Effect of Ambipolar Plasma Flow on the Penetration of Resonant Magnetic Perturbations in a Quasi-Axisymmetric Stellarator

A. Reiman[1], M. Zarnstorff[1], D. Mikkelsen[1], L. Owen[2], H. Mynick[1], S. Hudson[1],
D. Monticello[1]

[1] *Princeton Plasma Physics Laboratory*
[2] *Oak Ridge National Laboratory*

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Introduction

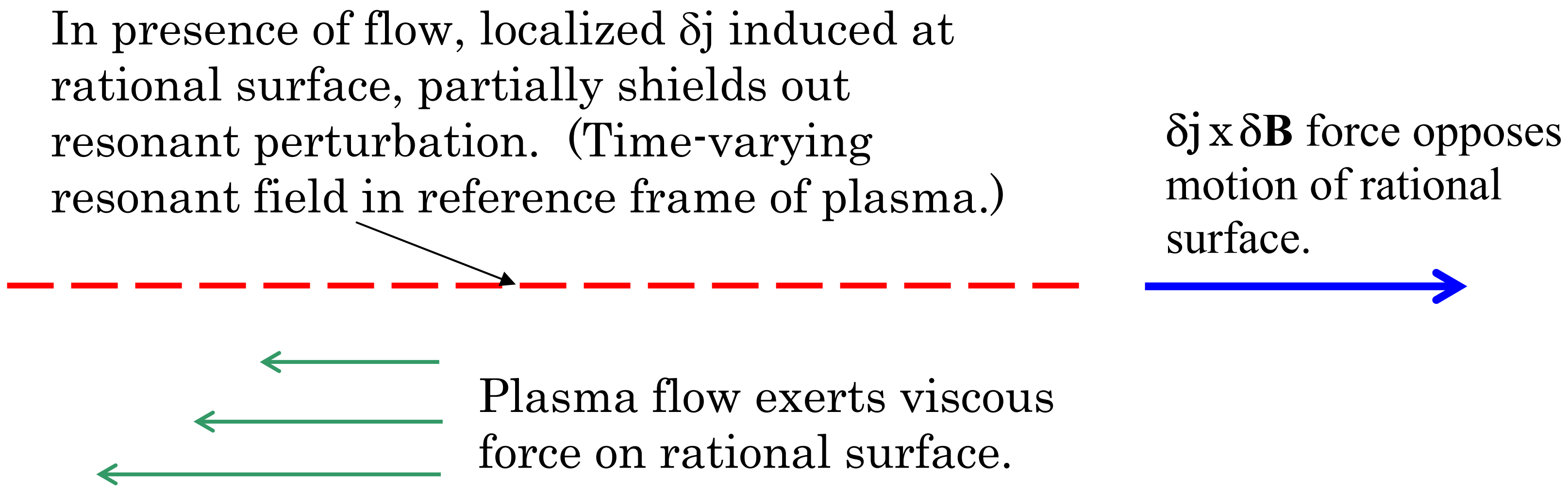
- Plasma flow at rational surfaces can shield out resonant magnetic perturbations that produce magnetic islands.
- The effect is believed to play an important role in reducing vulnerability of present day tokamaks to field errors.
    - An important issue for setting field error tolerance for ITER.
    - Effect studied systematically in tokamak experiments.
- Quasi-axisymmetry is predicted to allow strong toroidal flow in NCSX.
    - Ripple produces nonambipolar transport that modifies physics of flow shielding.

NCSX Design Incorporates Several Layers of Defense Against Magnetic Islands

- Fixed boundary configuration chosen in part because of good flux surfaces.
- For coil design, optimization code built around PIES code suppressed resonant field components while preserving desired engineering and physics properties.
- Two sets of trim coils for further control over resonant magnetic fields.
- Monotonically increasing ι for neoclassical suppression of magnetic islands. (Neoclassical effect not included in PIES calculations.)

- Flow effect could further improve flexibility to generate range of configurations with good flux surfaces.
- NCSX experiments will provide new perspective on physics of effect.

Effect of Flow on Penetration of Resonant Field, δB



In presence of flow, localized δj induced at rational surface, partially shields out resonant perturbation. (Time-varying resonant field in reference frame of plasma.)

