Modeling neutral-plasma interactions in scrape-off layer (SOLT) simulations*

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Abstract

The 2D scrape-off-layer turbulence (SOLT) code has been enhanced by the addition of kinetic-neutral physics. Plasma-neutral interactions include charge exchange (CX) and ionization (IZ). Under the assumption that the CX and IZ collision rates are independent of the ion-neutral relative velocity, a 1D (radial: x) Boltzmann equation has been derived [1] for the evolution of the (v_y,v_z)-averaged neutral distribution function (G), and that evolution has been added to SOLT. In first exercises of this new capability, the CX and IZ rates are determined by the poloidally (y) averaged plasma density and temperatures, and $G = G(x,v_x,t)$. (The neglect of the y-dependence may be justified for the long neutral mean free paths of the SOL.) Results from 1D simulations that use diffusion as a proxy for turbulent transport are presented to illustrate the capability and establish essential benchmarks, including the approach to a steady state driven by sustained neutral injection in the far-SOL and realistic heating in the core. Neutral density and energy profiles are obtained for the resulting *self-consistent* plasma profiles. Neutral drag of the poloidal ExB flow and the effect of CX on radial ExB shear rates are illustrated. Progress on 2D turbulence simulations is reported.

[1] J. R. Myra, this workshop: poster B-23.

Outline

Summary of Model Equations

Kinetic Neutrals added to SOLT

- evolved by up-wind free-streaming and Runge-Kutta
- run with NSTX-like parameters
- injected at the far-SOL boundary as Franck-Condon dissociated D_2
- (A recycling b.c. is built-in but not exercised here.)

Illustrating the capability in 1D (future work: with turbulence)

- compare core-fueled and neutral-fueled plasmas *in equilibrium*
- NSTX ~ Ohmic and ~ H-mode plasmas recovered for certain choices of neutral source amplitude (“n_{puff}”) and electron heating in the core (S_{Pe}).

Neutral diagnostics in development

- MFP and energy flux profiles suggest origins of hot (CX) neutrals reaching the wall and deposition domains for cold injected neutrals.

Conclusions

Model Equations
J.R. Myra, poster B-23

- Kinetic Neutrals + SOLT Plasma in 1D
- No Fluctuations (Blobs): $\partial_y = 0$ and $v_{Ex} \sim \partial_y \phi = 0$
- **We use Radial Diffusion as a Proxy for Turbulent Transport**

Boltzmann Neutrals (G)

$$\partial_t G + v_x \partial_x G = h_{cx} n_0 \cdot F - h_{cx} n_i \cdot G - h_{iz} n_e$$

$$\partial_t v_{0y} + v_{0x} \partial_x v_{0y} = h_{cx} n_i \cdot \left(v_{Ey} + v_{diy} - v_{0y} \right)$$

This 1D neutral evolution accommodates 2D plasma fluctuations via $n_i \rightarrow \langle n_i(x,y,t) \rangle_y$, etc.

where :

$$n_0 = \int dv_x G(x,v_x,t) \ , \ v_{0x} = \int dv_x v_x G(x,v_x,t) / n_0 \ , \ n_0 E_0 = \frac{3}{2} \int dv_x v_x^2 G(x,v_x,t)$$

$F = \exp\left[-v_x^2 / (2T_i(x,t)) \right] / (2\pi T_i(x,t))^{1/2}$: Maxwellian, isotropic ions

charge exchange* (CX) : $h_{cx} = h_{cx0} \cdot T_i(x,t)^{0.3}$

ionization* (IZ) : $h_{iz} = h_{iz0} \cdot T_e(x,t)^{1/2} \exp\left[-E_{iz} / T_e(x,t) \right] / (1 + 0.01 \cdot T_e(x,t))$

*D. P. Stotler et al., 26th IAEA Fusion Energy Conference, Kyoto, Japan 17-22 October 2016, IAEA-CN-234/TH/P6-7. N. Horsten et al., Phys. Plasmas **23**, 012510 (2016). R. J. Goldston and P. H. Rutherford, Introduction to Plasma Physics, CRC Press (1995). V. Rozhansky et al., Nucl. Fusion 41(4), 387 (2001).

Model Equations (cont.)

SOLT Plasma* + Neutrals

sources in the core, sinks in the SOL
diffusive transport, CX and IZ *everywhere*

Diffusive Radial Transport
No Blobs in 1D

$$\partial_t n_i = \partial_x(D_n \partial_x n_i) + S_n + h_{iz} n_0 n_e - \nabla_{||}\Gamma_{||}$$

$$\partial_t T_e = \partial_x(D_{Pe} n_e \partial_x T_e)/n_e - T_e \partial_x(D_n \partial_x n_e)/n_e + (S_{Pe} - T_e S_n)/n_e +$$

$$-h_{iz} n_0 \left(\frac{2}{3} E_{iz} + T_e\right) - \frac{2}{3n_e}\nabla_{||} q_{e||} + \frac{T_e}{n_e}\nabla_{||}\Gamma_{||}$$

