Preventing impurity accumulation

H-mode turbulence reduction & I-mode impurity removal

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Plasma Science and Fusion Center

Massachusetts Institute of Technology

10th Plasma Kinetics Working Meeting

July 18, 2017

Work supported by La Caixa Fellowship and DOE Grant DE-FG0291ER54109.

Outline

1) Introduction and motivation

2) New physical phenomena capturing pedestal poloidal variation measurements

3) Radial impurity flux evaluation: tokamak operation and I-mode explanation

Motivation
Impurity accumulation
In-out asymmetries
Poloidal variation
Diamagnetic effects
Impurity flow effects
Conservation equations
Momentum → Pol. n var.
E_r poloidal variation
Energy → Poloidal T var.
Poloidal flow
Pedestal profile alignment
Radial flux
Radial flux evaluation
Impurity confinement
I-mode explanation
Summary

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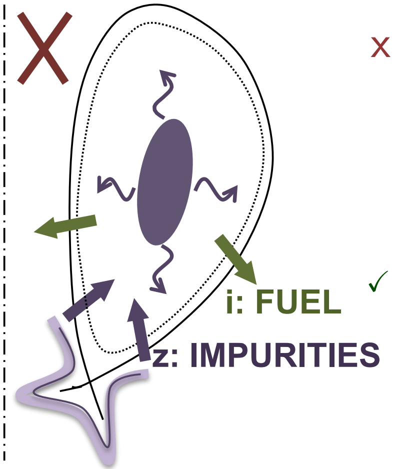
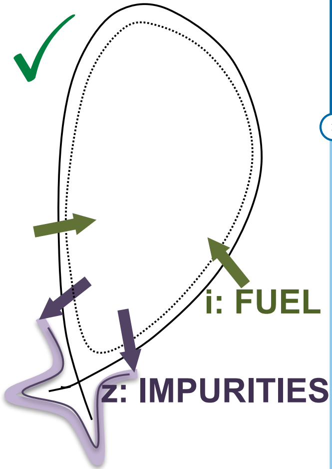


- ✗ Tokamaks with high-z divertors (e.g. JET and Alcator C-Mod) can experience large energy losses due to impurity accumulation.
- ✓ Measuring pedestal radial flux of non-trace impurities could suggest optimal tokamak operation.



⇒ Pedestal impurity radial flow provides insight on impurity confinement.

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Impurity accumulation ↔ Pedestal impurity radial flux ∝ Parallel friction ↔ Pedestal impurity poloidal variation

(∝: Toroidal mom.; ↔: Helander 1998)

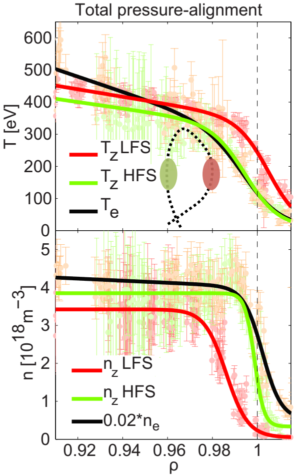
$\mathbf{E} \times \mathbf{B}$ shear stabilization of turbulence:

- Heat transport (high order) → turbulence
- H-mode flows (low order) → neoclassical theory

Pedestal poloidal asymmetries:

- Boron temperature larger on outboard (LFS) side compared to inboard (HFS).
- HFS accumulation of boron density up to six fold.

Can neoclassical theory predict H-mode pedestal flows?
Pedestal radial flux measuring method?



