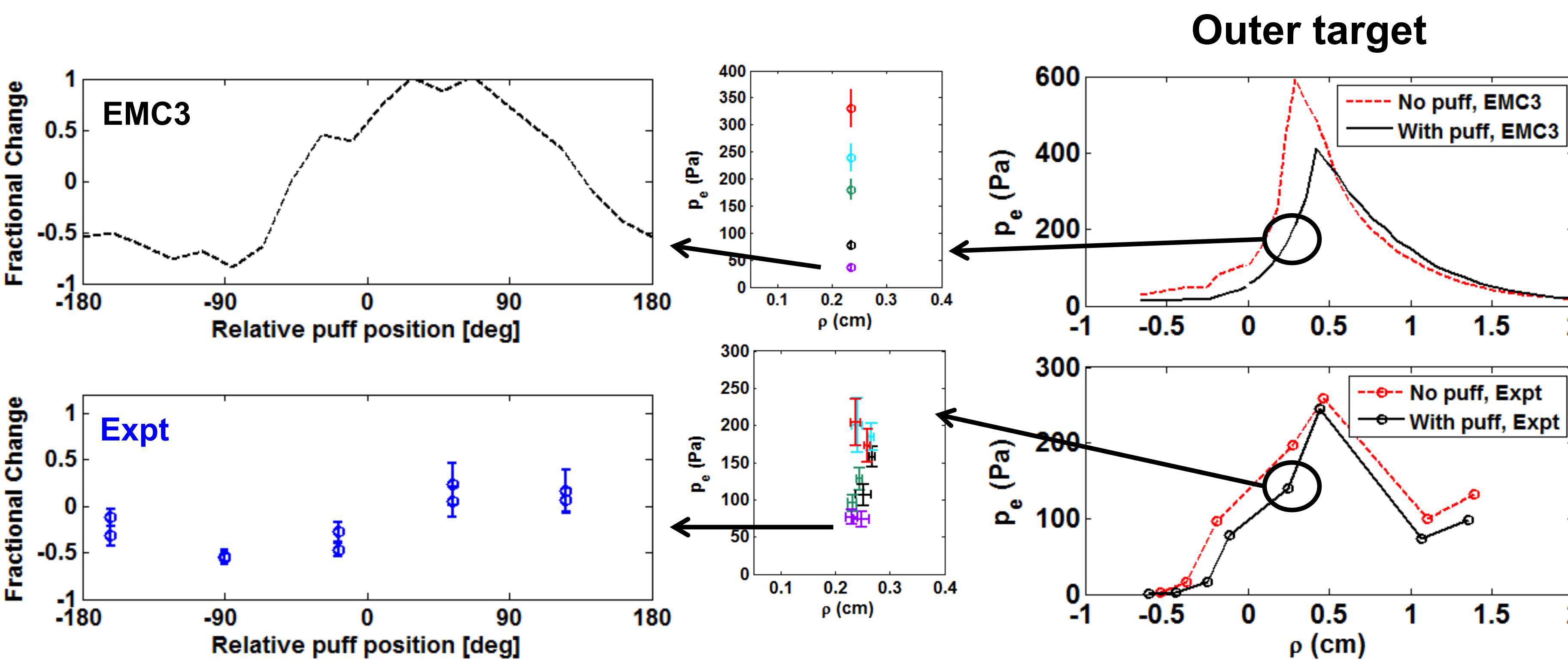
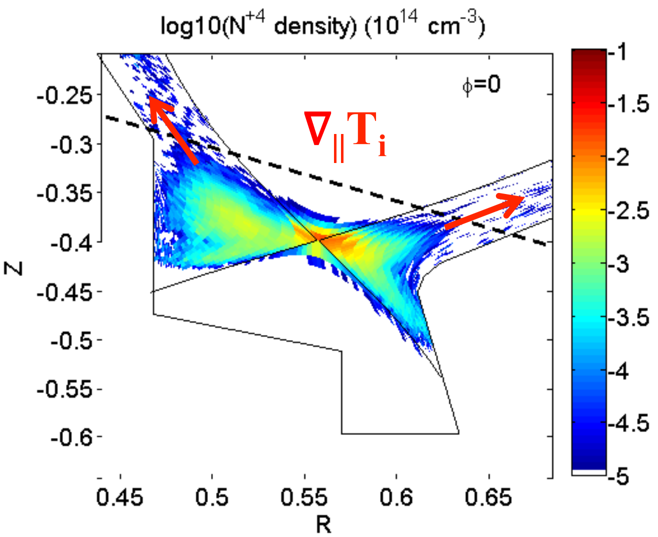
  - n≈1 toroidal variation in pressure qualitatively captured by model