Bohm Units

$$\partial_t T_i = \partial_x(D_{Pi} n_i \partial_x T_i)/n_i - T_i \partial_x(D_n \partial_x n_i)/n_i + (S_{Pi} - T_i S_n)/n_i +$$

$$+(h_{iz} + h_{cx}) n_0 \left(\frac{2}{3} E_0 - T_i\right) - \frac{2}{3n_i}\nabla_{||} q_{i||} + \frac{T_i}{n_i}\nabla_{||}\Gamma_{||}$$

$$\partial_t \rho = \partial_x^2(D_\rho \rho) - \partial_x\left[h_{cx} n_0 n_i \cdot (v_{0y} - v_{Ey} - v_{diy}) + h_{iz} n_0 n_e \cdot v_{0y}\right] - \nabla_{||} j_{||}$$

where $\rho + \partial_x(n\partial_x\phi + \partial_x P_i) = 0$, $v_{Ey} = \partial_x\phi$, $v_{diy} = \partial_x P_i / n_i$

*Russell, Myra and D'Ippolito, Phys. Plasmas **16**, 122304 (2009).

Neutrals Evolution Algorithm

1) free-streaming: upwind linear interpolation

$$G^{(1)} = a(\mathrm{v})G(\mathrm{t,x,v}) + b(\mathrm{v})G(\mathrm{t,x-sign(v)dx,v}), \quad \max(|\mathrm{v}|)\frac{\mathrm{dt}}{\mathrm{dx}} < 1$$

2) CX: Runge-Kutta 2nd order

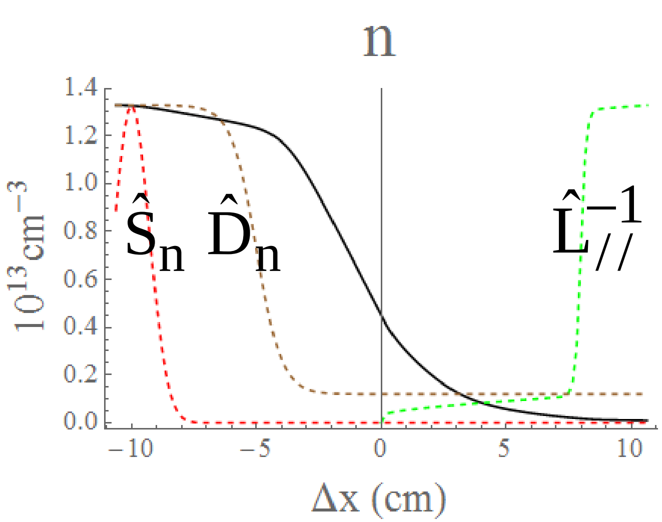
$$G^{(2)} = \left[G^{(1)} + \mathrm{dt}\cdot f_m(\mathrm{T_i})\cdot \mathrm{n_0 n}\cdot \mathrm{h_{cx}}\cdot(1+\tfrac{\mathrm{dt}}{2}\mathrm{h_{cx}n})\right]\cdot \exp\left[-\mathrm{dt}\cdot \mathrm{h_{cx}n}\right]$$

3) IZ: trivial $G(\mathrm{t+dt}) = G^{(2)}\cdot \exp\left[-\mathrm{dt}\cdot \mathrm{h_{iz}n}\right]$

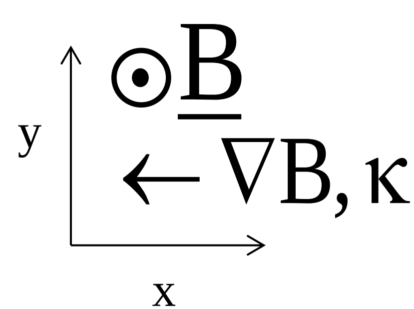
$\max(\mathrm{v}) \sim \mathrm{v_i} \sim \mathrm{c_s}$
$\mathrm{dx} \sim \rho_s$
$\Rightarrow \mathrm{dt} < \Omega_i^{-1}$
easily satisfied
in practice:
$\mathrm{dt} \sim 10^{-2}\Omega_i^{-1}$
set by
turbulence

Plasma Parameters : NSTX–like

ρ_s = 4.2 mm, $\Omega_i/2\pi$ = 2.6 MHz, c_s = 69 km/sec
Deuterium Plasma : $n_e = n_i = n$



2D (OM)



Neutrals are Injected at the SOL boundary

$$G(x = L_x, v_x < 0) = n_{puff} \cdot \exp[-(v_x - v_{D_2})^2 / 2T_{FC}] / (2\pi T_{FC})^{1/2}$$

