Radial Electric Field Effects on Pedestal Flows & Current

Peter J. Catto - *MIT PSFC*

Grigory Kagan - *LANL*

Matt Landreman - *MIT PSFC*

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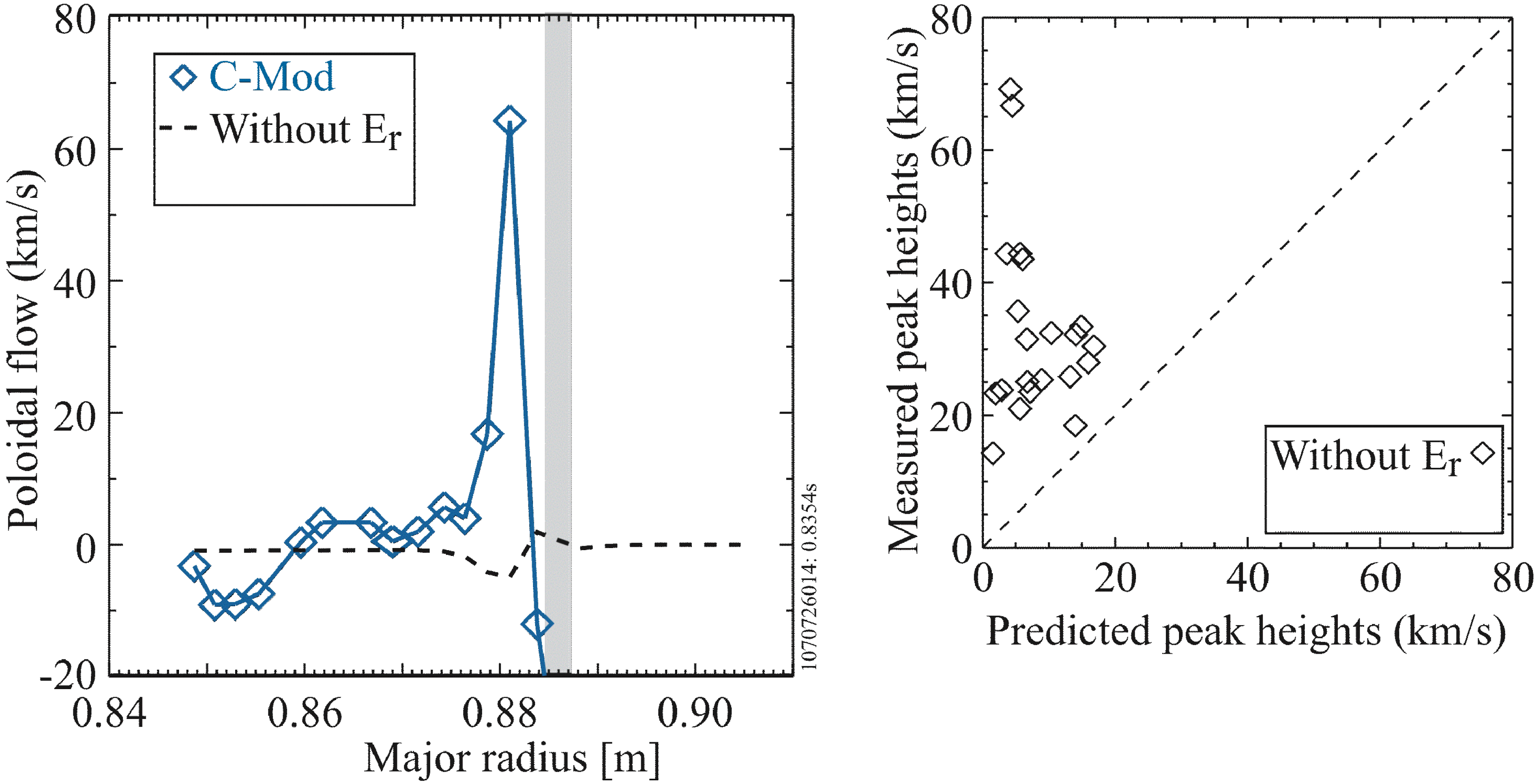
Bruce Lipschultz, Kenny Marr & Rachael McDermott