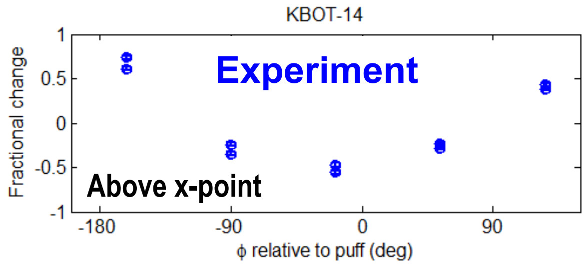


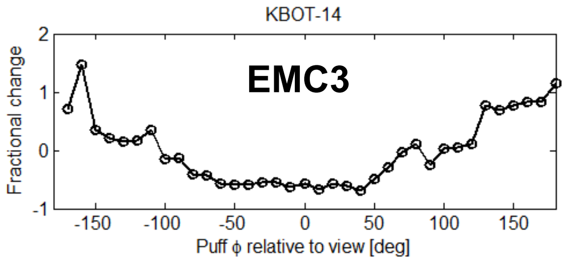


Trends in N line emission captured near x-point, PFR may require cross-field drifts

- Clear toroidal asymmetry in NV emission in chords viewing near x-point
- Above x-point temperature gradient force pushes impurities upstream into view, results in inverted profile







[1] Smick et al., Nucl. Fusion 53 (2013) 023001.
[2] Boswell et al., J. Nucl. Mater. 290-293 (2001) 556

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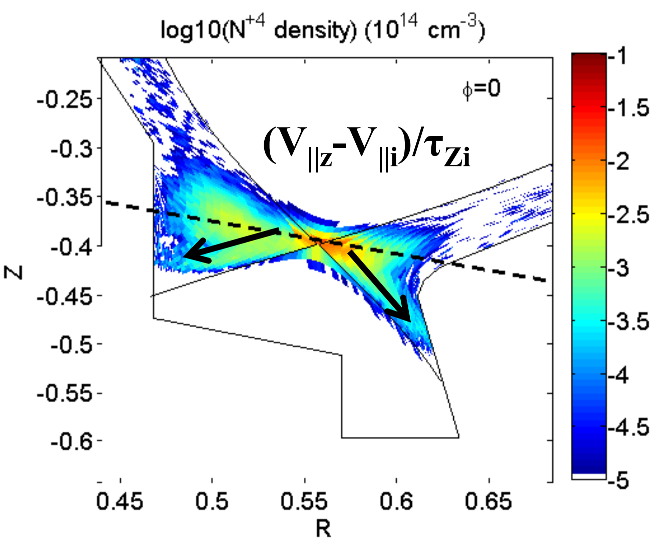
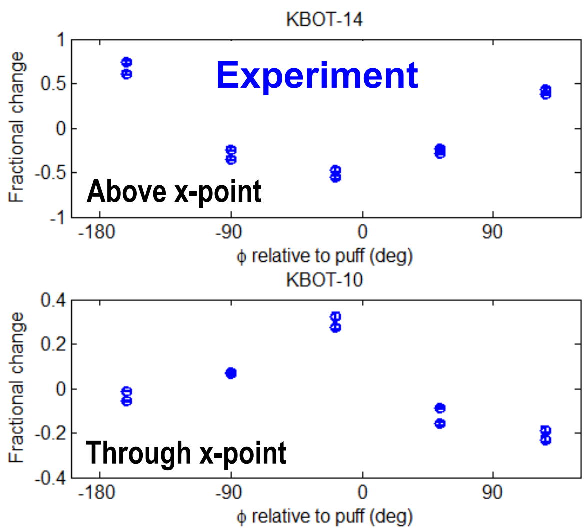
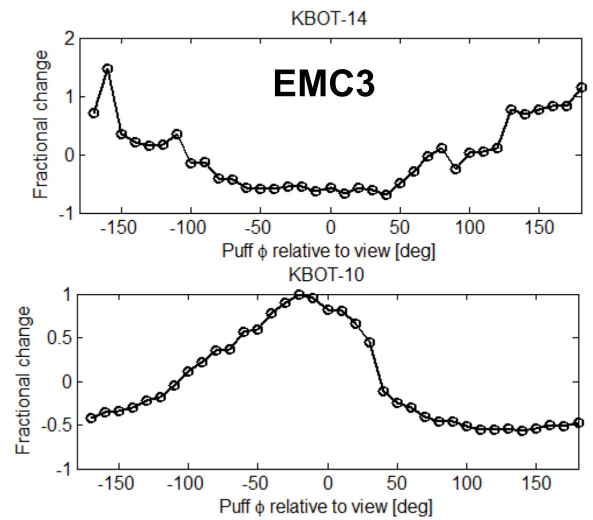
- View through x-point peaked at puff location, main ion friction dominates, pulls impurities out of view
- Toroidal behavior seems to be well described by parallel impurity forces in SOL near x-point