(Churchill 2015)

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Main novel physics self-consistently allowed in theory developed

Explaining pedestal in-out asymmetries

Species: (i) Banana Maxwell-Boltzmann bulk ions
(z) Collisional highly charged non-trace impurities

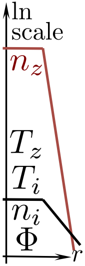
Orderings keep diamagnetic effects:

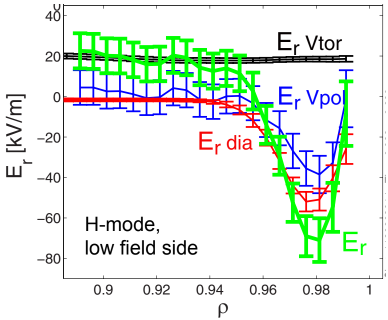
- Radial variation:

$$\mathbf{E}_r = \frac{1}{z_z e n_z}\frac{\partial p_z}{\partial r} + V_{zt}B_p - V_{zp}B_t$$

$$\Downarrow$$

$$\frac{\nabla_\perp n_z}{n_z} \sim \boxed{\frac{z_z}{z_i}} \frac{\nabla_\perp \Phi}{\frac{T_i}{z_i e}} \ll \frac{1}{\rho_{pz}}$$





(Theiler 2014)

- Poloidal variation: $\underbrace{\frac{\partial \ln B}{\partial \theta}}_{\sim\epsilon} \lesssim \frac{\partial \ln n_z}{\partial \theta}$

$\Rightarrow$ Strong radial and poloidal impurity density variation.

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Need to retain 2D radial flow effects for self-consistency

Explaining pedestal in-out asymmetries

- $\perp$ Momentum:

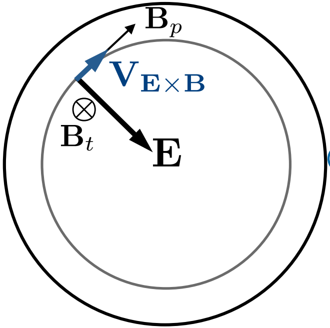
$$\mathbf{V}_{z\perp} = \frac{c}{B^2}\mathbf{B} \times \left[\nabla\Phi + \frac{1}{z_z e n_z}\nabla p_z\right]$$

- Particles:

$$\nabla \cdot [\mathbf{V}_z n_z] = \underbrace{\nabla \cdot [\mathbf{V}_{z\perp} n_z]}_{\text{Also radial flow!}} + \nabla \cdot \left[\mathbf{V}_{z\parallel} n_z\right] = 0$$

$$\Downarrow$$

$$V_{z\parallel} = V_{z\parallel}^{1D} + V_{z\parallel}^{diamagnetic} + V_{z\parallel}^{radial}$$



$\Rightarrow$ RADIAL FLOW affects PARALLEL FLOW due to the strong radial variation.

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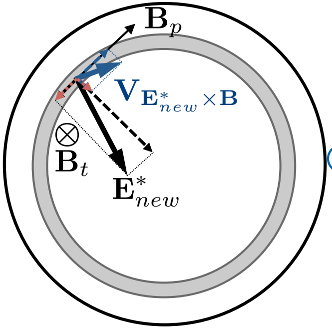

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Self-consistent set of conservation equations for impurities:

- $\parallel$ Momentum:

$$\underbrace{m_z n_z \mathbf{V}_z \cdot \nabla \mathbf{V}_z \cdot \frac{\mathbf{B}}{B}}_{\text{Inertial term}} + \underbrace{\frac{\mathbf{B}}{B} \cdot (\nabla \cdot \pi_z)}_{\text{Viscosity}} + \underbrace{\nabla_\parallel p_z}_{\text{Press.grad.}} + \underbrace{n_z z e \nabla_\parallel \Phi}_{\text{Pot.grad.}} = \underbrace{R_{zi\parallel}}_{\text{Frict.}}$$

$\Rightarrow$ The impurity parallel flow modifies the friction with the background ions.

- Energy:

$$\underbrace{\frac{3}{2} n_z \mathbf{V}_z \cdot \nabla T_z}_{\text{Convection}} + \underbrace{p_z \nabla \cdot \mathbf{V}_z}_{\text{Comp.heating}} + \underbrace{\nabla \cdot \mathbf{q}_z}_{\text{Heat flux}} + \underbrace{\pi_z : \nabla \mathbf{V}_z}_{\text{Viscous}} = \underbrace{\frac{3}{2} n_z \nu_{zi} (T_i - T_z)}_{\text{Equilibration}}$$

$\Rightarrow$ Compressional heating drives impurity temperature poloidal variation.
Its importance grows with the size of the flows.