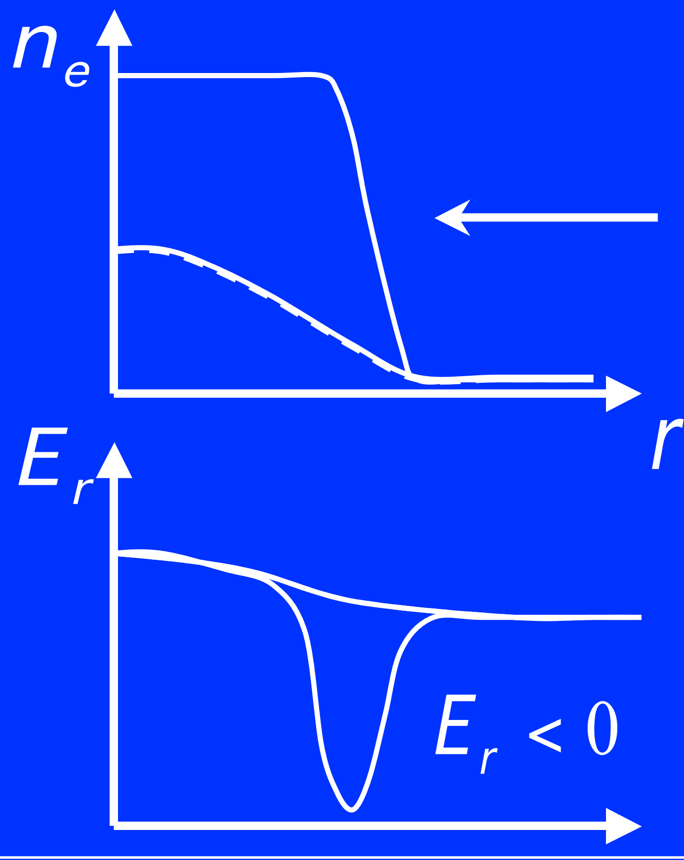
C-Mod pedestal flow in banana regime

C-Mod: Marr,Lipschultz,McDermott (plateau shaded)
Theory without E: standard banana - - - - -



Pedestal profiles steep: large $E_r < 0$

- Suppressed turbulence due to strong electric field



- High confinement or H-mode transport barrier
- Poloidal streaming and **ExB** drift compete
- T_i pedestal >> ρ_{ipol} makes entropy production = 0 in banana & plateau regimes

Pedestal pressure balance

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

$\Omega_\zeta = -c[\partial\Phi/\partial\psi + (1/en)\partial p_i/\partial\psi]$ where $U_i \propto \partial T_i/\partial\psi$

subsonic pedestal ($w \sim \rho_{pol}$)

$$\frac{\Omega_\zeta e n_i}{T_i \partial n/\partial\psi} \sim \frac{\Omega_\zeta R}{v_i} << 1 \quad \Rightarrow \quad \frac{\partial\Phi}{\partial\psi} \approx -\frac{1}{en_i}\frac{\partial p_i}{\partial\psi} > 0$$

Pedestal electric field inward for subsonic ion flow

Radial electron pressure balance: $\vec{V}_e = \Omega_{e\zeta} R\vec{\zeta} + U_e\vec{B}$

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

Additive, making $\Omega_{e\zeta}R \sim v_i$ 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 complications

- For a sub-sonic banana regime density pedestal of width ρ_{ip}

$$E_r \approx \frac{1}{en_i}\frac{\partial p_i}{\partial r} \approx \frac{T_i}{en_i}\frac{\partial n_i}{\partial r} \Rightarrow \text{electrostatically confined ions}$$

- Distinction between flux and drift surfaces matters!

- Competition between **E**x**B** and poloidal streaming (Kagan & Landreman) results in finite E_r orbit modifications:
  - Reducing ion neoclassical transport (fewer trapped)
  - Altering ion poloidal flow (can reverse direction)
  - Enhancing bootstrap current (via electron-ion friction)
  - Increased zonal flow regulation

  (all analytic results for a/R << 1)

Ion motion for ε = a/R << 1

Assume a quadratic potential well and expand about ψ_*

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

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

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

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

S > 0 (S < 0) trapped particles outboard (inboard)

For ε << 1 can find the useful form

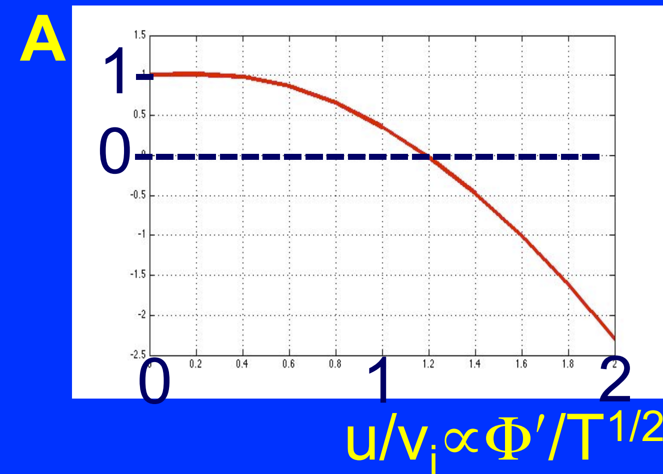
$$\tfrac{1}{2}(v_\parallel + u)^2 = W\left(1 - \lambda B/B_0\right) \qquad B_0/B = 1 - 2\varepsilon \sin^2(\vartheta/2)$$

