Thermal Ion Orbit Loss and Intrinsic Toroidal Velocity Near the Last Closed Flux Surface

by
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Recent Mach probe measurements of bulk ion toroidal velocity near the outer LCFS in DIII-D agree in sign, profile width and approximately in magnitude with a simple thermal ion loss model:

- ECH H-mode => No NBI drive; intrinsic rotation conditions
- An edge source may be an important ingredient for intrinsic rotation
- See S.H. Müller, PI2.00003, 3 pm Wednesday

Formerly, we considered orbit loss near the top of the pedestal, since momentum needs density. These new measurements indicate that orbit loss plays a role in velocity generation to and through the LCFS.

The importance of limiting surfaces in the SOL and the strong radial electric fields measured near the edge in H-mode conditions has motivated us to modify the simple loss model accordingly.

The basic result is that the calculated velocity profile is modified, but the general width and height remain.
Simple Orbit Loss Model Compares Reasonably well with Mach Probe Measurements of Bulk Ion $V_\phi$

- Compare thermal Mach number values
  - Removes some temperature uncertainty in the probe conversion
  - Loss model calculation scales as the ion thermal velocity at the LCFS

- ECH H-mode $\Rightarrow$ Intrinsic conditions
Profile Width from the Simple Model is Given by the Poloidal Ion Gyroradius; the Height Increases with Thermal Velocity

- Absolute model-computed velocity profile from the previous slide, showing the width of the narrow velocity layer in mm

- This simple model velocity calculation assumes loss cones are empty, that loss is only through the X-point, and neglects any radial electric field effects
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![Graph showing velocity profile and model calculations](image-url)
Thermal Ion Orbit Loss from the Edge of A Tokamak Has Been Considered by Many, for Some Time

- Typically, related to looking for a bifurcation mechanism in the radial electric field, or concerning energy transport. Recently, velocity generation has been addressed.

  Berk and Galeev, PF 10, 441 (‘67).
  Pre-divertor torus. Investigating loss cone generated instabilities.

  Hinton and Chu, NF 25, 345 (‘85).
  Shaing and Crume, PRL 63, 2369 (‘89).
  Shaing, PF-B 4, 3310 (‘92).
  Chankin and McCracken, NF 33, 1459 (‘93).
  Miyamoto, NF 36, 927 (‘96).
  Heikkinen, Kiviniemi, and Peeters, PRL 84, 487 (‘00).
  Kiviniemi, Heikkinen, and Peeters, NF 40, 1587 (‘00).

  Ku, Baek, and Chang, PoP 11, 5626 (‘04) “velocity space hole” numerical orbits.
  Chang and Ku, PoP 15, 062510 (‘08). Simulation; co-ip rotation due to edge orbit loss

  deGrassie, Groebner, Burrell, and Solomon, NF 49, 085020 (‘09). “former”
Consider Orbit Loss Dynamics on the Backdrop of An H-mode Density Pedestal Profile

\[ n_i \]

\[ \sim \text{H-mode edge} \]

\[ (X) \]

\[ \tilde{\psi} \]

Normalized Psi
Inside, counter-$I_p$ Starting Guiding Center Orbit Can Be Lost with Sufficient Orbit Width

\[ \bar{\rho}_\theta = \bar{v}_i / \omega_{c\theta} \]

• Orbit loss is limited to a few poloidal gyro-radii from the LCFS

\[ \nabla \times \vec{B} \]

Counter-$I_p$

\[ \text{pitch} < p_x \]
Inside, co-$I_p$ Starting Guiding Center Orbit is Confined, As it Drifts Further from the LCFS

\[ \bar{\rho}_\theta = \frac{\bar{v}_i}{\omega_{c\theta}} \]

\[ n_i \]

\[ Z=0 \]

\[ \text{start} \]

\[ \text{Counter-}I_p \]

\[ \text{Loss} \]

\[ Co-I_p \]

\[ 1 \]

\[ (X) \]

\[ \tilde{\psi} \]

\[ Co-I_p \]

\[ (X) \]

- Preferential counter loss creates a hole in velocity space, leaving excess co-directed momentum.
Outside, “Low” Energy co-$I_p$ and Counter-$I_p$ Starting g.c. Orbits are Lost

Provided pitch $< p_x$
Outside, “Higher” Energy co-$I_p$ Orbits Have Sufficient Width to Get Inside at The X-point Major Radius, and Be Confined.