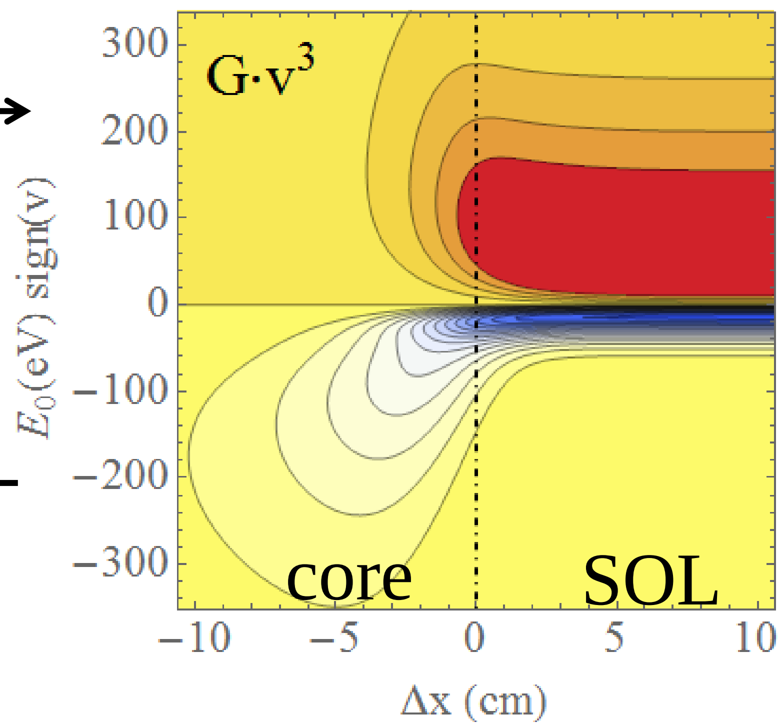
$$v_{D_2} = -0.8 \text{ km/sec}, \; T_{FC} = 3 \text{ eV}$$

Franck-Condon (FC) atomic deuterium neutrals dissociated from molecular D_2 leaving the wall at room-temperature (300°K)*

No neutrals enter at the core boundary: $G(v_x > 0) = 0$.

Neutrals free-stream out

neutral energy flux



CX neutrals free-stream out

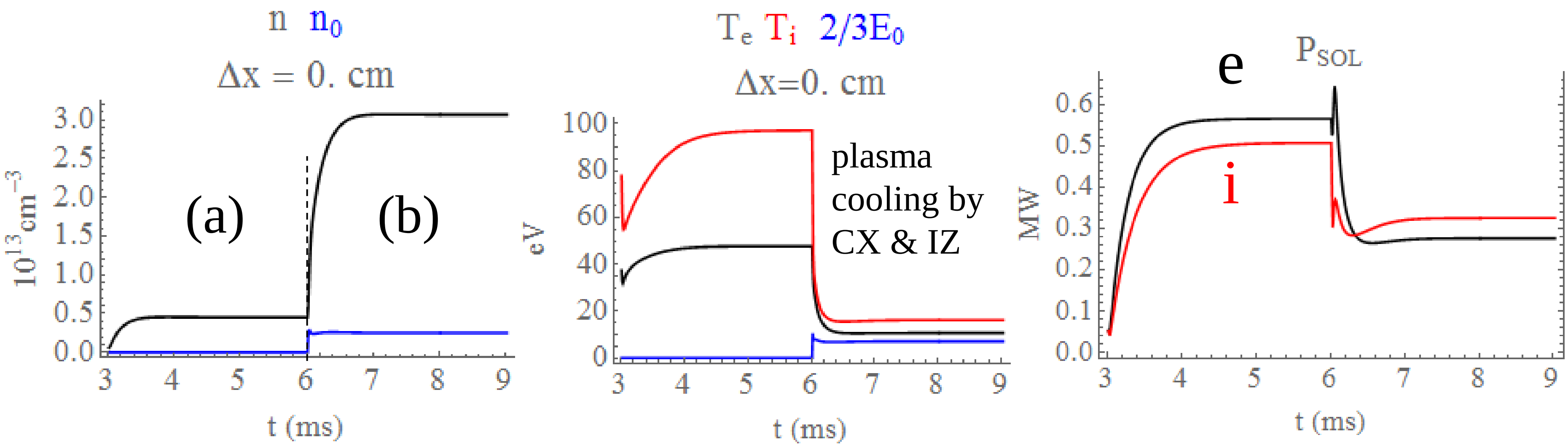
FC neutral D source

We do not consider recycling here but study the response to a prescribed neutral in-flux at the wall with adjustable density “n_{puff}.”

*D. Stotler et al. Phys. Plasmas **22**, 082506 (2015).

