SOME THINGS (WE THINK) WE HAVE LEARNED ABOUT PEDESTALS

Peter J. Catto, Plasma Science and Fusion Center, MIT
Matt Landreman (MIT PSFC), Grigory Kagan (LANL)
& Istvan Pusztai (Chalmers)

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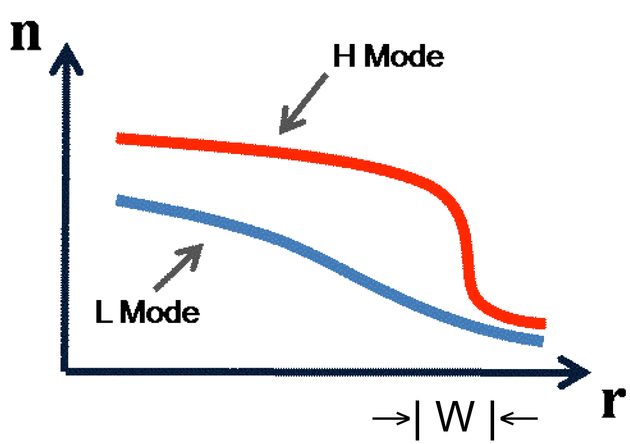
Motivation: pedestal = transport barrier



- Higher energy content
- Larger energy confinement time

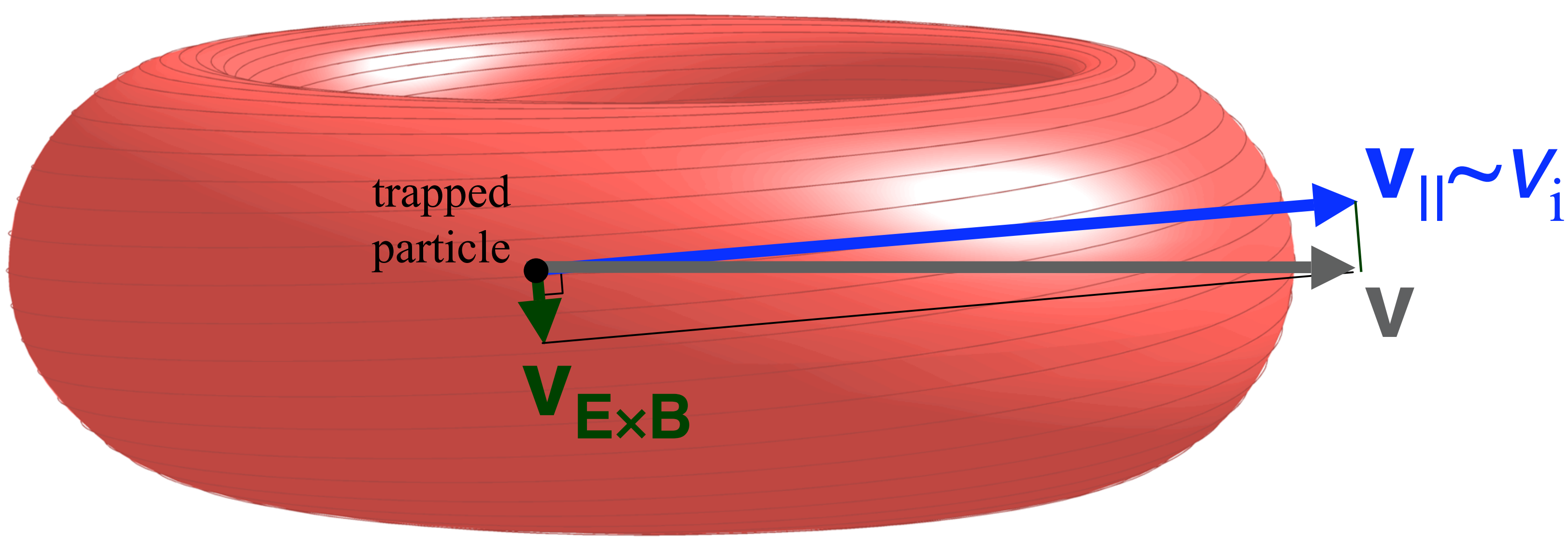
Existence of the pedestal associated with decreased transport and turbulence

Density pedestal results in strong radial electric field and electrostatically confined banana regime ions

Pedestal width w ~ ρ_{pol}

Particle orbits in pedestal

Strong radial electric field: $(v_{||}\vec{n} + \vec{v}_E)\cdot\nabla\theta \approx (v_{||} + cI\Phi'/B)\vec{n}\cdot\nabla\theta$