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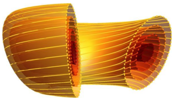
Momentum: Diamagnetic effects $\rightarrow$ Poloidal density variation

Explaining pedestal in-out asymmetries

Non-linear $\|$ momentum: $\nabla_{\|} p_z + n_z z e \nabla_{\|} \Phi = R_{zi\|} \overset{-\langle\rangle}{\Rightarrow}$ ~~drives~~

$$(1+\alpha n)\frac{\partial n}{\partial \vartheta} = g\left(n - b^2\right) + U\left(n-1\right) - D\left[\left(1-b^2\right) - \alpha\left(n-1\right)\right]$$



(Ball 2014)

Non-dimensionalization:

- Poloidal variation:

$$n = \frac{n_z}{\langle n_z \rangle}$$

$$b^2 = \frac{B^2}{\langle B^2 \rangle}$$

$$T = \frac{T_z}{T_i}$$

- Amplification factors (flux functions):

$$g = -\xi \left\langle \frac{\partial \ln p_i}{\partial \psi} - \frac{3}{2}\frac{\partial \ln T_i}{\partial \psi} \right\rangle$$

$$U = \xi \gamma \int d^3 v_i \frac{h_i}{B}\frac{v_{i\|}}{v_i^3}$$

$$D = -\xi \frac{\langle T_z \rangle}{T_i}\frac{z_i}{z_z}\frac{\partial \ln \langle p_z \rangle}{\partial \psi}$$

$$\alpha = \frac{\frac{z_z^2 \langle n_z \rangle}{z_i^2 \langle n_i \rangle}\frac{T_i}{\langle T_z \rangle}}{1 + \frac{\langle n_e \rangle}{z_i \langle n_i \rangle}\frac{T_i}{z_i T_e}} \sim 1$$

Radial derivatives of poloidal variation $\Rightarrow$ (cancel) As 1D with 2D effects

Known	Unknown
Magnetic field: b^2 Radial variation: g, U, D	Poloidal variation: n, T

$$\underbrace{n_z = \langle n_z \rangle}_{\text{known}} \Bigg(1 + \underbrace{\frac{n_z - \langle n_z \rangle}{\langle n_z \rangle}}_{\text{unknown}}\Bigg)$$

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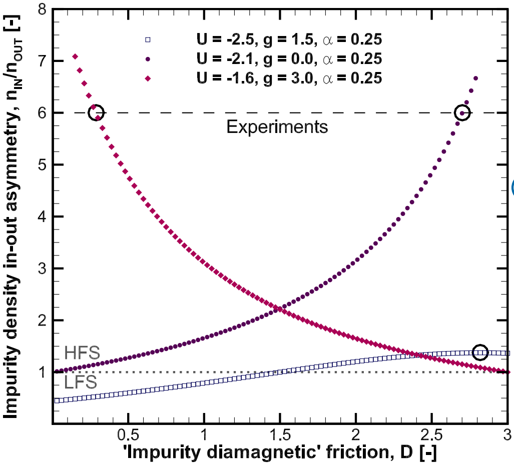
Linear parallel momentum: $(1+\alpha)\dfrac{\partial n}{\partial \vartheta} = (g - D)\left(1 - b^2\right) + (g + U + \alpha D)(n-1)$

E.g.
$$b^2 = 1 - 2\epsilon \cos\vartheta$$
$$n = 1 + C\cos\vartheta + S\sin\vartheta$$
with $S^2 + C^2 \leq 1$ $(n \geq 0)$

The ◯ corresponds to the 'impurity diamagnetic' friction D with the closest in-out asymmetry to the experiments.

⇒ Physical diamagnetic and radial effects allows to robustly capture much stronger in-out asymmetries.