Neutrals Impact the Plasma
low power ~ NSTX Ohmic

(a) core fueled ($S_{n,Pe,Pi}$ >0; n_{puff} = 0)
(b) neutral fueled ($S_n \rightarrow 0$, $n_{puff} \rightarrow 10^{13}$ cm^{-3})



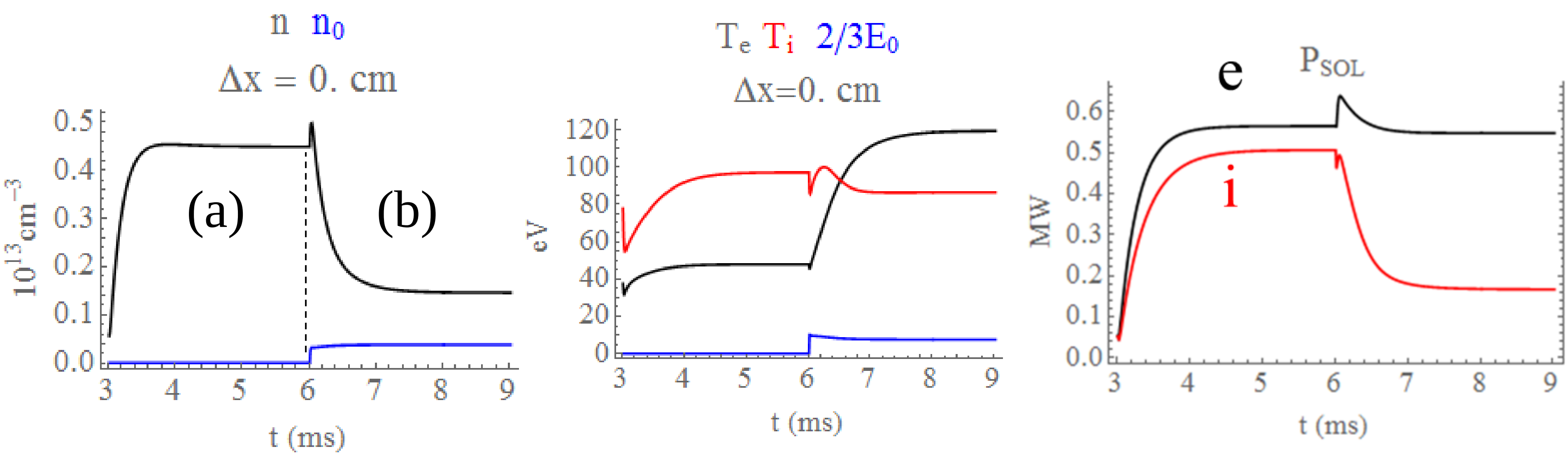
NSTX typical Ohmic L-mode
n_e(Δx=0) = 0.37±0.23 10^{13} cm^{-3}
T_e(Δx=0) = 23±4 eV
P_{nb} = 0 MW
P_{total} ~ 1 MW

In the neutral-fueled equilibrium (b):
- T_e and P_{SOL} are in fair agreement.
- n_e is too large by x10;
  a smaller n_{puff} might bring this down.

S.J. Zweben et al., Nucl. Fusion **55** 093035 (2015).

A lower neutral density (n_{puff}) gets closer to the NSTX Ohmic $n_e(\Delta x=0)$, but $T_e(\Delta x=0)$ rises.

(a) core fueled ($S_{n,Pe,Pi} > 0$; $n_{puff} = 0$)
(b) neutral fueled ($S_n \rightarrow 0$, $n_{puff} \rightarrow 10^{12}\ cm^{-3}$)

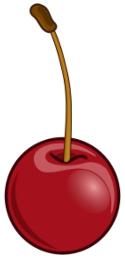


$$\partial_t T_e = (S_{Pe} - T_e \cdot S_n)/n_e - h_{iz} n_0 (\tfrac{2}{3} E_{iz} + T_e) + \ldots$$

- $S_n \rightarrow 0 \Rightarrow T_e$ tends to increase in the core, at constant pressure. The higher neutral density ($n_{puff} = 10^{13}\ cm^{-3}$, previous slide) provides enough ionization cooling to overcome this increase at the separatrix, while $n_{puff} = 10^{12}\ cm^{-3}$ does not.

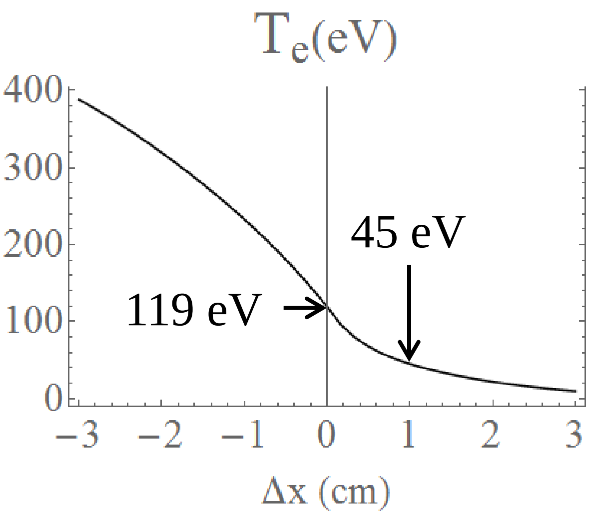
A lower neutral density …(cont.)