δj x δ**B** force opposes motion of rational surface.

Plasma flow exerts viscous force on rational surface.

- When resonant perturbation sufficiently large, δj x δ**B** torque becomes large enough to locally suppress plasma flow, allowing resonant perturbation to fully penetrate rational surface.
- Threshold for penetration of resonant field perturbations determined by relative magnitudes of electromagnetic torque and of torques associated with the plasma flow.

Quasi-Axisymmetric Stellarator:

Strong Poloidal Flow Damping, Weak Toroidal Damping

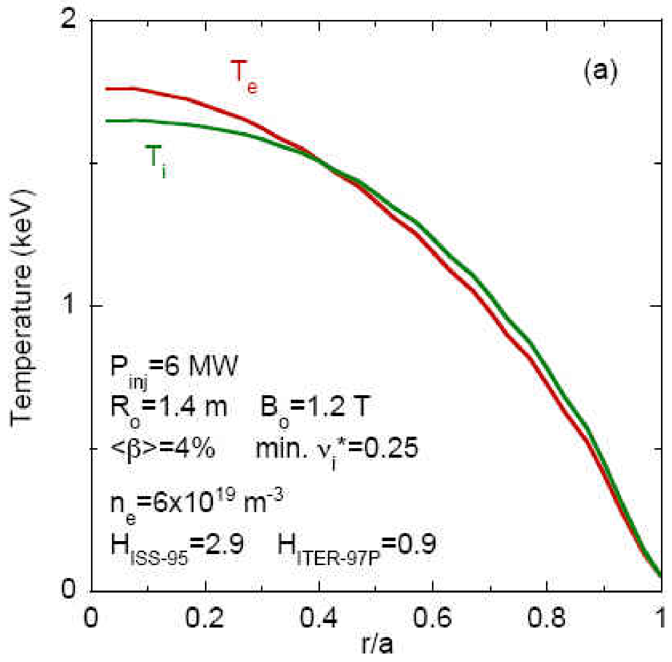
$$\mathrm{v}_{i\perp} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} - \frac{1}{ne}\frac{\nabla p_i \times \mathbf{B}}{B^2}$$

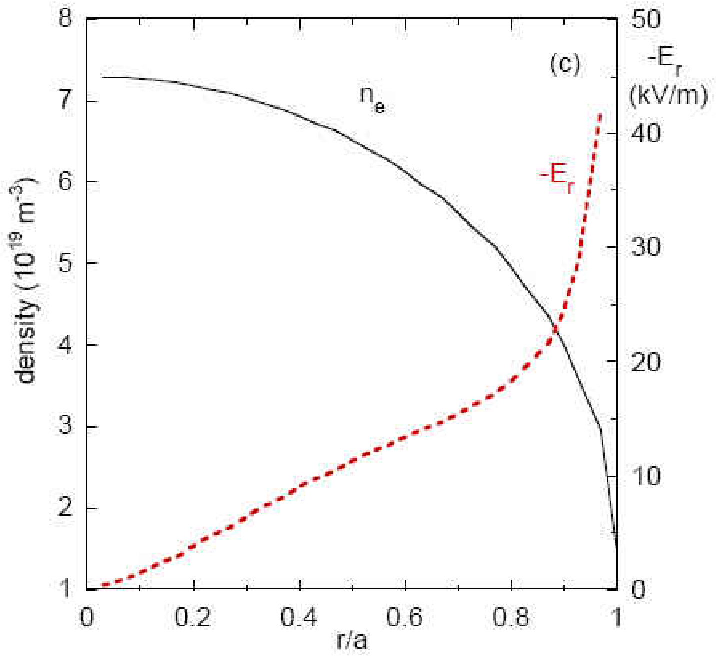
$$\mathbf{v} = \mathrm{v}_{\perp}\hat{r}\times\hat{b} + \mathrm{v}_{\|}\hat{b}, \text{ where } \hat{b} = \mathbf{B}/B\,,\ \mathbf{B} = B_{\mathrm{p}}\hat{\theta} + B_t\hat{\phi}\,.$$