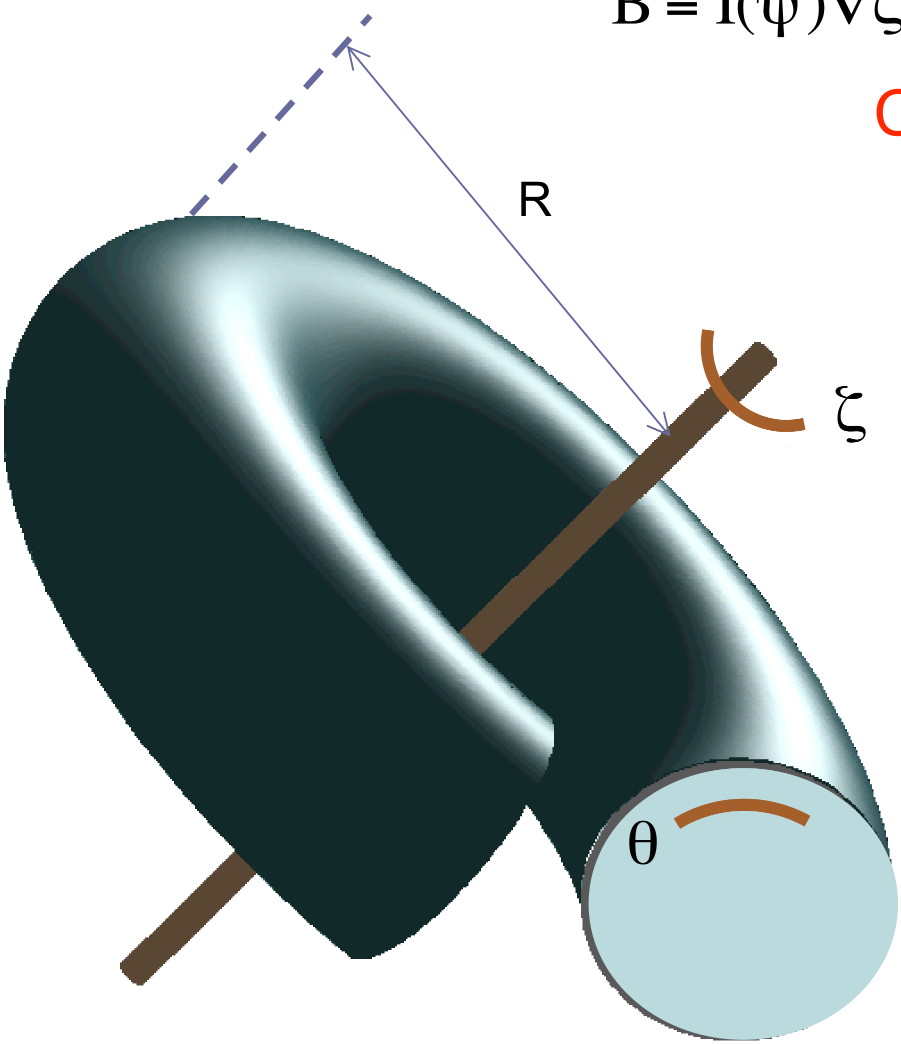
ExB drift ~ $v_i\rho/w$ ~ $v_i\rho/\rho_{pol}$ << $v_{||}$ ~ v_i, but geometry makes it comparable to poloidal projection of $v_{||}$

Overview of Topics

- Version of gyrokinetics useful in pedestal: w ~ ρ_{pol}
- Ion temperature profile: DIII-D
- Subsonic flow implications
- Ion and impurity flow with finite ExB
- C-Mod comparisons
- Bootstrap current enhanced since ion flow modified
- Neoclassical ion heat flux
- Intrinsically ambipolar but diffusivities depend on E
- Modification to the Rosenbluth-Hinton zonal flow

Gyrokinetic variables

$$\vec{B} = I(\psi)\nabla\zeta + \nabla\zeta \times \nabla\psi = B\vec{n}$$



Canonical angular momentum

$$\psi_* = \psi - (Mc/Ze)R^2\nabla\zeta \cdot \vec{v}$$
$$= \psi + \Omega^{-1}\vec{v} \times \vec{n} \cdot \nabla\psi - I v_{\|}/\Omega$$

gyration — drift

$(\rho/a)\psi$ — $(\rho_{pol}/a)\psi$

Toroidal angle ζ_*

Poloidal angle θ_*

Total energy E

Magnetic moment μ

Gyrophase φ

Axisymmetric gyrokinetic equation

Axisymmetric ($\partial/\partial\zeta = 0$) gyrokinetic equation

$$\frac{\partial\langle f\rangle}{\partial t} + \langle\frac{d\theta_*}{dt}\rangle\frac{\partial\langle f\rangle}{\partial\theta_*} = \langle C\{f\}\rangle - \frac{Ze}{M}\frac{\partial\langle\Phi\rangle}{\partial t}\frac{\partial\langle f\rangle}{\partial E}$$

Steady state ($\partial/\partial t = 0$) to leading order in ρ_{pol}:
transit averaging in banana regime

$$\overline{\langle C\{f_*\}\rangle} = 0$$

where $\overline{Q} = \oint d\tau Q / \oint d\tau$ with $d\tau = d\theta_* / \langle\dot{\theta}_*\rangle$

Are there non-Maxwellian solutions in pedestal?

Entropy production analysis: no!

*Kagan & Catto 2008 PPCF **50** 085010*

Pedestal ion temperature variation

In the banana regime $\partial f_* / \partial\theta_* = 0$ so $f_*(\psi_*, E, \mu)$

The only Maxwellian possible is

$$f_* = \eta\left(\frac{M}{2\pi T}\right)^{3/2} \exp\left(-\frac{Ze\Phi}{T} + \frac{M\omega^2 R^2}{2T} - \frac{Ze\omega\psi}{cT}\right)\exp\left[-\frac{M(\vec{v} - \omega R\vec{\zeta})^2}{2T}\right]$$