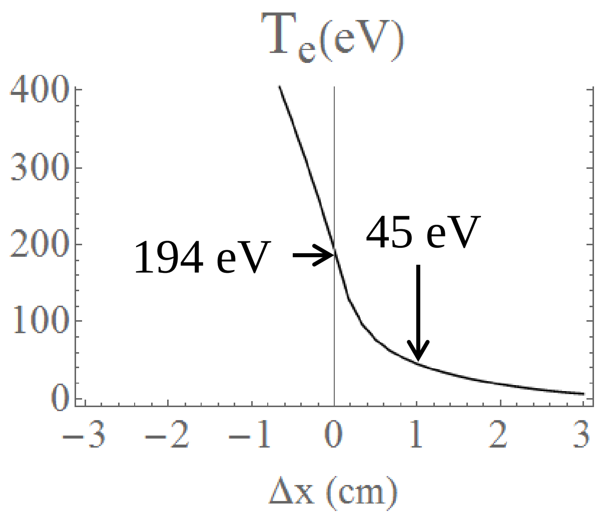
There is a ± 1 cm uncertainty in the location of the separatrix in the NSTX data.

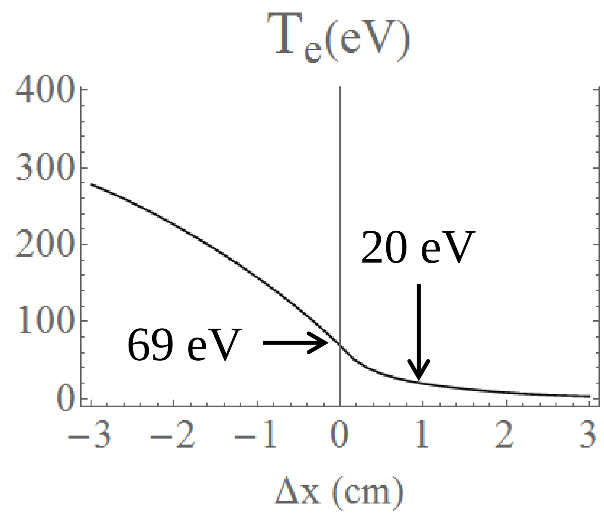


D_{Pe} = 0.1 (28 m^2/sec) $\longrightarrow$ D_{Pe} = 0.05 (14 m^2/sec) | D_{Pe} = 0.05 (14 m^2/sec)

S_{Pe} = 2.5x10^{-3} (6.5 Pa/μs) | S_{Pe} = 2.5x10^{-3} (6.5 Pa/μs) $\longrightarrow$ S_{Pe} = 1.25x10^{-3} (3.3 Pa/μs)





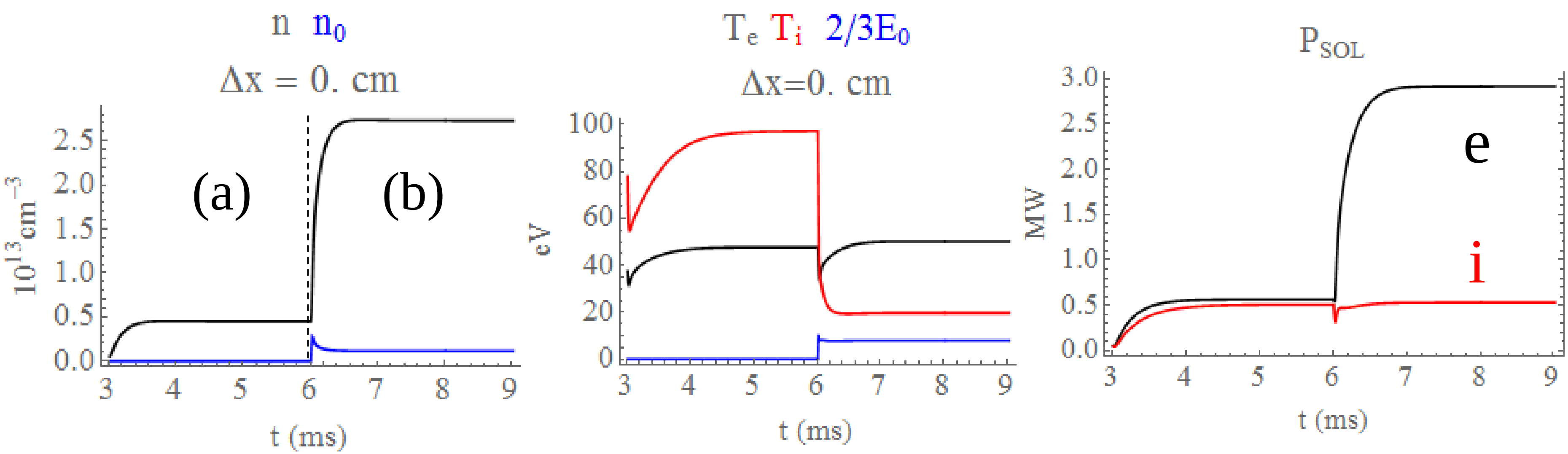


Decreased energy diffusion rates (blob transport) at the separatix result in steeper profiles, at fixed heating rates, increasing the variation in T_e over ± 1 cm.