Confinement on the co-side again leaves a hole on the counter side of phase space.
Outside, “Higher” Energy Co-Iₚ Orbits Have Sufficient Width to Get Inside and Be Confined

- Confinement on the co-side again leaves a hole on the counter side of phase space

- Assume steady state, empty loss cone

- The radial E field is a measured quantity. The process that ensures charge balance is not specified. e⁻ loss?

- Orbit loss is by no means a self contained model for intrinsic rotation, but may have some role as a seed
The Loss Cones Computed By the Model Show the Asymmetry in Parallel Velocity

- The loss boundaries are calculated using the constants of motion and the requirement that $\tilde{\psi} > 1$ at $R = R_x$
  - Inside Start
  - $\tilde{\psi} = 0.988$
  - $K_\perp$ (eV)
  - Numerical guiding center orbits in the actual EFIT equilibrium are used to check these model-computed boundaries
  - A Maxwellian at rest in the lab frame is placed over empty loss cones to compute $<V_{\parallel}>$
- SOL Start
  - $\tilde{\psi} = 1.0125$
  - $K_{\parallel}$ (eV)
The Agreement with Probe Measurements Motivated Including Other Effects in the Loss Model: SOL Limiters

- Outside starting ions can be lost without sufficient pitch angle to reach $R = R_X$

- Expansion of the flux surfaces leads orbits to the **baffle**, away from the X-point surface. This effect becomes larger as the starting distance from the LCFS increases.
The Agreement with Probe Measurements Motivated Including Other Effects in the Loss Model: E Field

- Nonzero E shifts the loss boundaries in phase space, modifying $p_x$, and the trapped/passing boundaries.
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- Nonzero E shifts the loss boundaries in phase space, modifying $p_x$, and the trapped/passing boundaries.

Have only considered effects of rigid rotor E fields on the loss cone velocity, $\Phi = \text{const} \times \Psi$.
These Additional Effects Modify But Do Not Wipe Out 
The Computed Loss Cone Model Velocity Profile

- Baffle loss increases the co-I_p computed velocity, primarily in the SOL
These Additional Effects Modify But Do Not Wipe Out The Computed Loss Cone Model Velocity Profile

- Add $E$ field effect for values comparable to those measured in ECH H-modes, negative inside, positive outside
- Negative $E$ reduces and positive $E$ increases the computed co-$I_p$ loss cone model velocity
- Considering a measured electric potential profile is best left to Monte-Carlo simulations, which can also include collisions
If Measurements Indicate A Loss Cone Distribution Exists in the Tokamak Edge, What About Instabilities?

• Our interest here is whether an instability can tap into the asymmetry in $V_{//}$ and have consequences for momentum transport. Former well-studied instabilities should be reconsidered in toroidal geometry with pedestal-like gradients

• Some candidates
  - Drift Cyclotron Loss Cone (DCLC)
  - Drift Cyclotron
  - Inverse Gradient
  - Current Driven Ion Cyclotron

• The loss cone drive for the diverted tokamak is weak compared to a mirror

• These will be considered more in the future
Summary

• A simple thermal ion orbit loss model is in approximate agreement with Mach probe measurements for the bulk ion, near the LCFS in H-modes without NBI drive

• The velocity profile features are not washed out with the addition of other experimental effects; limiters in the SOL and a radial E field

• The steady state distribution function in the presence of a measured H-mode radial E field and collisions should be addressed with simulations

• Many more experiments are needed, to test the simple model qualitatively, and to see if there is a relation to intrinsic rotation

• Instabilities?