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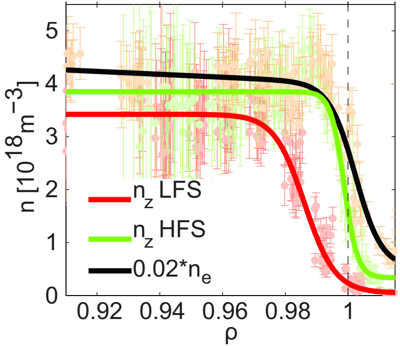
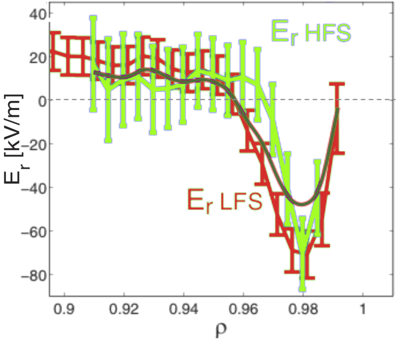
From quasineutrality and Maxwell-Boltzmann electron and main ions:

$$\underbrace{\frac{z_i}{z_z}\frac{\nabla_\perp\left(n_z - \langle n_z\rangle\right)}{n_z}}_{\text{More (-) } n_z \text{ slope on HFS}} \sim \frac{\nabla_\perp\left(\Phi - \langle\Phi\rangle\right)}{\frac{T_i}{z_i e}} \sim \boxed{-}\; \underbrace{\frac{E_r - \langle E_r\rangle}{\frac{T_i}{z_i e}}}_{E_r \text{ less (-) on HFS}}$$



(Churchill 2015)



(Theiler 2014)

Strong poloidal impurity density variation

⇓

Poloidal radial electric field variation in agreement with experiments.

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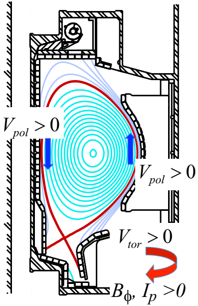
Energy: Compressional heating → Poloidal temperature variation

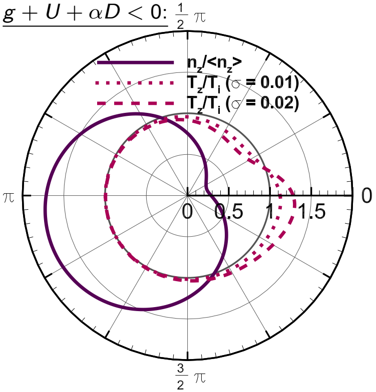
Explaining pedestal in-out asymmetries

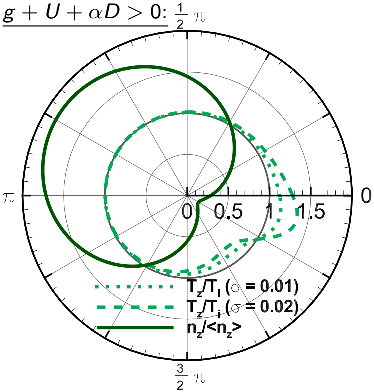
Energy conservation equation for impurities:

$$\underbrace{p_z \nabla \cdot \mathbf{V}_z}_{\text{Comp.heating}} = \underbrace{\frac{3}{2} n_z \nu_{zi} \left(T_i - T_z \right)}_{\text{Equilibration}} \Rightarrow \boxed{\frac{T_z - T_i}{T_z} = \underbrace{\sigma(\psi)}_{\geq 0} \left(g + U + \alpha D \right) \frac{1}{n^2} \frac{\partial n}{\partial \vartheta}}$$



(Theiler 2014)





Impurity up-down asymmetry ⇒ Impurity temperature in-out asymmetry.