Adjusting the heating rate (S_{Pe}) recovers the NSTX-Ohmic T_e (23±4 eV) in a neighborhood of the separatrix.

Higher core heating rates yield ~ NSTX H-mode powers

(a) core fueled ($S_{n,Pe,Pi} > 0$; $n_{puff} = 0$)
(b) neutral fueled ($S_n \rightarrow 0$, $n_{puff} \rightarrow 10^{13}$ cm^{-3} , $S_{Pe} \rightarrow 1.5x10^{-2}$)



- The higher electron heating rate compensates for the ionization cooling that gave the L-mode for the same n_{puff} but lower S_{Pe} two slides previously.

NSTX typical H-mode
$n_e(\Delta x=0) = 0.92 \pm 0.54\ 10^{13}$ cm^{-3}
$T_e(\Delta x=0) = 29 \pm 17$ eV
$P_{nb} = 4$ MW
$P_{total} \sim 5$ MW

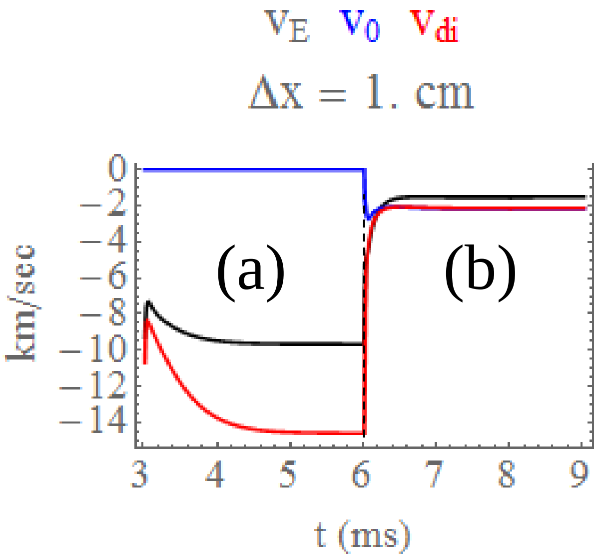
- T_e and P_{SOL} in fair agreement
- n_e too large by x 3†

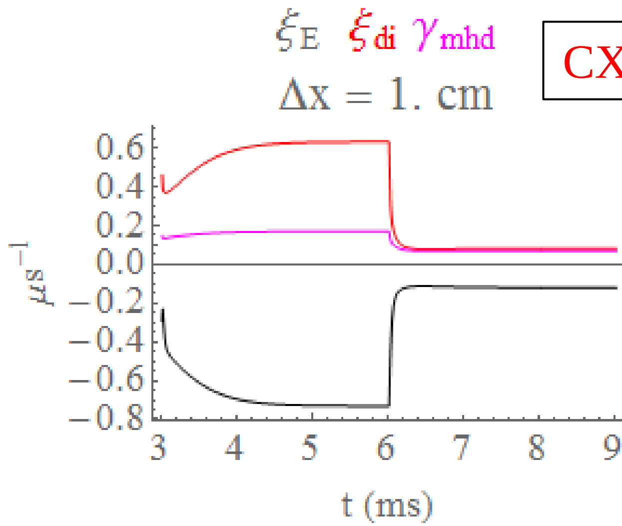
†Note again the ±1 cm uncertainty in the location of the separatrix in the NSTX data.

S.J. Zweben et al., Nucl. Fusion **55** 093035 (2015).

Neutrals Drag Poloidal Flow
low power ~ NSTX Ohmic

(a) core fueled ($S_{n,Pe,Pi} > 0$; $n_{puff} = 0$)
(b) neutral fueled ($S_n \rightarrow 0$, $n_{puff} \rightarrow 10^{13}\ cm^{-3}$)

