Mechanisms of Edge-Core Coupling: Some Speculations on How SOL Flows Influence Intrinsic Rotation and the L→H Transition

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Caveat: - Speculative, by any standard.....
- Work in progress.....

Outline

- → Key Points of SOL Flow Story, a la' LaBombard, et. al.
- → Critical Questions
- → Scenario – a trial balloon
- → Beginnings of a Calculation . . . .
- → Suggestions for Future Work

Disclaimer

- No pretense of a "final answer"
- Presentation in 'spirit of a workshop' ....

→ **Key Points of SOL Flow Story**

- **dual asymmetry of:** — as always symmetry breaking crucial

→ turbulent particle flux $\Gamma_r^{+}(r_{sep}, \theta)$

→ upper vs. lower null point location
i.e. some symmetry-breaking in SOL

⇒ net SOL flow → substantial inboard

⇒ $\pm \Delta V_{\phi_{co}}$ for $\underline{B} \times \underline{\nabla} B$ {toward / away} null point

⇒ impact on {L-mode intrinsic rotation / L→H transition}

- non-trivial case that SOL flow phenomenon impacts core physics process

(LaBombard, '04)

⊥ transport-driven parallel SOL flows:

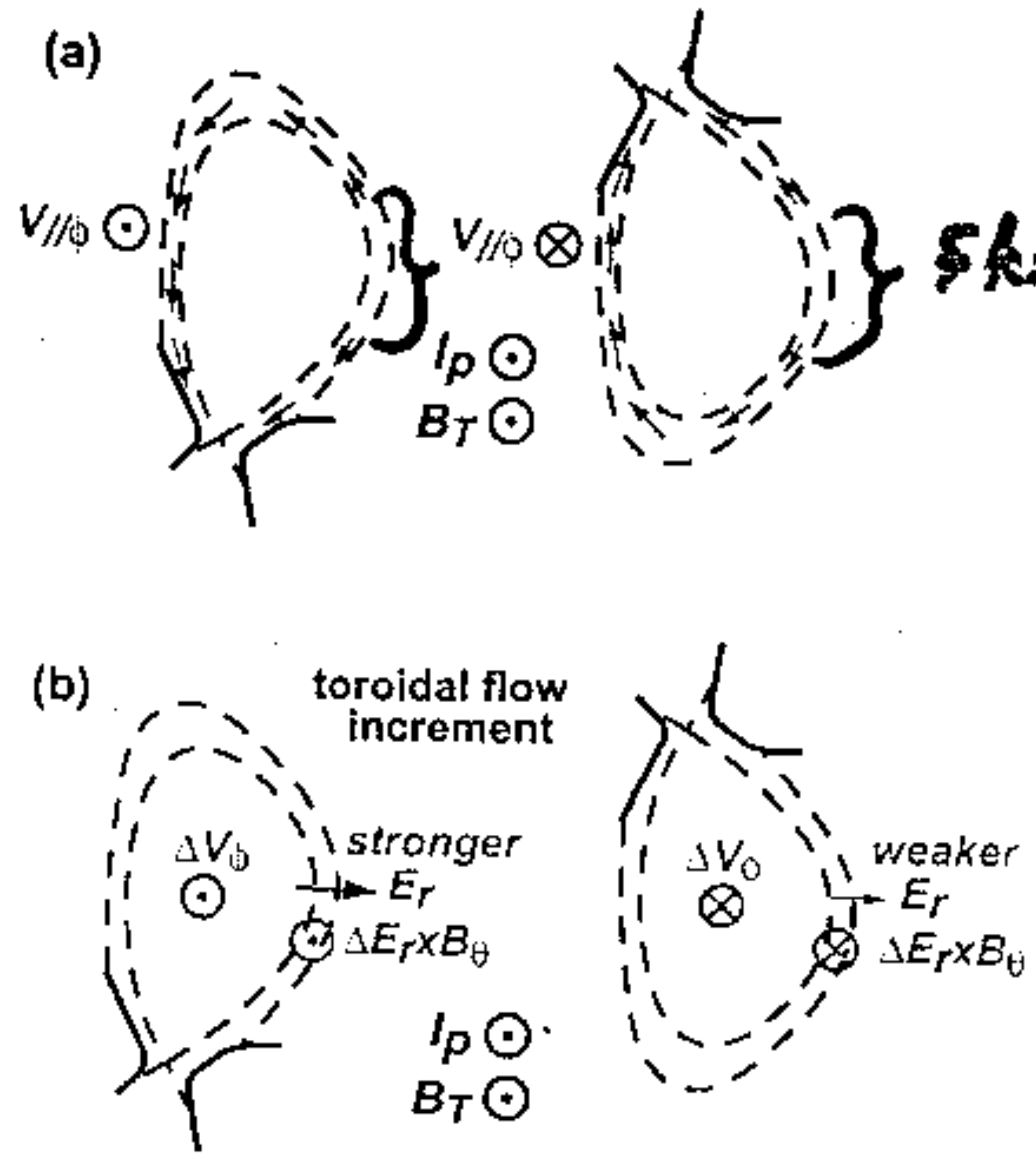


Figure 16. (*a*) Ballooning-like transport leads to a net volume-averaged SOL plasma momentum, co- or counter-current directed, depending on X-point location. (*b*) Data in figures 17 and 18 show that the confined plasma can react to this boundary condition with a positive (negative) increment in the co-current rotation when $B \times \nabla B$ is towards (away from) the X-point. Correspondingly, the toroidal rotation and radial electric fields in the SOL are influenced (as suggested from data in figure 11), becoming more (less) positive.

SOL → localized, outboard flux

⇓ input

⇒ ⇒ LSN
flow

⇓ input

⇐ ⇐ USN

- USN vs LSN changes flow direction (where is long way 'round?)

- 1D flow structure ⟺ Bernoulli Eqn.

inboard: flux compression ⇒ ⊙ sonic inboard flow.
⇒ prominence on inboard side.

- H-mode ⟺ turbulence driven process
↕

- link between separatrix rotation and central rotation severed in H-mode.

→ Critical Questions

(I)
- role / interplay } of multiple symmetry breaking mechanisms ?

① → SOL long vs short leg ⇒ LSN vs USN