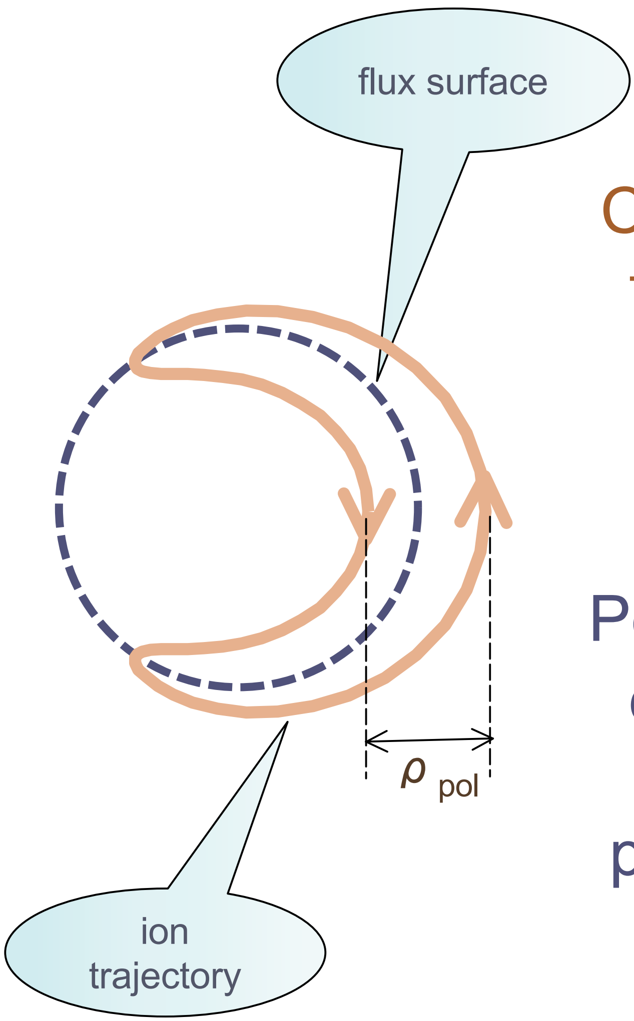
where η, ω, and T are constants to lowest order, n is Maxwell-Boltzmann, and

$$\omega = -c[\partial\Phi/\partial\psi + (1/Zen)\partial p/\partial\psi]$$

Non-isothermal modifications can only enter to next order in the B_p/B expansion

T, η, ω must vary slowly compared to ρ_{pol}

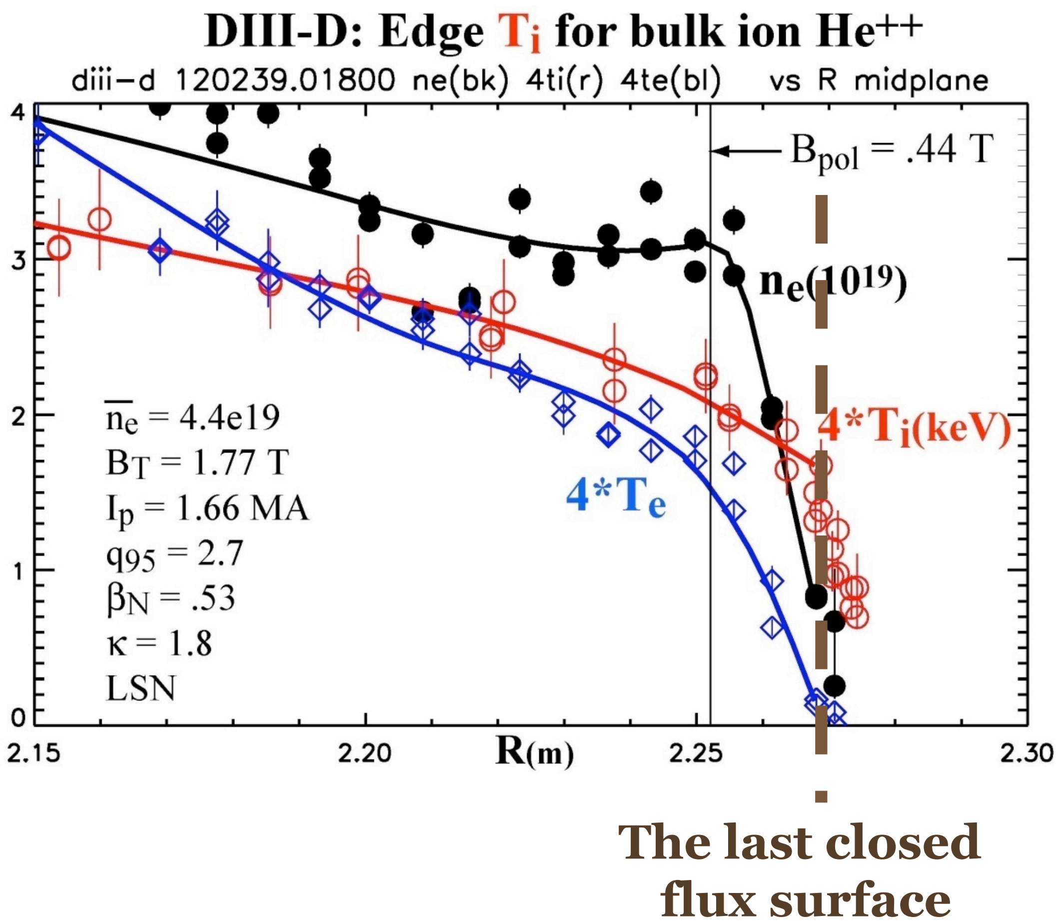
Physical interpretation



Core gradients are weak so ion departures from a flux surface are unimportant - any flux surface is a closed system

Pedestal gradients are as large as $1/\rho_{pol}$ so drift departures affect the equilibration of neighboring flux surfaces - the entire pedestal region is a closed system (rather than individual flux surfaces)

The T_i gradient for the bulk ion in a DIII-D ECH H-mode pedestal is small relative to gradients in electron temperature and density



- The thermal ion full banana width is computed to be $2\rho_\theta$ = 10 mm for He^{++} at the top of the density pedestal.
- The smooth spline fits to the data (solid lines) end at the LCFS as computed by EFIT. Note the clear break in slope for T_i beyond the LCFS.
- In a nominally identical companion discharge we measured T_i for the minor C^{6+} impurity constituent. The T_i profile for C^{6+} has a very similar slope to that for He^{++}, but is ~ 150 eV greater in this region, probably because this discharge had an increase in β_N of ~ 10% compared with the one shown here.