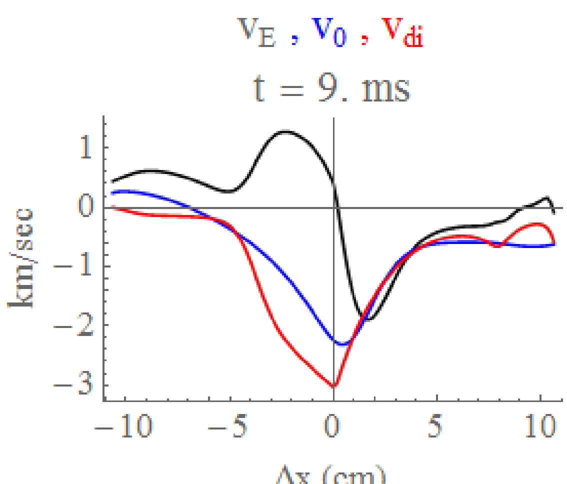


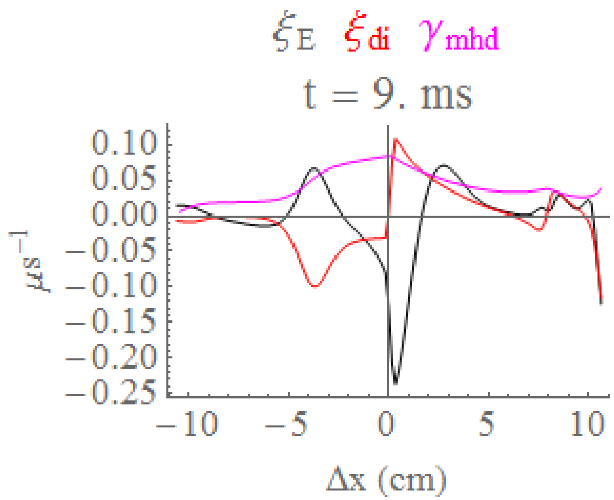


CX reduces v_E shear*

$\xi = \partial_x v$: flow shearing rate

$$\gamma_{mhd}^2 = -\frac{2\rho_s}{R}\partial_x P / n$$

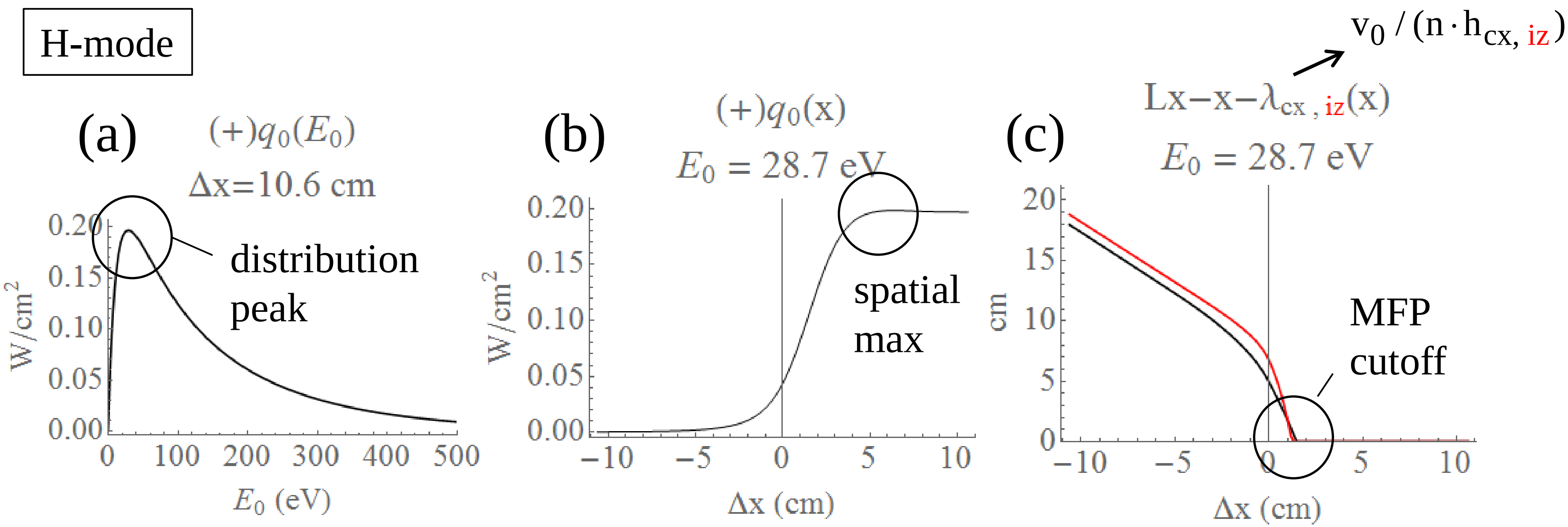




- $\xi_E \sim \gamma_{mhd}$ with neutral drag
- "mirroring"
  $\xi_E + \xi_{di} \sim$ constant
  in the core region

*D. P. Stotler et al., 26th IAEA Fusion Energy Conference, Kyoto, Japan 17-22 October 2016, IAEA-CN-234/TH/P6-7.

Neutral Energy Flux (q_0) and MFP ($\lambda_{cx,iz}$) reveal the origin of neutrals reaching the wall



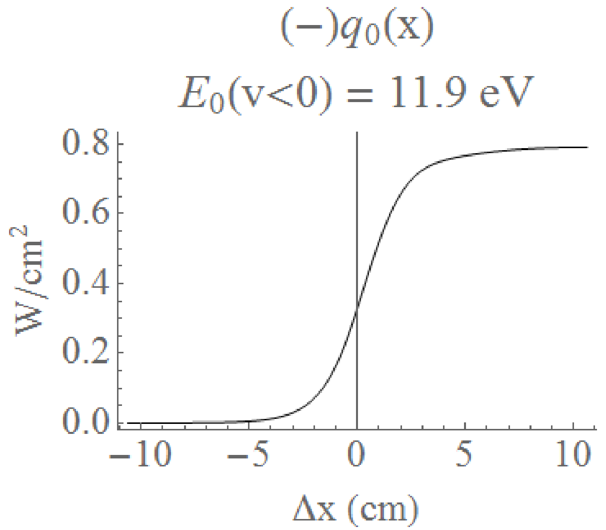
(a) The distribution function of neutral energy flux at the wall is maximized at $E_0 = 28.7$ eV.