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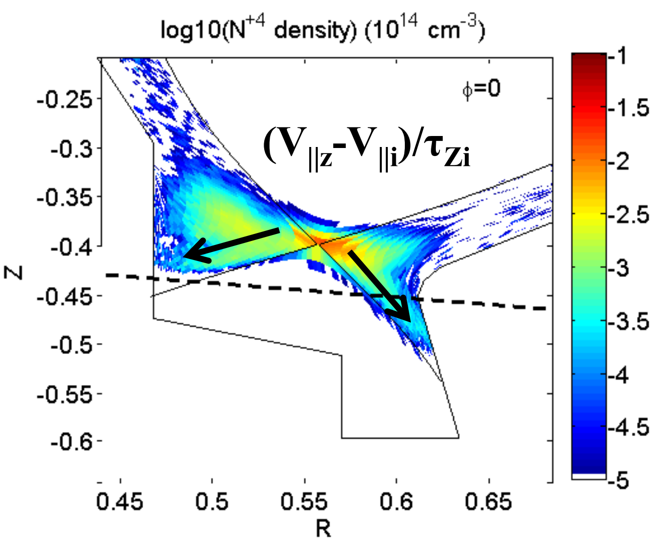
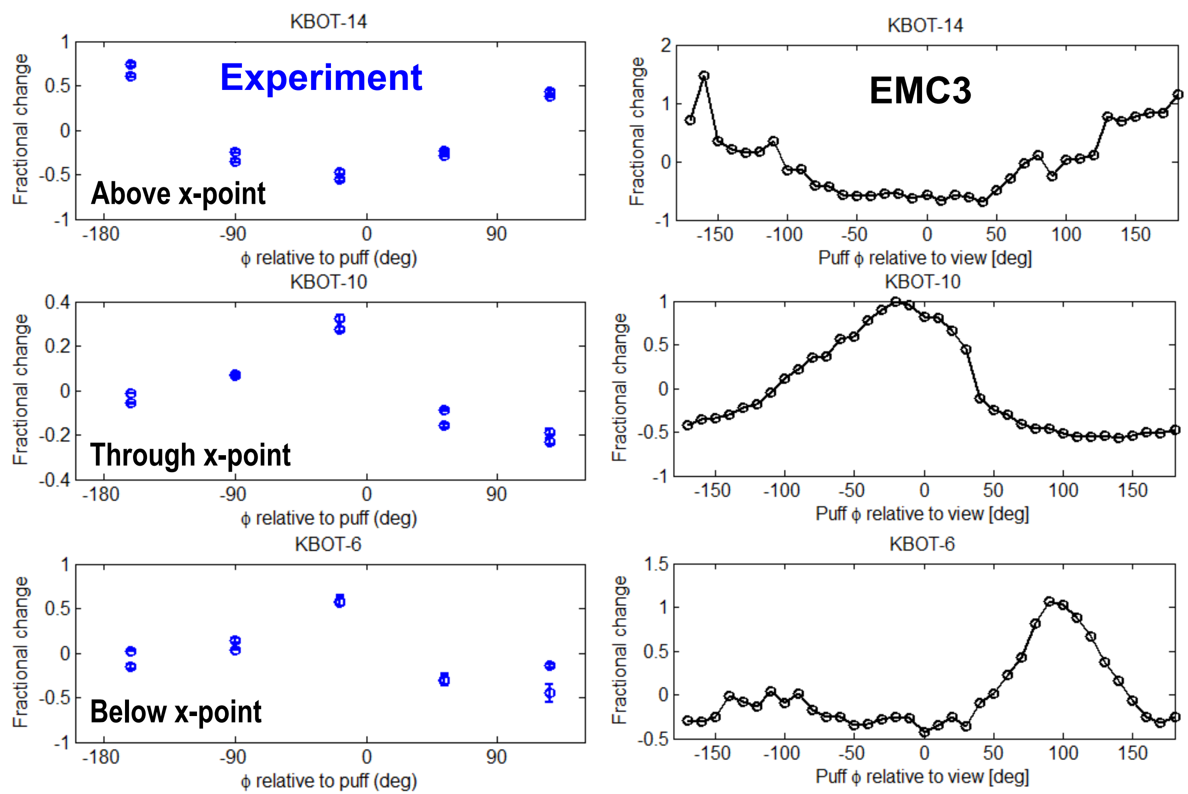
- Above x-point temperature gradient force pushes impurities upstream into view, results in inverted profile
- View through x-point peaked at puff location, main ion friction dominates, pulls impurities out of view
- Toroidal behavior seems to be well described by parallel impurity forces in SOL near x-point
- Below x-point: Friction dominates in model, results in in downstream peaking. Experiment peaked at puff loc.
  - Cross-field drifts may be required to capture impurity behavior in PFR, experiments have demonstrated importance [1,2]