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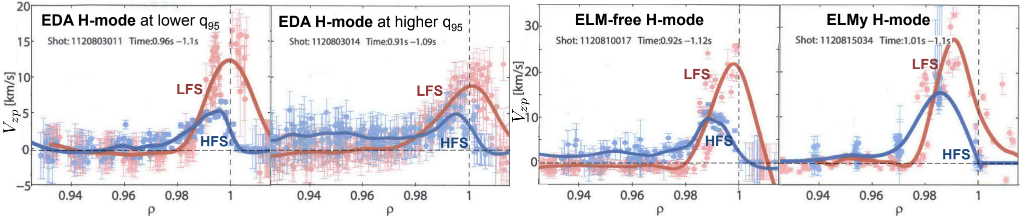
Pedestal impurity poloidal flow affects impurity accumulation
Explaining pedestal in-out asymmetries

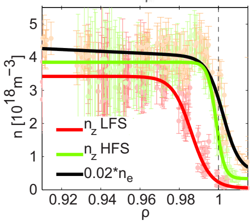
Impurity poloidal flow: Much larger on the LFS and positive.



(Churchill 2014)

Without diamagnetic effects: $$\frac{\mathbf{V}_z \cdot \boldsymbol{\nabla}\theta}{\mathbf{B} \cdot \boldsymbol{\nabla}\theta} = \overbrace{\chi_1(\psi)}^{\geq 0} \frac{g + U}{n}$$

↓ larger on LFS



(Churchill 2015)

⇒ The impurity poloidal flow affects the radial impurity flux via $g + U$.

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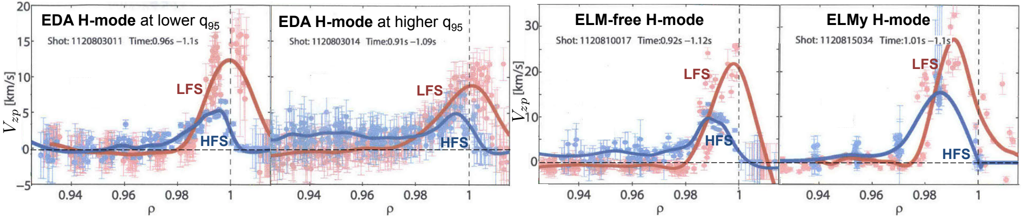
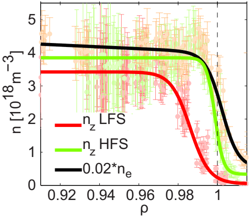


(Churchill 2014)

$$\frac{\mathbf{V}_z\cdot\nabla\theta}{\mathbf{B}\cdot\nabla\theta} = \overbrace{\chi_1(\psi)}^{\geq 0}\frac{g+U+\overbrace{\alpha D}^{\geq 0}}{n} + \overbrace{\chi_2(\psi)}^{\geq 0}\frac{\partial \ln n_z}{\partial\psi}(1+\alpha n)$$

$\downarrow$ Even larger on LFS

$\downarrow$ Larger on LFS (more – on HFS)



(Churchill 2015)

$\Rightarrow$ Stronger poloidal variation of the impurity flow.

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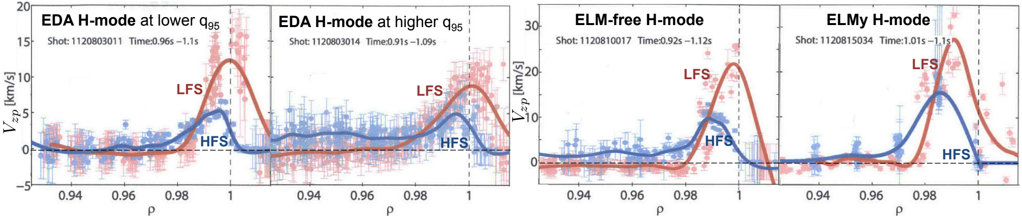
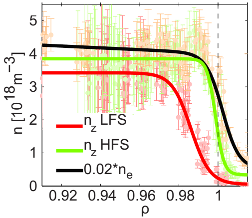


(Churchill 2014)

$$\overbrace{\frac{\mathbf{V}_z \cdot \nabla\theta}{\mathbf{B}\cdot\nabla\theta}}^{\oplus} = \overbrace{\chi_1(\psi)}^{\geq 0} \frac{g + U + \alpha D}{n} \overbrace{+ \overbrace{\chi_2(\psi)}^{\geq 0} \frac{\partial \ln n_z}{\partial \psi}(1+\alpha n)}^{\ominus}$$

↓ Even larger on LFS

↓ Larger on LFS (more − on HFS)



(Churchill 2015)

⇒ For positive poloidal flow, $g + U + \alpha D \geq 0$.