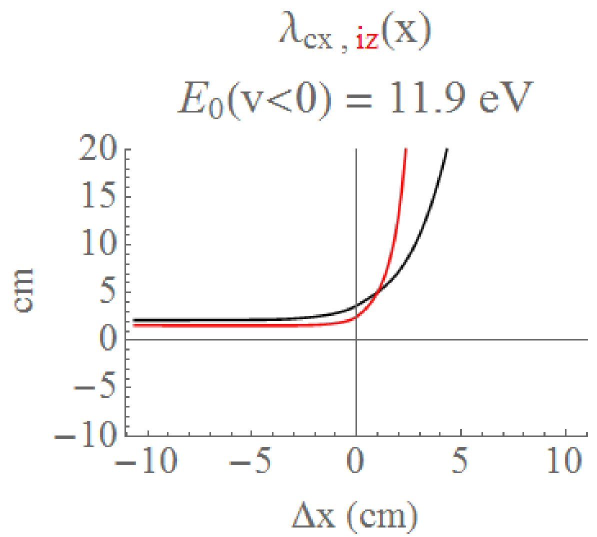
(b) At that energy, the flux reaches a maximum in the SOL at $\Delta x = 5$ cm.

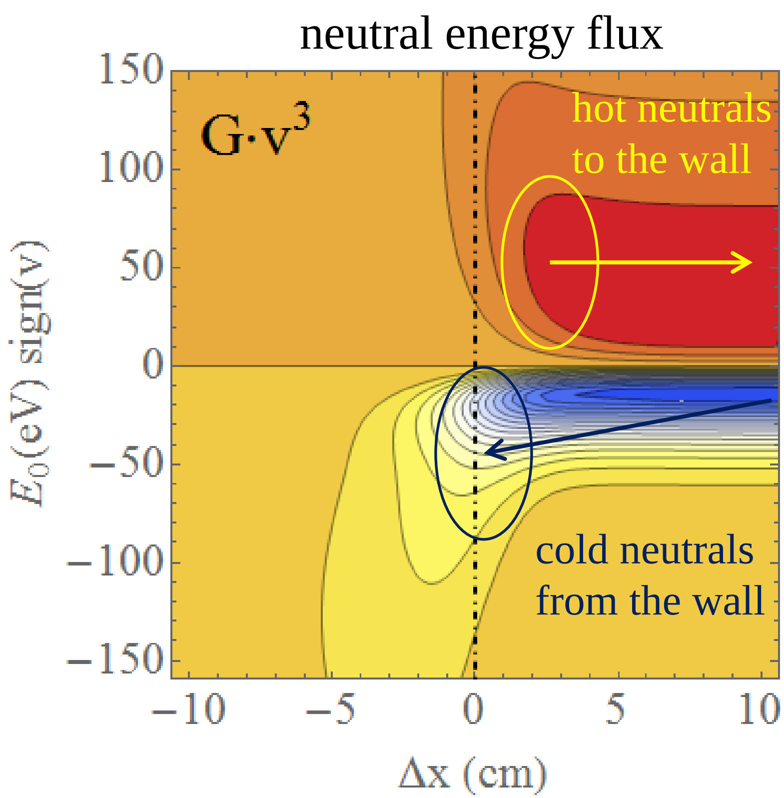
(c) The local MFP (λ) is < the distance to the wall ($Lx - x$) for $\Delta x < 1$ cm.

⇒ Neutrals are free-streaming to the wall from 1 cm < Δx < 5 cm.

The neutral energy flux profile and rapid decrease in MFP locate the deposition domain for injected neutrals.







H-mode

Summary

Neutral physics has been added to the reduced model scrape-off layer turbulence model (SOLT) and illustrated, in 1D, for NSTX–like parameters.

- Realistic *self-consistent* equilibrium plasma profiles are obtained for prescribed neutral densities ("n_{puff}") at the far-SOL boundary and *no additional plasma density source*.
- Both Ohmic L–mode and H–mode states were simulated, the latter obtained with increased core heating. Results are sensitive to n_{puff}. Poloidal flow (v_E) damping and flow shear reduction scale with n_{puff}.
- Neutral MFP and energy flux diagnostics find the origins of hot (CX) neutrals reaching the wall, and deposition domains for cold injected neutrals, in the near-SOL and edge region.

To Do : 2D turbulence (blobs)