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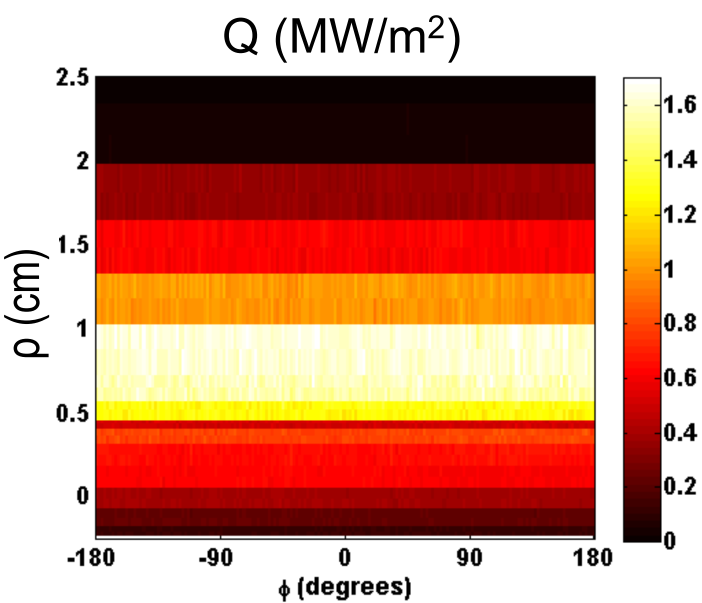
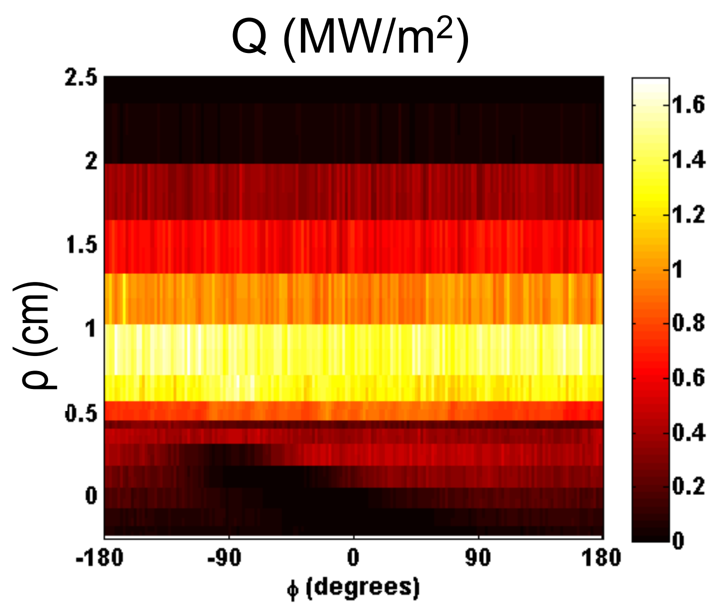
Toroidally asymmetry in target heat flux predicted near outer strike point

- Impurity radiation results in net reduction in power carried by plasma to targets
  - P_{targ}^{plasma} reduced from 930kW to 730kW (P$_{in}$=1.25MW)
- Toroidal asymmetry in P$_{rad}$ results in toroidal asymmetry in heat flux near outer strike point
  - Toroidal extent will depend on machine size, divertor geometry

No puff



With puff



Summary

- C-Mod experiments were performed to assess toroidal asymmetry caused by local divertor impurity injection for ITER
- The 3D edge transport code EMC3-Eirene has been applied to model these experiments
  - Validation will give confidence in predictive simulations for ITER
- Measured net reduction and toroidal variation in divertor pressure at OSP are qualitatively reproduced
- Modeled toroidal asymmetry in NV emission near x-point have similar trends as experiment, however cross-field drifts are likely required to match behavior in PFR
- Toroidal asymmetry in target heat flux is predicted with a single divertor injection location
- Ongoing work: Continue investigation of diagnostic data and model validation, quantify effect of multiple injection locations, determine scaling with machine size