DIII-D NATIONAL FUSION FACILITY

c.f. deGrassie, Groebner, and Burrell, PoP vol 13, 112507-1 (2006).

Pedestal pressure balance

Radial ion pressure balance using $\vec{V}_i = \omega_i R\vec{\zeta} + u_i\vec{B}$ gives

$$\omega_i \approx -c[\partial\Phi/\partial\psi + (1/en)\partial p_i/\partial\psi]$$

subsonic pedestal ($w \sim \rho_{pol}$) $\omega_i/[(T_i/en)\partial n/\partial\psi] \sim \omega_i R/v_i << 1 \Rightarrow \dfrac{\partial\Phi}{\partial\psi} \approx -\dfrac{1}{en_i}\dfrac{\partial p_i}{\partial\psi} > 0$

pedestal electric field inward for subsonic ion flow

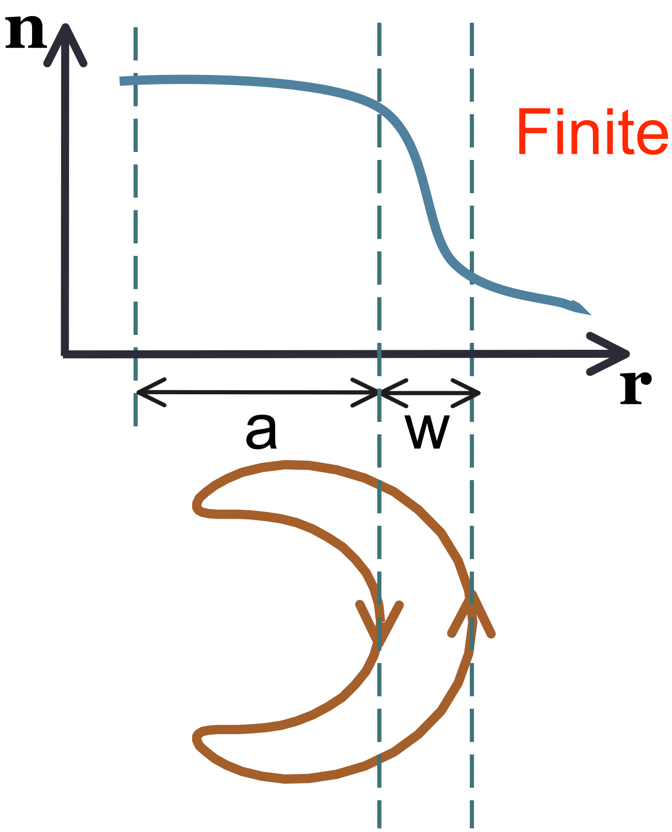
Radial electron pressure balance: $\vec{V}_e = \omega_e R\vec{\zeta} + u_e\vec{B}$

$$\omega_e = -c[\partial\Phi/\partial\psi - (en_e)^{-1}\partial p_e/\partial\psi]$$

Additive, making $\omega_e R \sim v_i$ so that $J_{ped} \sim env_i$ & co-current

Thus, the electric field balancing the $1/\rho_{pol}$ density gradient requires a stationary ion Maxwellian & large *electron* flow

Pedestal orderings & ExB drift effects



Drift departure ρ_{pol} is of order pedestal width w

Finite drift orbits effects enter in leading order

Estimating $Ze\nabla\Phi \sim T/\rho_{pol}$ gives

$$\vec{v}_E \cdot \nabla\theta \sim v_{\|}\vec{n}\cdot\nabla\theta$$

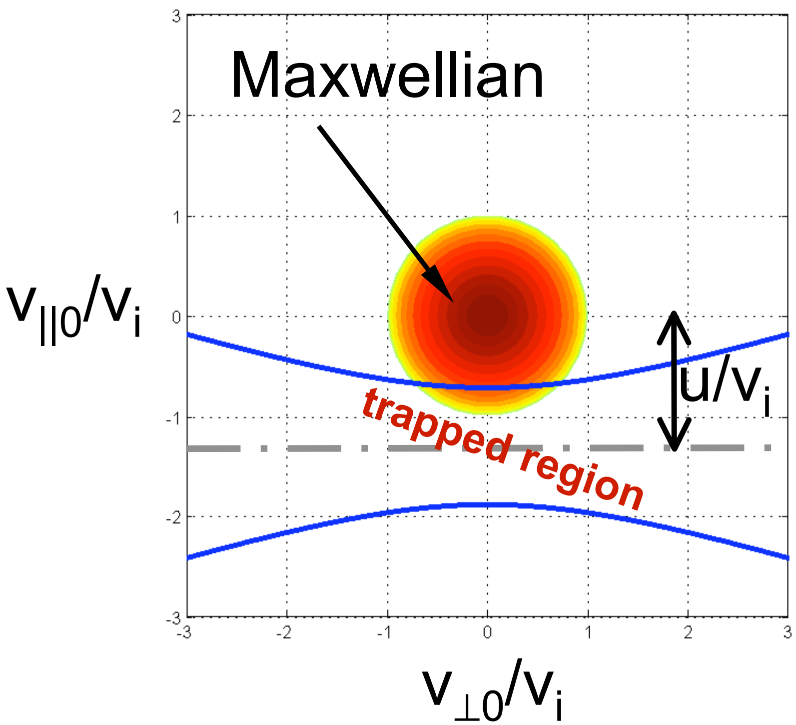
where $\vec{v}_E$ is the ExB drift velocity

ExB ~ poloidal streaming

Orbit localization from $\varepsilon = a/R << 1$

Decouple neoclassical & classical by assuming $\rho_{pol} >> \rho$

Trapped particles: $\Phi(\psi) \neq \Phi(\psi_*)$



ExB drift:

i) Increases effective potential well depth: μ = 0 trapped by Φ poloidal variation at fixed ψ_*

ii) Shifts the axis of symmetry of the trapped particle region - fewer trapped!