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

Ion & impurity flow + bootstrap current

- Ion temperature gradient term in banana regime for poloidal flow modified: $u \approx (c/B_P)d\Phi/dr$

$$V_i^{pol} \approx \frac{1.17c}{eB}\frac{\partial T_i}{\partial r} A\left(\frac{u^2}{v_i^2}\right)$$



- Banana ions and PS impurities:

$$V_z^{pol} \approx V_i^{pol} - \frac{c}{eB}\left(\frac{1}{n_i}\frac{\partial p_i}{\partial r} - \frac{1}{Z_z n_z}\frac{\partial p_z}{\partial r}\right)$$

- Bootstrap current (Z=1): No direct E_r effects on electrons - know about E_r via friction between ion and electron flows

$$J_{\parallel}^{bs} \approx -2.4\frac{c\sqrt{\varepsilon}}{B_p}\left[\frac{dp}{dr} - 0.74 n_e \frac{\partial T_e}{\partial r} - 1.17 A\left(\frac{u^2}{v_i^2}\right) n_e \frac{\partial T_i}{\partial r}\right]$$

- Increased bootstrap current in pedestal!

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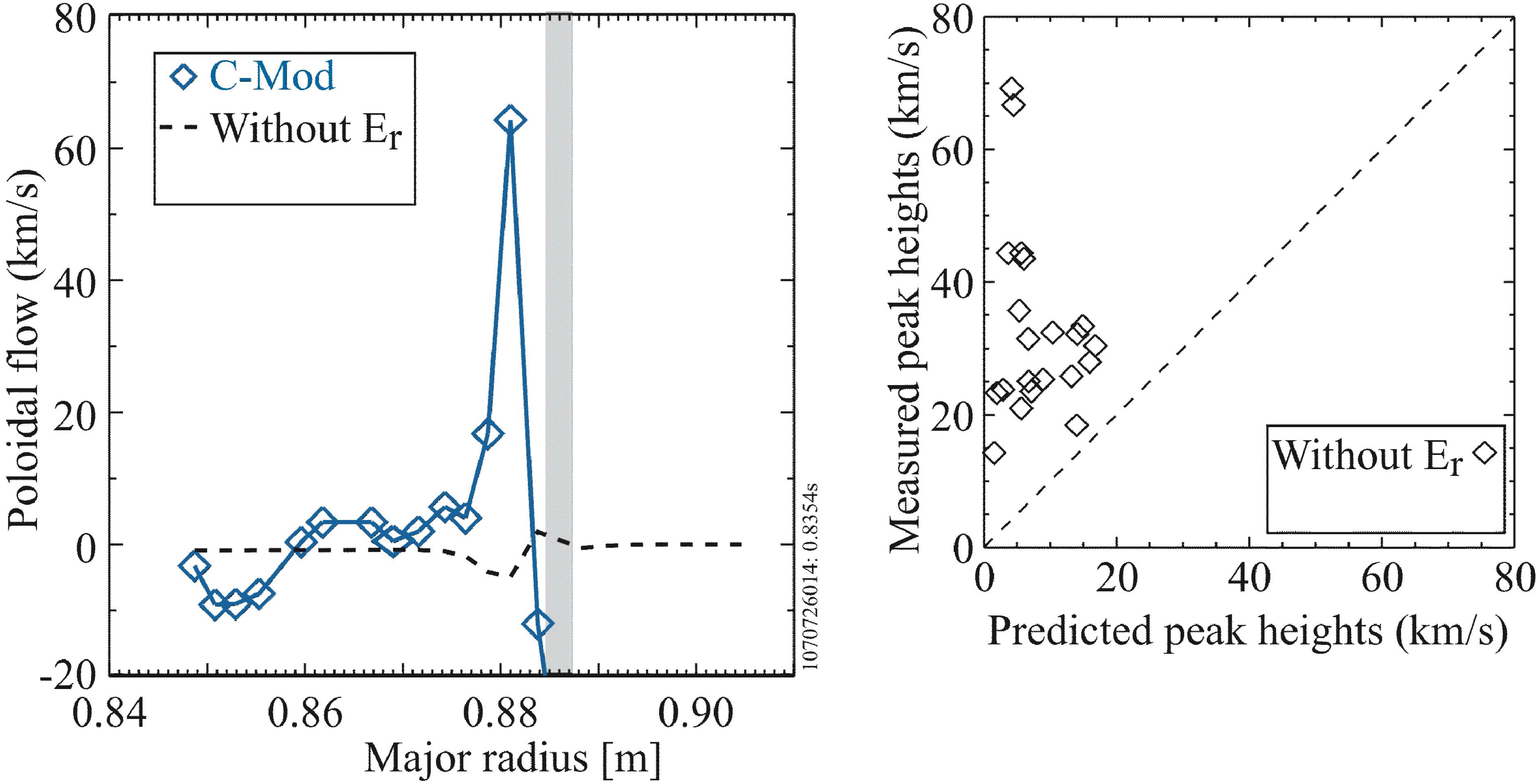