Extra slides

EMC3-Eirene fluid equations

$$\nabla\cdot\left(n_i V_{i\parallel}\boldsymbol{b} - D\nabla_\perp n_i\right) = \boxed{S_p}$$

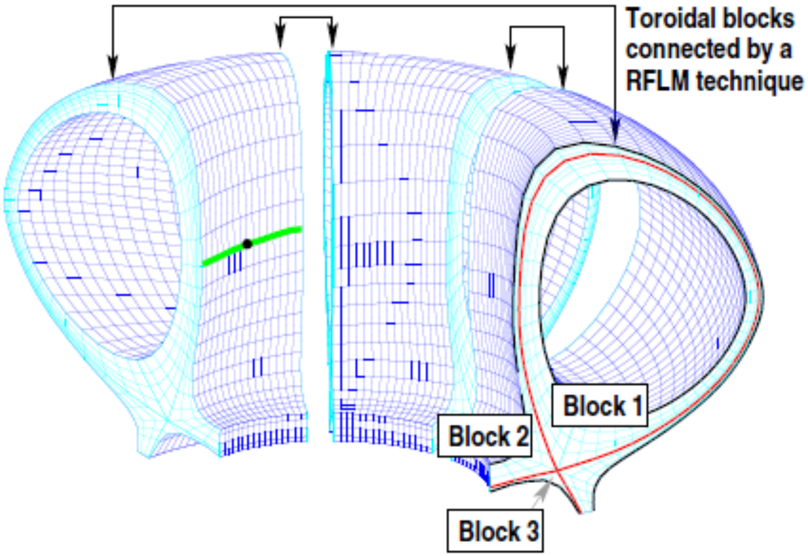
$$\nabla\cdot\left(m_i n_i V_{i\parallel} V_{i\parallel}\boldsymbol{b} - \eta_\parallel \nabla_\parallel V_{i\parallel} - m_i V_{i\parallel} D\nabla_\perp n_i - \eta_\perp \nabla_\perp V_{i\parallel}\right) = -\nabla_\parallel p + \boxed{S_m}$$

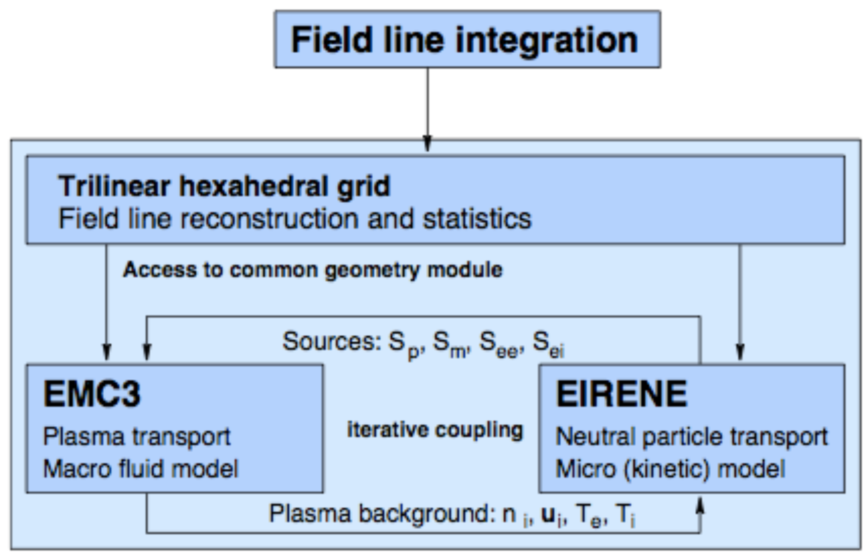
$$\nabla\cdot\left(\tfrac{5}{2} n_e T_e V_{i\parallel}\boldsymbol{b} - \kappa_e \nabla_\parallel T_e - \tfrac{5}{2} T_e D\nabla_\perp n_e - \chi_e n_e \nabla_\perp T_e\right) = -k\left(T_e - T_i\right) + \boxed{S_{ee}} + \boxed{S_{imp}}$$

$$\nabla\cdot\left(\tfrac{5}{2} n_i T_i V_{i\parallel}\boldsymbol{b} - \kappa_i \nabla_\parallel T_i - \tfrac{5}{2} T_i D\nabla_\perp n_i - \chi_i n_i \nabla_\perp T_i\right) = +k\left(T_e - T_i\right) + \boxed{S_{ei}}$$