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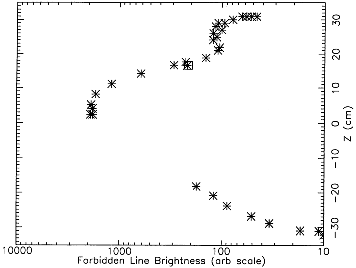
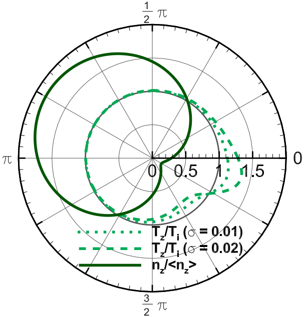
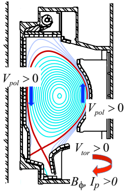
Model predictions in agreement with experimental observations

Explaining pedestal in-out asymmetries



(Rice 1997)





(Theiler 2014)

⇒ Upper impurity accumulation in agreement with the experiments.

Experimental physics captured	Us
Strong poloidal imp. **density** variation	✓
Weak poloidal imp. **temperature** variation	✓
Weak poloidal **radial electric field** variation	✓

- ✓ The measured impurity density and temperature in-out asymmetry can be successfully captured without invoking anomalous transport.
- ✓ Self-consistent '2D' radial and impurity diamagnetic flow effects!

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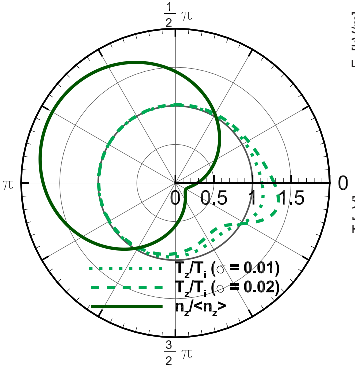
Pedestal profile alignment: Total pressure with HFS temperature

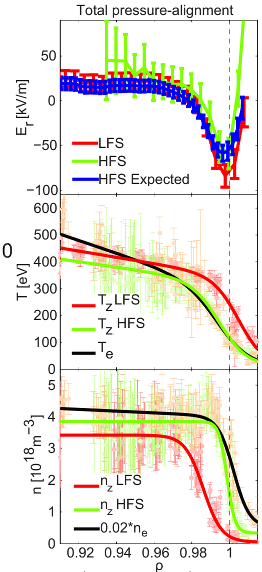
Explaining pedestal in-out asymmetries

Poloidal variation	Variables
Strong	n_z
Weak	~~T_z~~, ~~E_r~~
Very weak	Φ, n_i, n_e
Flux functions	T_i, T_e

$$p_{tot} = n_e T_e + n_i T_i + \underbrace{n_z T_z}_{\sim \frac{z_i^2}{z_z^2} n_i T_i}$$

~~T_z~~ $\rightarrow T_{z,HFS}$





(Churchill 2015)

⇒ Sharp prediction of the pedestal profile alignment: total pressure with inboard impurity temperature.

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Radial flux evaluation
Impurity confinement
I-mode explanation
Summary

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Novel insight: Radial impurity flux from existing measurements

Radial flux measurement to avoid impurity accumulation

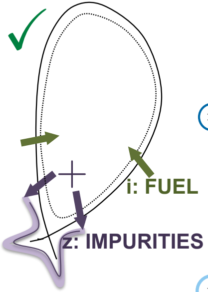
1. Large aspect ratio (without diamagnetic effects) → *Espinosa & Catto, POP 2017*