Trapped fraction decays exponentially if $u = cI\Phi'/B > v_i$

Neoclassical and polarization phenomena strongly modified

Recall $u \approx (\rho_{pol}/\rho)v_E >> v_E$ so particle dynamics qualitatively changed by a finite subsonic ExB drift

Neoclassical ion heat flux & parallel flow

∇T drive only

$$\overline{C_1\{g + f_M \frac{I v_{||} M v^2}{2\Omega T^2} \frac{\partial T}{\partial \psi}\} = 0}$$

Need a model for the collision operator - must keep energy scatter as well as pitch angle scatter

⇩

Solve for *g*

⇩

Calculate flow & transport (take appropriate moments of the distribution function)

Ion motion for $\varepsilon = a/R << 1$

Assume a quadratic potential well and expand about ψ_*

$$\Phi = \Phi_* + \frac{Iv_{||}}{\Omega}\Phi'_* + \frac{I^2 v_{||}^2}{2\Omega^2}\Phi''_* \qquad \psi_* \approx \psi - Iv_{||}/\Omega \qquad u = cI\Phi'/B$$

$$u_* = cI\Phi'_*/B$$

using E -ZeΦ_*/M, μ and ψ_* invariance:

$$\frac{(v_{||}+u)^2}{2S} + \mu B + \frac{u_*^2}{2S} = E - \frac{Ze\Phi_*}{M} \qquad v_{||} + u = Sv_{||} + u_*$$

orbit squeezing — magnetic dipole energy — ExB energy

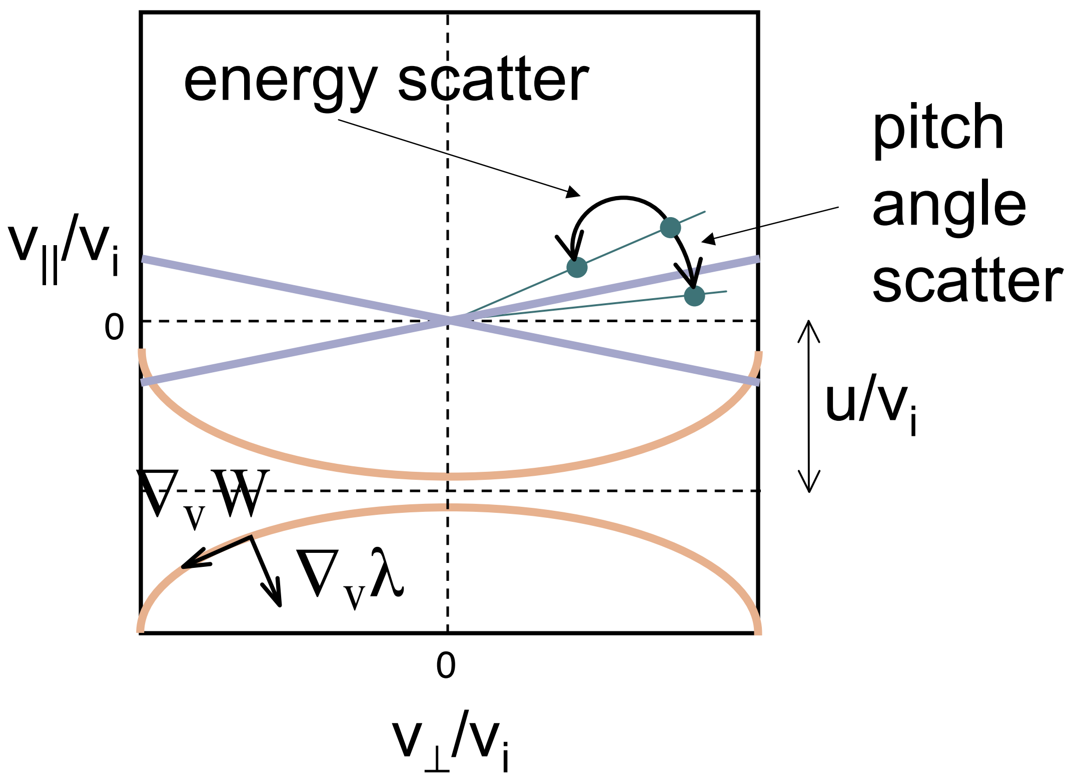
$$S = 1 + cI^2\Phi''/B\Omega$$

S > 0 (S < 0) trapped particles outboard (inboard)
For ε << 1 can find the useful form

$$\frac{1}{2}(v_{||}+u)^2 = W(1-\lambda/h) \qquad h = 1 - 2\varepsilon\sin^2(\vartheta/2) = B_0/B$$

with $\lambda = 1/(1+2\varepsilon)$ at trapped-passing boundary

Collisions in the pedestal



Convenient variables are λ and W (S = 1):

$$\lambda = \frac{\mu B_0 + u^2/h^2}{W}$$

$$W(1-\lambda/h) = \frac{1}{2}(v_{||}+u)^2$$

Pitch-angle scattering is not sufficient to retain transitions across the trapped-passing boundary!