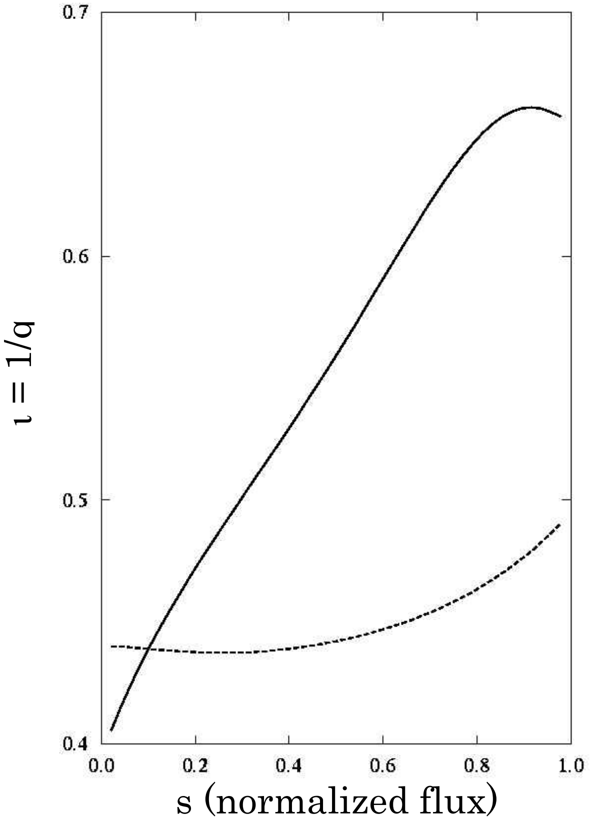
$$\mathrm{v}_{\theta} = 0 \;\Longrightarrow\; \mathrm{v}_{\|} = (B_t/B_p)\mathrm{v}_{\perp}$$

- E_r determined by ambipolarity constraint. Calculate via Mikkelsen-Zarnstorff 1D transport code.
- NCSX in interesting intermediate ripple regime: Ripple sufficiently small that toroidal flow damping weak, large enough to produce substantial E_r.

Do Numerical Calculations for β = 4% Reference NCSX Equilibrium







Momentum Diffusion Differs from that in Tokamak by Presence of j x B Force Due to Nonambipolar Current

$$\rho\frac{d\mathrm{v}_z}{dt}=\frac{1}{r}\frac{d}{dr}(\mu\rho r\frac{d\mathrm{v}_z}{dr})-j_r(\mathrm{v}_z)B_\theta$$

Use linear approximation for $j_r(\mathrm{v}_z)$, $j_rB_\theta\approx-\alpha(r)[\mathrm{v}_z-\mathrm{v0}(r)]$, interpolating between $\mathrm{v}_z=0$ and ambipolar value of E_r:

$$\rho\frac{d\mathrm{v}_z}{dt}=\frac{1}{r}\frac{d}{dr}(\mu\rho r\frac{d\mathrm{v}_z}{dr})-\alpha(r)[\mathrm{v}_z-\mathrm{v0}(r)]$$