Solubility: $\left\langle BR_{zi\|}\right\rangle = 0$

$$\text{Radial impurity flux} \propto -\left\langle \frac{BR_{zi\|}}{1+(b^2-1)} \right\rangle \overset{\downarrow}{=} \underbrace{\left\langle BR_{zi\|}\left(b^2-1\right)\right\rangle}_{\text{Available measurements}} \left[1 + O(\epsilon)\right]$$

$$\text{Radial impurity flux} \propto -\left\langle \left(1-b^2\right)^2 \right\rangle g + \left\langle (n-1)\left(b^2-1\right)\right\rangle (g+U)$$

- $\left\langle \left(1-b^2\right)^2 \right\rangle \to 2\epsilon^2$
- $(n-1) \to$ Imp. density: $\epsilon \frac{n_{HFS}-n_{LFS}}{n_{HFS}+n_{LFS}}$
- $g \to$ Radial profiles: $\propto \left(\frac{1}{2}\frac{\partial \ln T_i}{\partial \psi} - \frac{\partial \ln n_i}{\partial \psi}\right)$
- $U \to$ Computationally demanding kinetic calculation of full bulk ion response



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New realization: Radial impurity flux from existing measurements

Radial flux measurement to avoid impurity accumulation

Charge exchange spectroscopy

Imp. density $\epsilon \frac{n_{HFS}-n_{LFS}}{n_{HFS}+n_{LFS}}$

Imp. pol. flow $\propto \frac{n_z \mathbf{V}_z \cdot \nabla\theta}{\mathbf{B}\cdot\nabla\theta}$

$2\epsilon^2$

$$\text{Radial impurity flux} \propto -\left\langle \left(1-b^2\right)^2 \right\rangle g + \left\langle (n-1)\left(b^2-1\right)\right\rangle (g+U)$$

Thomson scattering $\propto \left(\frac{1}{2}\frac{\partial \ln T_e}{\partial\psi} - \frac{\partial \ln n_e}{\partial \psi}\right)$

✓ Electron temperature profile twice as steep as the electron density or more.

✓ HFS impurity accumulation with poloidal flow in the magnetic field direction OR LFS accumulation with poloidal flow in the opposite direction.

⇒ Novel insight: The impurity radial flux can be obtained from measurements currently available, bypassing the computationally demanding kinetic calculation.

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Impurity accumulation
In-out asymmetries
Poloidal variation
Diamagnetic effects
Impurity flow effects
Conservation equations
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E_r poloidal variation
Energy → Poloidal T var.
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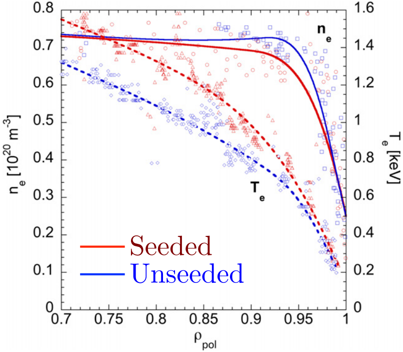
Techniques for actively preventing impurity accumulation

2. General geometry with inertia and plasma heating → *Espinosa&Catto,PPCF 2017*

- Outboard → Inertia
- Inboard → Plasma heating (ICRH,NBI)
- $\uparrow \frac{\partial \ln T_e}{\partial \ln n_e}$ → Seeding



(Schweinzer 2011)

Solubility constraint $\left\langle \frac{BR_{zi\|}}{n_z} \right\rangle = 0$ ⇝ Relates
- fluid i (g) ✓
- kinetic i (U)
- poloidal flow z ✓

⇒ Solve the solubility condition for the kinetic effects, which cannot be measured, to express the radial impurity flux as a function of available diagnostics.