Sources from plasma-neutral interactions provided by Eirene

Trace impurity model





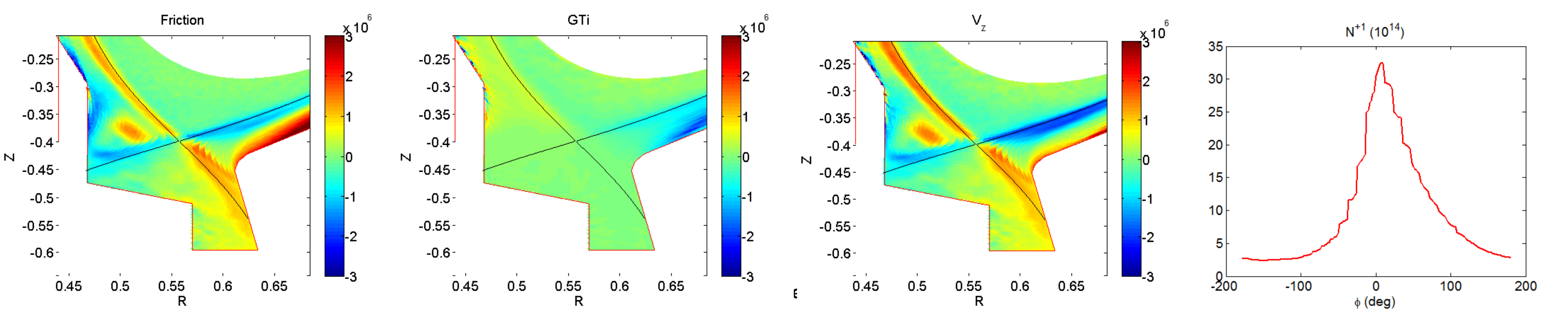
Feng, J. Nucl. Mater. (1999)

Impurity forces in EMC3

$$V_z - V_i \sim \frac{T_i^{3/2}}{n_e} \nabla_{\parallel} T_i$$

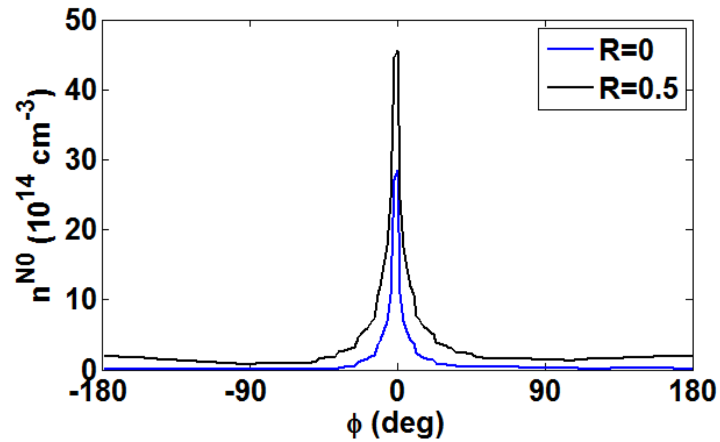
$$0 = \underbrace{-\frac{1}{n_z}\nabla_{\parallel} p_z}_{\text{Impurity pressure gradient}} + \underbrace{m_z \frac{(V_i - V_z)}{\tau_{Zi}}}_{\text{Main ion friction}} + \underbrace{eZ_z E_{\parallel}}_{\text{Electro-static}} + \underbrace{\alpha_{Ze} \nabla_{\parallel} T_e}_{\text{Electron Temp. Gradient}} + \underbrace{\beta_{Zi} \nabla_{\parallel} T_i}_{\text{Ion Temp. Gradient}}$$