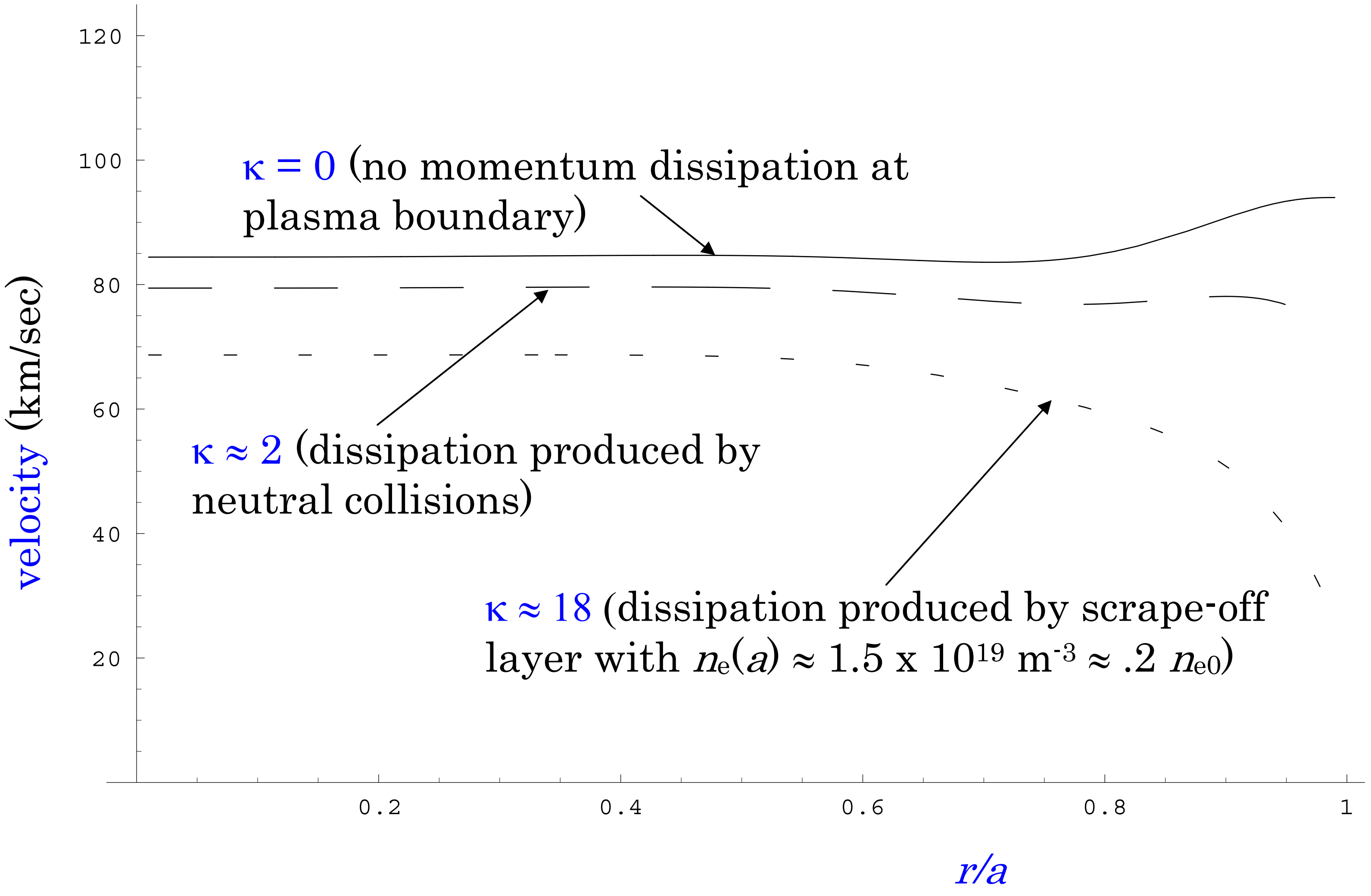
Take momentum diffusivity μ ≈ thermal diffusion coefficient ≈ constant.

Boundary Condition Determined by Momentum Dissipation at Plasma Boundary

- Momentum flow through plasma edge = $-4\pi^2 aR\mu\rho d\mathrm{v}_z / dr$.
  - ○ Momentum transfer to neutrals estimated by Monte Carlo calculation using Degas code with model axisymmetric geometry. Gives $a\, d\mathrm{v}_z(a) / d\, r = -\kappa\, \mathrm{v}_z(a)$, $\kappa \approx 2$.
  - ○ Momentum loss in scrape-off layer $\approx \rho\, \mathrm{v}_z / \tau$, where $\tau \approx L / \mathrm{v}_{ti}$. (ion mean free path ≈ connection length). Sensitive to assumed $\rho(a)$. $\kappa \approx 18$ for $n_e(a) \approx 1.5 \times 10^{19}\ \mathrm{m}^{-3} \approx .2\, n_{e0}$.