Kagan & Catto 2010 PPCF ***52*** *055004 and 079801*

Neoclassical parallel ion flow

Localized portion of g higher order in ε

$$V_{\|i} = -\frac{cI}{B}\left(\frac{\partial\Phi}{\partial\psi} + \frac{1}{Zen}\frac{\partial p_i}{\partial\psi}\right) - \frac{7cI}{6ZeB_0}\frac{\partial T_i}{\partial\psi} J(u/v_i)$$

(Kagan & Catto PPCF 2010 + errata)

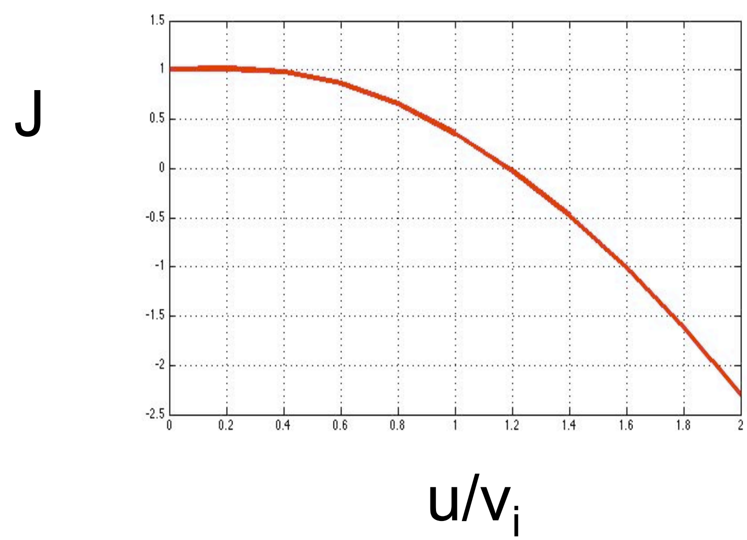
J(0) = 1

No orbit squeezing effect on ion flow

J changes to Pfirsch-Schluter sign at $u/v_i \sim 1.2$

Seems to explain C-Mod flow measurements in pedestal

More pedestal bootstrap current

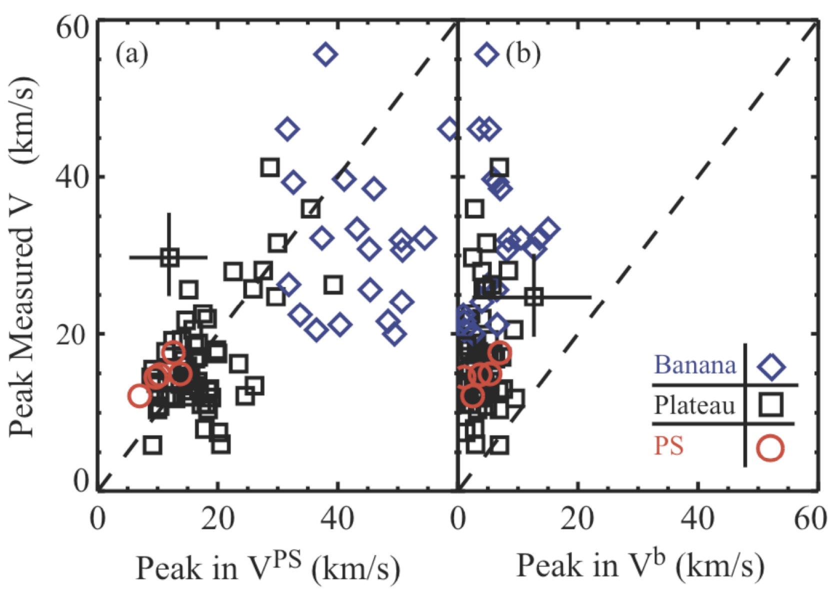


Pedestal impurity flow

Change in poloidal ion flow alters impurity flow

For Pfirsch-Schluter impurities & banana ions:

$$V_z^{pol} = V_i^{pol} - \frac{cIB_{pol}}{eB^2}\left(\frac{1}{n_i}\frac{\partial p_i}{\partial \psi} - \frac{1}{Zn_z}\frac{\partial p_z}{\partial \psi}\right) \quad \& \quad V_i^{pol} \approx \frac{7cIB_{pol}}{6eB_0^2}\frac{\partial T_i}{\partial \psi} J\left(\frac{u}{v_i}\right)$$