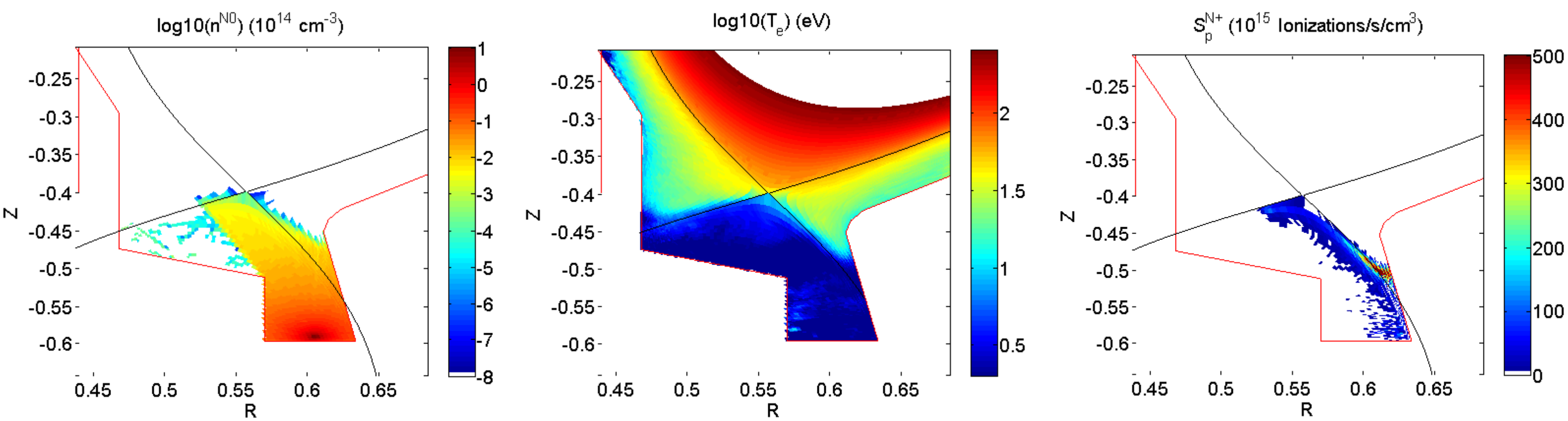
- **Dominant forces are friction and ion temperature gradient, and independent of Z**
  - **Divertor temperature is low, friction dominates in PFR**
  - **Non-recycling neutrals are trapped in PFR**
- **Experiments have shown evidence of drifts in SOL and PFR, not accounted for in this model**



Impurity ionization in PFR

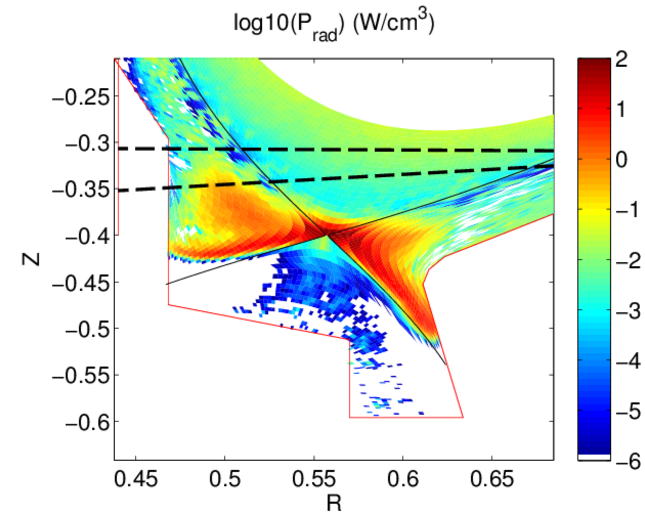
- Gas injection is deep in divertor
- Plasma is nearly transparent to neutrals, ionization occurs near separatrix where T_e>10eV