Numerical Solution of Momentum Diffusion Equation for Unperturbed Flow

Three Different Levels of Momentum Dissipation at Plasma Edge



$\kappa = 0$ (no momentum dissipation at plasma boundary)

$\kappa \approx 2$ (dissipation produced by neutral collisions)

$\kappa \approx 18$ (dissipation produced by scrape-off layer with $n_e(a) \approx 1.5 \text{ x } 10^{19}\ \text{m}^{-3} \approx .2\ n_{e0}$)

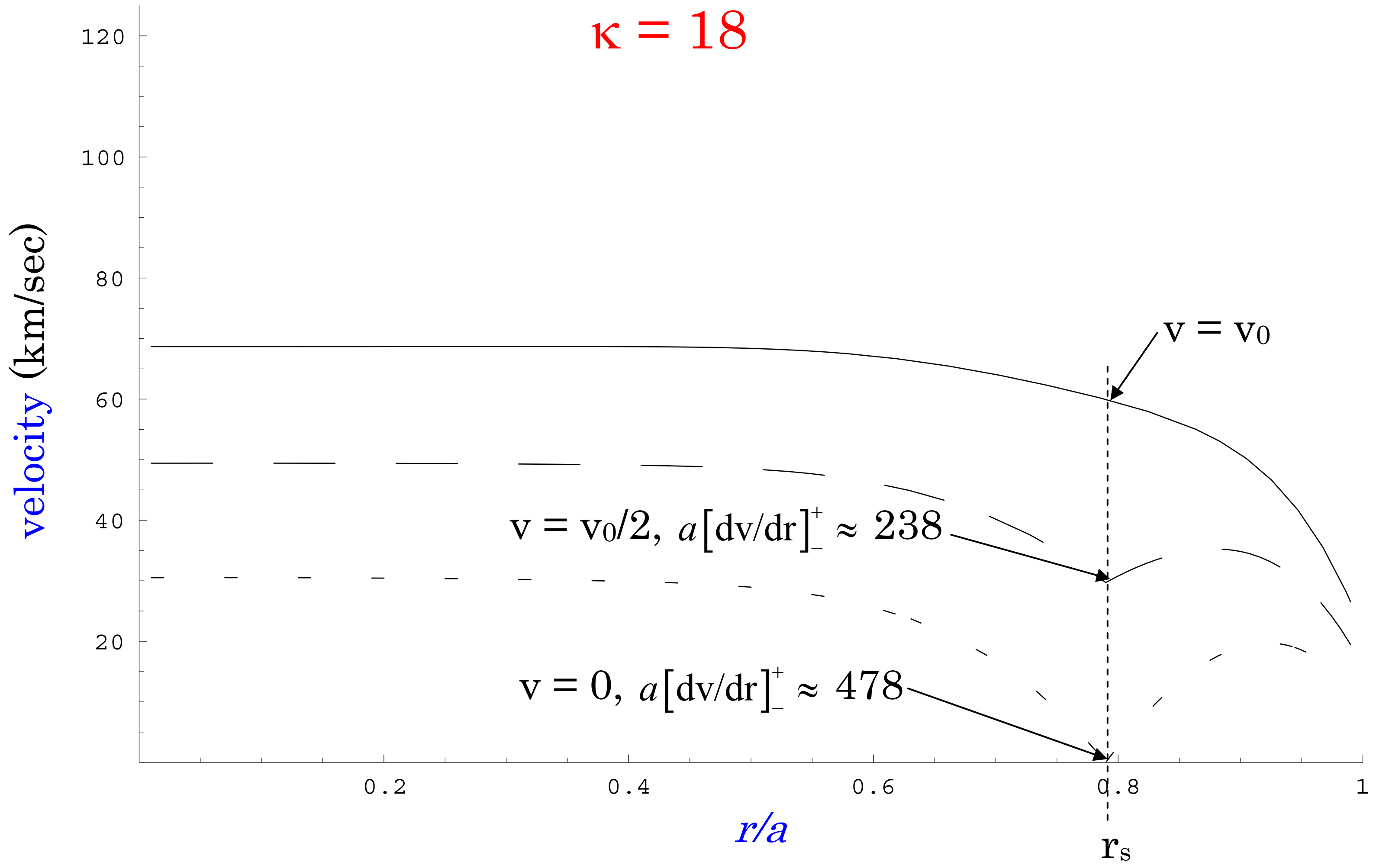
Electromagnetic Torque

- Induced current at rational surface partially shields out resonant field, interacts with resonant magnetic field to produce electromagnetic torque.
- Response of rotating plasma at rational surface to externally imposed resonant perturbation has been calculated theoretically for variety of regimes and under variety of assumptions.