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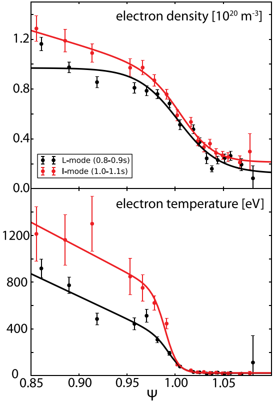
Theoretical explanation of impurity removal on I-mode

Radial flux measurement to avoid impurity accumulation

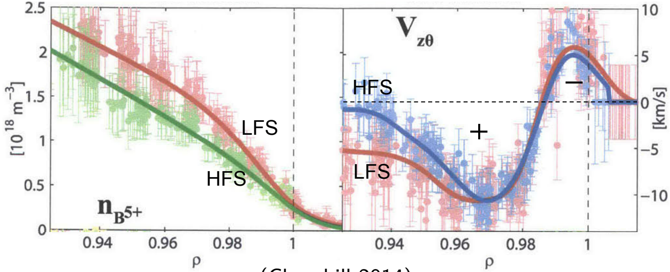
E.g. I-mode: Radial impurity flux

$$\propto -\underbrace{\left\langle \left(1-b^2\right)^2 \right\rangle g}_{\text{Outward}} + \underbrace{\left\langle (n-1)\left(b^2-1\right) \right\rangle (g+U)}_{\text{Outward (close to separatrix)}}$$

- g ↑ Thomson scattering: - $\propto \left(\frac{1}{2}\frac{\partial \ln T_e}{\partial \psi} - \frac{\partial \ln n_e}{\partial \psi}\right)$
- $(n-1)$ ↑ Imp.density: - $\epsilon \frac{n_{HFS}-n_{LFS}}{n_{HFS}+n_{LFS}}$
- U ↑ Imp.pol.flow: +/- $\propto \frac{n_z \mathbf{V}_z \cdot \nabla\theta}{\mathbf{B}\cdot\nabla\theta}$



(Walk 2014)



(Churchill 2014)

⇒ I-mode regime is favourable to avoid impurity accumulation.

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Theoretical explanation of impurity removal on I-mode

Radial flux measurement to avoid impurity accumulation

E.g. I-mode: Radial impurity flux

Outward / Outward (close to separatrix)

$$\propto -\left\langle \left(1-b^2\right)^2 \right\rangle g + \left\langle (n-1)\left(b^2-1\right) \right\rangle (g+U)$$

Thomson scattering: -

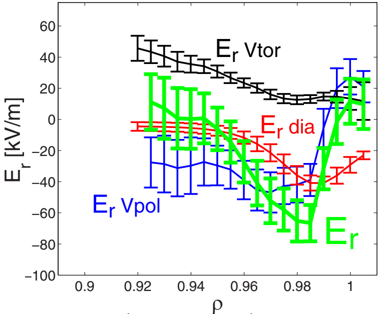
$$\propto \left(\frac{1}{2}\frac{\partial \ln T_e}{\partial \psi} - \frac{\partial \ln n_e}{\partial \psi} \right)$$

Imp.density: -

$$\epsilon \frac{n_{HFS} - n_{LFS}}{n_{HFS} + n_{LFS}}$$

Imp.pol.flow: +/-

$$\propto \frac{n_z \mathbf{V}_z \cdot \nabla\theta}{\mathbf{B} \cdot \nabla\theta}$$



(Theiler 2014)

⇒ I-mode regime is favourable to avoid impurity accumulation, without invoking anomalous transport due to weakly coherent mode.

Preventing impurity accumulation
Silvia Espinosa
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Major ideas and results

✓ Self-consistent model with '2D' radial and impurity diamagnetic flow effects.

✓ Experimental values of impurity density, temperature and radial electric field in-out asymmetries successfully explained neoclassically.

2D diamagnetic	→	Espinosa & Catto 2017, prep.
Density asymmetry	→	"
Temperature asymmetry	→	"

✓ First method of measuring the radial impurity flux from available diagnostics, without the need of a computationally demanding kinetic calculation.

✓ Outward neoclassical impurity flux and inward fueling found for I-mode.

Large aspect ratio	→	Espinosa & Catto 2017, POP
General geometry	→	Espinosa & Catto 2017, PPCF
I-mode	→	Espinosa & Catto 2017, PRL sub.

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Preventing impurity accumulation

H-mode turbulence reduction & I-mode impurity removal

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10th Plasma Kinetics Working Meeting
July 18, 2017

Work supported by La Caixa Fellowship and DOE Grant DE-FG0291ER54109.