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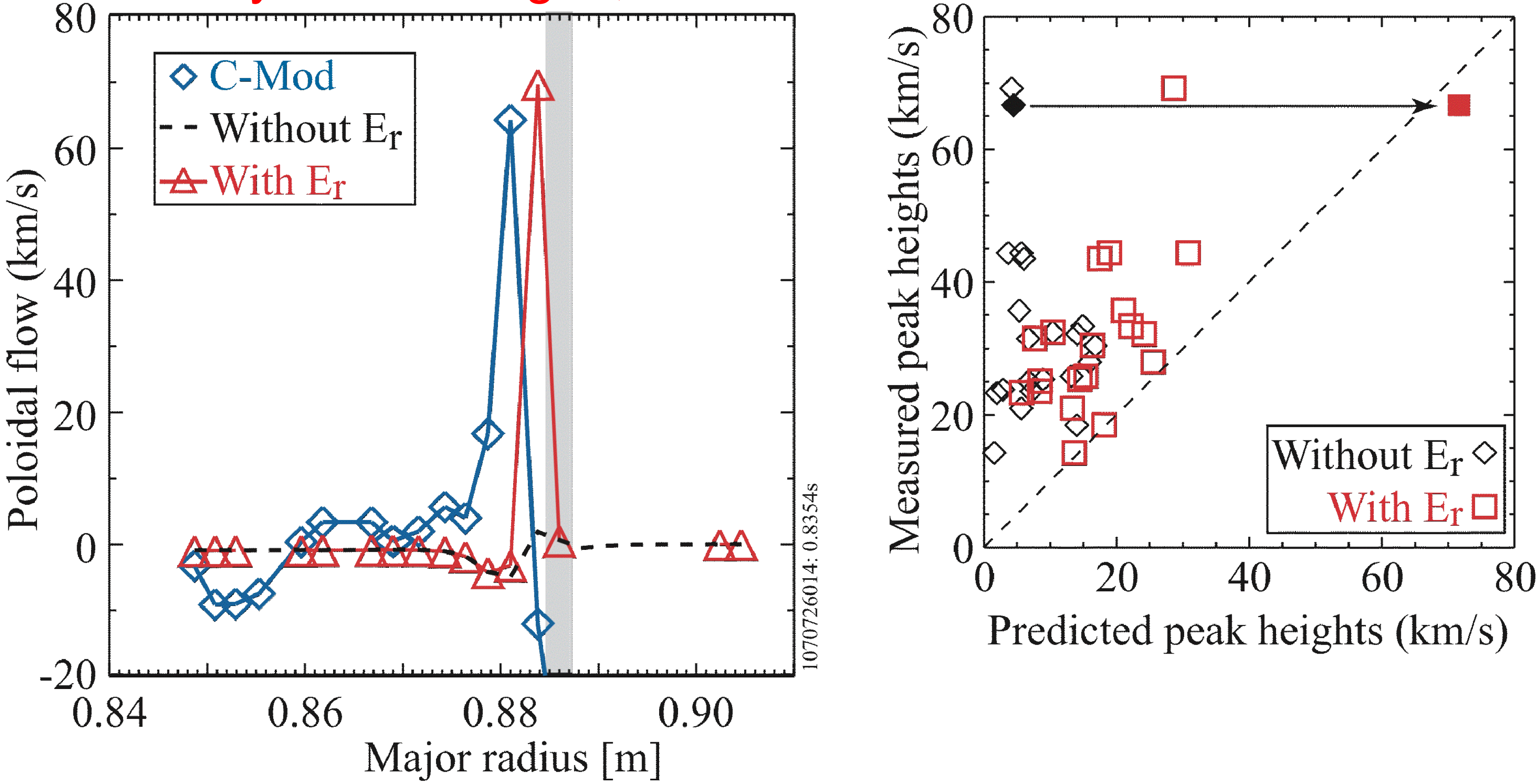
Theory with E: Kagan,Landreman



Summary

- Radial electric field as well as its shear matter in pedestal:
  - Alters ion & impurity flow in agreement with C-Mod
  - Enhances the bootstrap current
  - Reduces ion heat diffusivity (fewer trapped)
  - Stronger regulation of turbulence (fewer trapped)
  - All results hold for quasisymmetric stellarators