  (see e.g. R. Fitzpatrick and T.C. Hender, Phys. Fluids B 3, 644 (1991); R. Fitzpatrick, Nucl. Fusion 33, 1049 (1993); Z. W. Ma, X. Wang, and A. Bhattacharjee, Phys. Plasmas 3, 2427 (1996); X. Wang and A. Bhattacharjee, Phys. Plasmas 4, 748 (1997); O. A. Hurricane, T.H. Jensen, and A. B. Hassam, Phys. Plasmas 2, 1976 (1995); R. Fitzpatrick, Phys. Plasmas 5, 3325 (1998); F. L. Waelbroeck, Phys. Plasmas 5, 4040 (2003))

  - Calculations for either slab or cylindrical geometry.
  - Because local induced current determined by layer physics, calculations relevant for shaped tokamaks and for stellarators.

Numerical Solution of Momentum Diffusion Equation, Three Different Magnitudes of v at Rational Surface, $\kappa = 18$

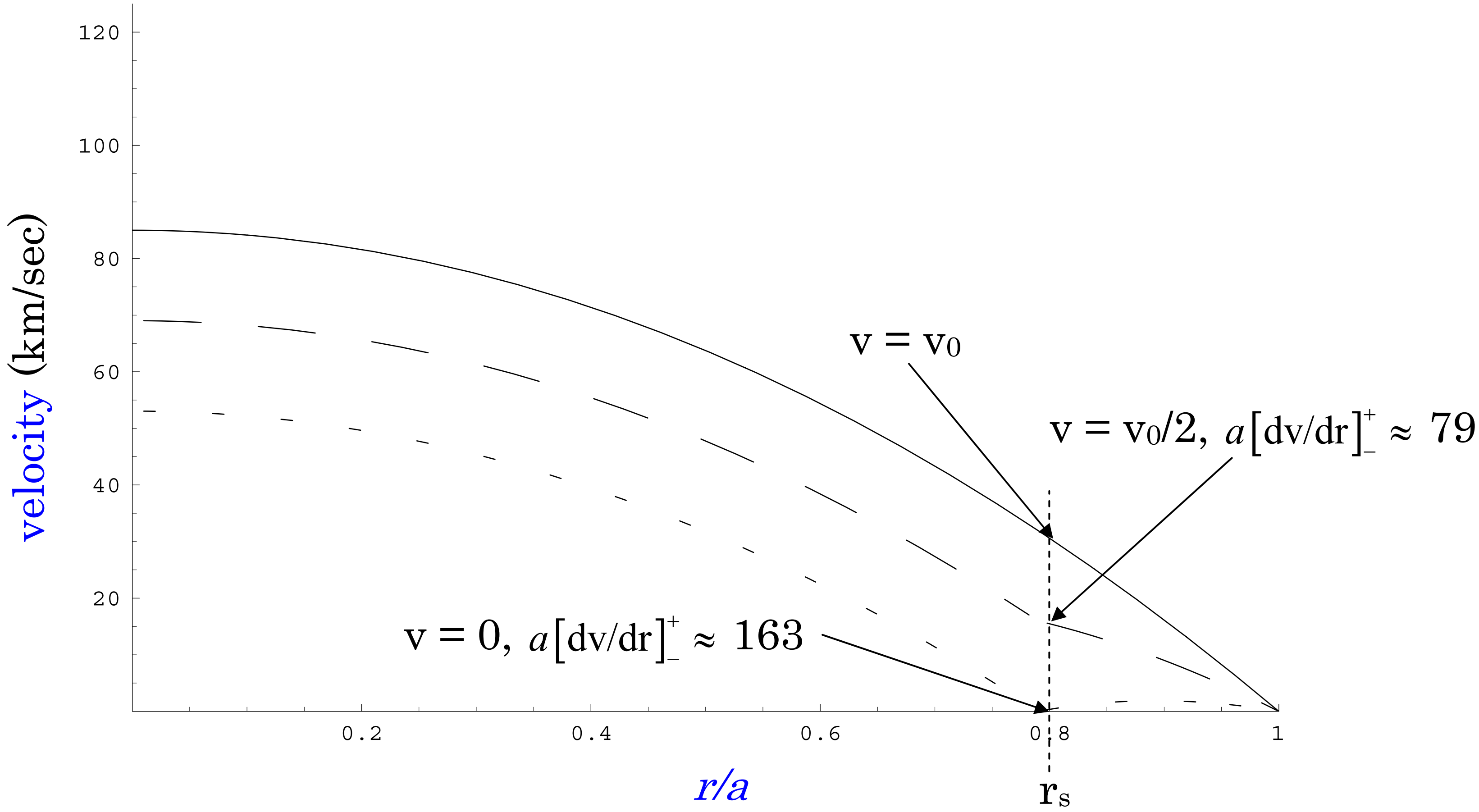


Viscous Torque on Rational Surfaces in Presence of Resonant Magnetic Perturbation

- Electromagnetic torque exerted by resonant magnetic perturbation on rational surface balanced by viscous torque.
- Viscous force exerted on rational surface by plasma flow given by $4\pi^2 rR\rho\mu[\mathrm{dv/dr}]_-^+$, where $[\mathrm{dv/dr}]_-^+$ is jump in radial derivative of fluid velocity across boundary layer.

Compare with a Simple Tokamak Model

- Rotating plasma driven by neutral beams with uniform deposition profile.
- Take viscosity, μρ, to be constant.



Comparison with Tokamak (continued)

- Nonambipolar transport ⇒ radial current ⇒ j x B force ⇒ shorter velocity gradient scale length ⇒ stronger viscous force enhances shielding effect.
- If $v_s \equiv v(r_s) > 0$, it must satisfy $F_{visc}(v_s) = F_{em}(v_s)$. $F_{visc} \approx$ linear function of v_s, as in tokamak ⇒ threshold value of v_s for mode penetration is same as in tokamak.
- Resonant mode amplitude penetration threshold scales as $F_{visc}^{1/2}$.
- Compare with a DIII-D reference shot.