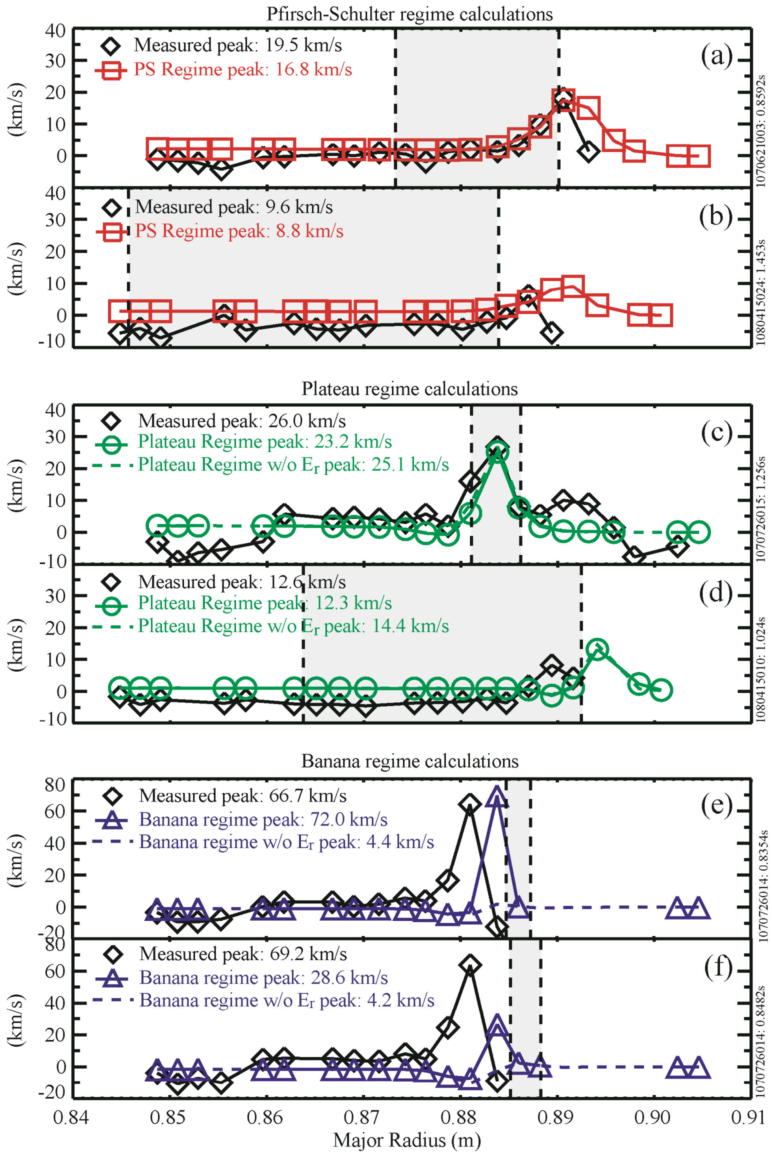


C-Mod pedestal flow (Marr *et al* 2010):

Pfirsch-Schluter: ~ agree

Banana: problem - need E_r

Poloidal ion flow: C-Mod vs theory

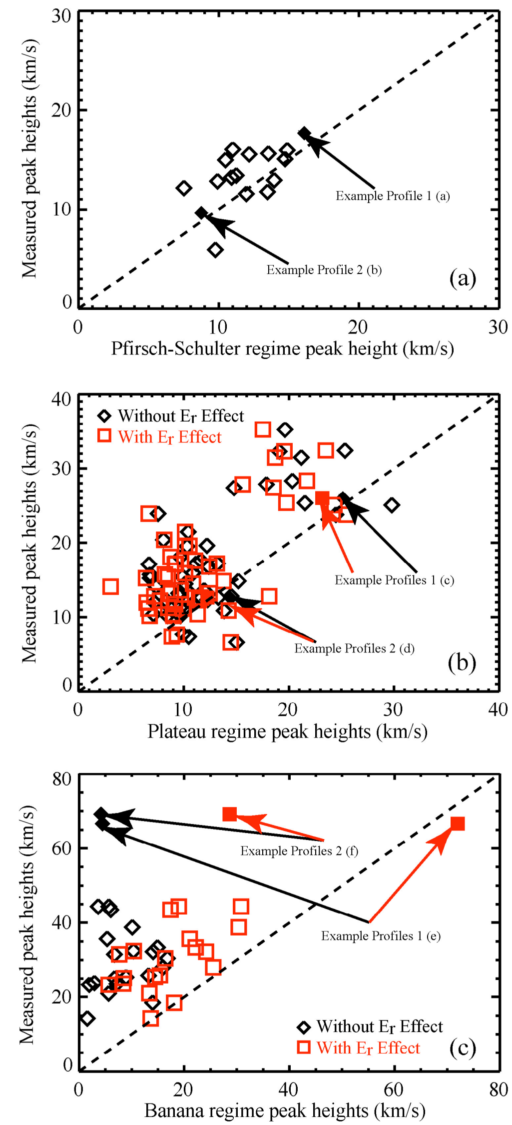


Pfirsch-Schluter

plateau (*shaded*)

banana

(Marr *et al*)



Pedestal bootstrap

J(u) alters electron friction with ions thereby modifying the bootstrap current (p = total pressure)

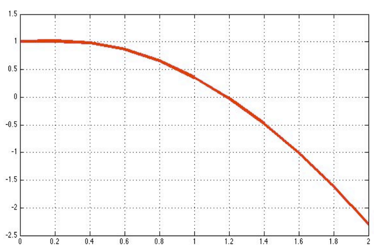
Z >> 1:

$$J_{\|}^{bs} = -1.46\sqrt{\varepsilon}\frac{cIB}{\langle B^2\rangle}\left[\frac{dp}{d\psi} - 1.17J(u/v_i)\frac{n_e}{Z}\frac{\partial T_i}{\partial\psi}\right]$$

Arbitrary Z:

$$J_{\|}^{bs} = -1.46\sqrt{\varepsilon}\frac{cIB}{\langle B^2\rangle}\left[\frac{Z^2+2.21Z+0.75}{Z(Z+1.414)}\right]$$

$$\left[\frac{dp}{d\psi} - \frac{(2.07Z+0.88)n_e}{(Z^2+2.21Z+0.75)}\frac{\partial T_e}{\partial\psi} - 1.17J(u/v_i)\frac{n_e}{Z}\frac{\partial T_i}{\partial\psi}\right]$$



J vs u/v_i

J(u/v_i) changes sign at u/v_i ~ 1.2 to enhance bootstrap current in pedestal (Kagan & Catto PRL 2010)