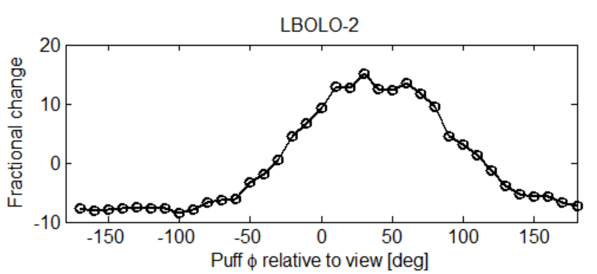


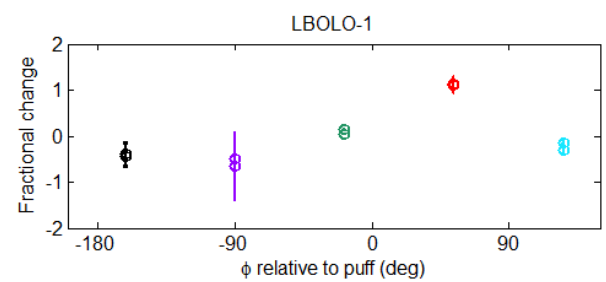


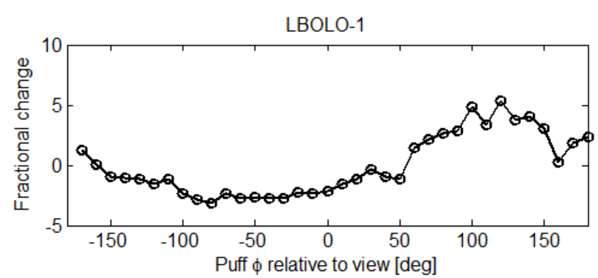
Comparison to ledge bolometers

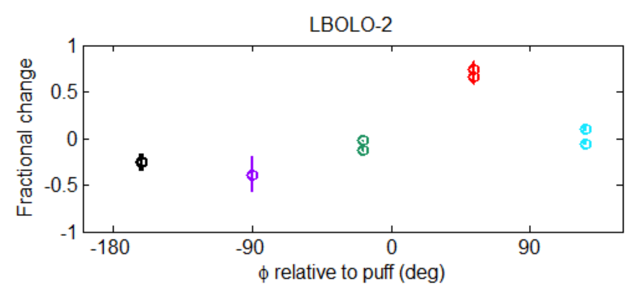
- Similar trends in LBOLO, large discrepancies in DBOLO
  - Strike point position is critical for DBOLO

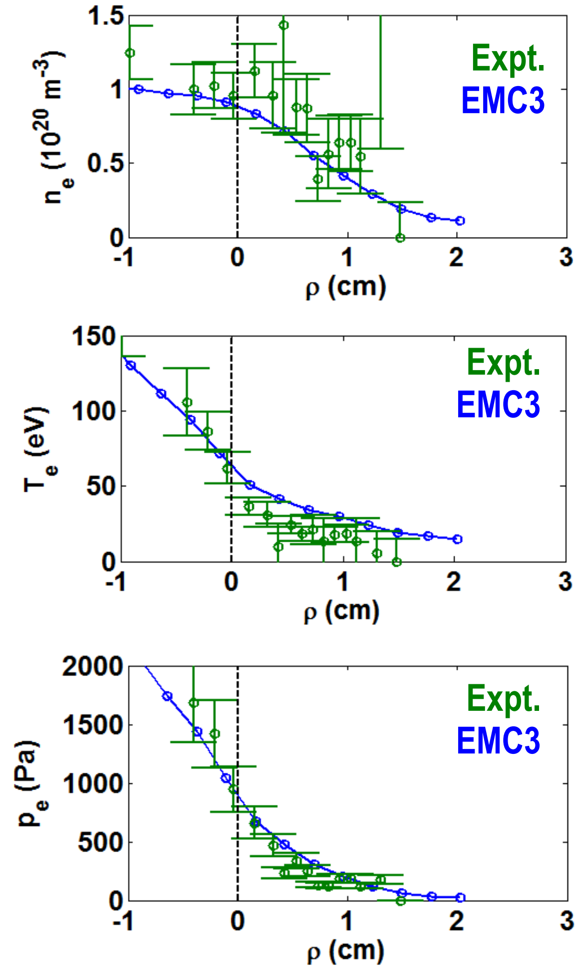


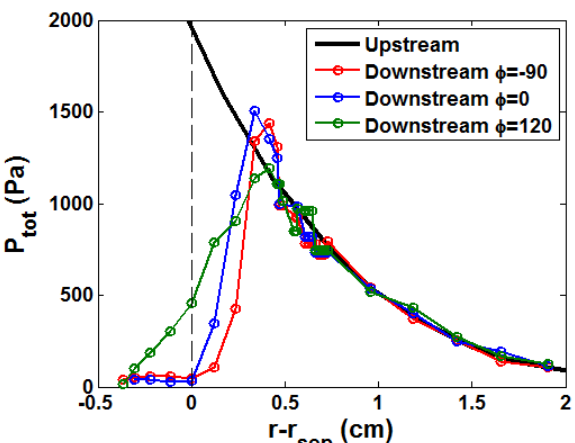


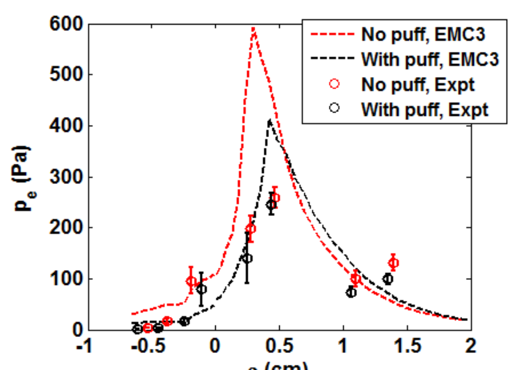







Expt.
EMC3
n_e (10^{20} m^{-3})
ρ (cm)
T_e (eV)
p_e (Pa)


Upstream
Downstream ϕ=-90
Downstream ϕ=0
Downstream ϕ=120
P_{tot} (Pa)
$r-r_{sep}$ (cm)


No puff, EMC3
With puff, EMC3
No puff, Expt
With puff, Expt
p_e (Pa)
ρ (cm)