  - DIII-D: $\langle \beta \rangle \approx 3.7\%$, $\langle n_e \rangle \approx 5 \times 10^{19}$ m^{-3}, ellipticity $\kappa \approx 1.8$, $B \approx 1.2$ T, rotation of rational surface ≈ 12 kHz, $R \approx 1.67$ m, $R/\langle a \rangle \approx 2.1$.
  - NCSX: $\langle \beta \rangle = 4\%$, $\langle n_e \rangle = 6 \times 10^{19}$ m^{-3}, ellipticity $\kappa \approx 1.8$, $B \approx 1.2$ T, rotation ≈ 7 – 9 kHz, $R \approx 1.42$ m, $R/\langle a \rangle \approx 4.3$.
  - DIII-D penetration threshold $B_{r21}/B \approx 4\text{x}10^{-4}$.

Discussion

- Initial NCSX coil design algorithm that did not explicitly target resonant field error reduction yielded $B_{rnm} / B \approx 1.3\text{x}10^{-3}$ for $m = 5$, $n = 3$. Further coil optimization using PIES code to reduce magnitude of resonant field components was prudent step in coil design process.
- Flow shielding will further improve flexibility to generate range of configurations with good flux surfaces and further reduce vulnerability to field errors.
- Ripple magnitude increases rapidly towards plasma edge ⇒ flow velocity profile broad relative to that in a tokamak ⇒ stronger shielding for low order rational surfaces near plasma edge. Potential implications for startup scenarios.
- Radial current driven by nonambipolar transport exerts j x B force that resists departures from ambipolar velocity, enhances shielding effect.

- Flexibility of 3D device will potentially allow a range of experiments to clarify physics of shielding and contribute towards the goal of being able to reliably predict field error penetration thresholds in tokamaks and stellarators.
  - Control over magnitude of non-quasisymmetric ripple will provide knob for controlling magnitude of nonambipolar current, toroidal flow damping.
  - Externally generated rotational transform will allow control over q profile independent of Δ’.
  - Control over neutral beam power & ohmic current drive will allow modification of rotation with fixed current profile.
  - Two sets of trim coils will provide control over resonant components of field.