Pedestal ion heat flux

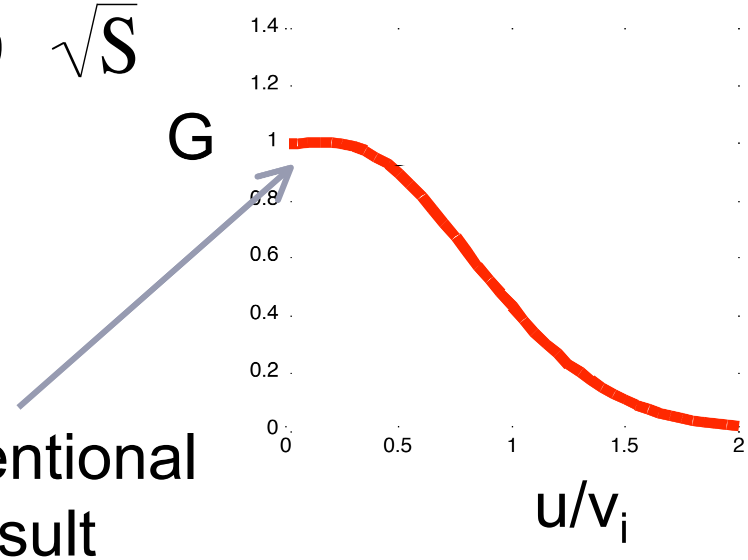
Modified ion heat flow:

$$\langle \vec{q} \cdot \nabla\psi \rangle = -\frac{McIT}{Ze} \left\langle \int d^3v \left(\frac{Mv^2}{2T} - \frac{5}{2} \right) \frac{v_\parallel}{B} C_1\{g_{local}\} \right\rangle$$

Evaluating:

$$\langle \vec{q} \cdot \nabla\psi \rangle = -1.35\sqrt{\varepsilon} n \nu_i \frac{I^2 T_i}{M\Omega^2} \frac{\partial T_i}{\partial \psi} \frac{G(u)}{\sqrt{S}}$$

$S = 1 + cI^2\Phi''/B\Omega$



Radial ion heat flux & trapped population exponentially small for $u/v_i > 1$

Ion heat flux more sensitive to Φ' than Φ''

Neoclassical polarization in the pedestal

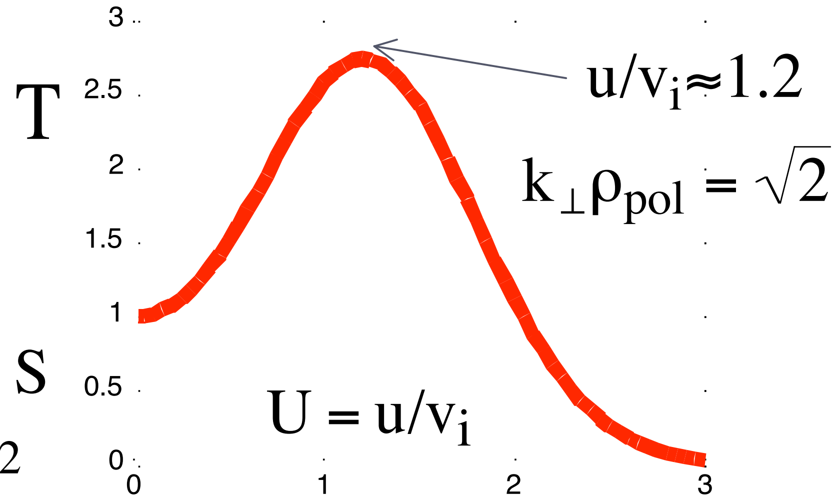
Ignore collisions, but retain strong radial electric field:

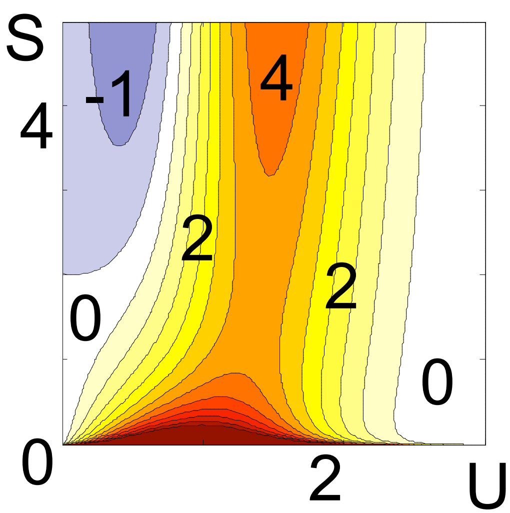
$$\frac{\partial g}{\partial t} = f_M \frac{Ze}{T} \frac{\partial \Phi_*}{\partial t} \overline{J_0\left(\frac{k_\perp v_\perp}{\Omega}\right) e^{iQ}}$$

$$\frac{\Phi_1(t \to \infty)}{\Phi_1(t=0)} = \frac{\varepsilon_{cl}^{pol}}{\varepsilon_{cl}^{pol} + \varepsilon_{nc}^{pol}}$$

Solving keeping distinction between ψ and ψ_* gives

$$\frac{\varepsilon_{nc}^{pol}}{\varepsilon_{nc}^{RH}} = \left(\frac{T(U)}{\sqrt{S}} + i \frac{\Xi(U,S)}{k_\perp \rho_{pol}} \right)$$





$\Xi(U,S)$

$$\sqrt{\varepsilon} k_\perp \rho_{pol} << S$$

$$\sqrt{\varepsilon} << e^{-U^2}$$

Exponential reduction due to decrease in trapped making $\frac{\Phi_1(t \to \infty)}{\Phi_1(t=0)} \to 1$

Summary

- Pedestal ions nearly isothermal ($\rho_{pol}\nabla T_i$ «1): subsonic ions electrostatically confined + magnetically confined electrons
- Banana regime ion heat flux reduced & poloidal ion flow can change sign in the pedestal due to Φ' as in C-Mod
- Pedestal bootstrap current enhanced!
- Pedestal zonal flow turbulence regulation stronger due to Φ' (see Kagan PoP and Landreman PPCF)
- Plateau regime ion heat flux increases before decreasing, no sign change for ion flow (remains PS sign) or bootstrap current, no orbit squeezing effects (Pusztai & Catto)
- QSS almost the same as a tokamak! (Landreman & Catto)