② → SOL deposition ⇒ strong in-out asymmetry in turbulence
may be simple ...
but also:

→ existing toroidal rotation
i.e. is mechanism self-reinforcing?
↔ feedback instability ?!

(II)
- L→H transition / intrinsic rotation } develop at/inside LCFS ...

⇒ So Central Question

⇒ **How does SOL flow impact/control core plasma dynamics ?**

③ → What happens in H-mode ?

- seamless L→H story on intrinsic rotation ? — possible ?

→ A Possible Scenario

⇒ SOL flow exerts shear stress on core via:

$$\left.\begin{array}{l}\nabla_r \langle V_\parallel \rangle \\ \text{turbulence}\end{array}\right\} \rightarrow \langle \tilde{v}_r \tilde{v}_\parallel \rangle \cong -\chi_\phi \nabla_r \langle V_\parallel \rangle$$

- mediated by ambient SOL/edge electrostatic turbulence (ITG, RBM, ...)

or/and

- parallel shear flow instability – $\nabla_r \langle V_\parallel \rangle$ drive (akin $n_i < 0$)

~~CORE, SOL stresses must match at r_{LCFS} ⇒ synergy~~

⇒ Critical element is $\nabla_r \langle V_\parallel \rangle_{SOL}$

* – need $\nabla_r \langle V_\parallel \rangle > 0$ in SOL for SOL to exert viscous stress on core

- opposite of usual trend (inward off-diagonal)
- coupled flow, transport determines $\nabla_r \langle V_\parallel \rangle \rightarrow \partial_r^2 \Gamma_{i,T}$ (?)
- stress match ⇒ "boundary condition"

⇒ $\langle V_\phi \rangle$ indeed also breaks symmetry, enters poloidal mass flux

⇒ in H-mode, strong $\langle V_E \rangle'$

- shears eddys → reduces poloidal asymmetry
- reduces turbulent particle flux

and

- drives turbulent residual stress, linking $\langle V_\phi \rangle \leftrightarrow$ pedestal $\left\{ \begin{matrix} \nabla T \\ \nabla P \end{matrix} \right.$

Π_{origin} scales differently from Π

(c.f. Hahm, this meeting; Gurcan, et al.)

∴ mechanism largely decoupled from SOL flow

→ Calculation – <u>Crude</u> Beginnings

- need $\nabla_r \langle V_\parallel \rangle$, $\langle \tilde{V}_r \tilde{V}_\parallel \rangle$
- particle balance in SOL

$$\underline{\nabla} \cdot \underline{\Gamma} = S$$

$$\nabla_\parallel \Gamma_\parallel = S - \partial_r \Gamma_r$$

$$\langle n\rangle\langle V_\parallel\rangle = \int_{l_0}^{l_\parallel} dl_\parallel' \left\{ S(r, l_\parallel') - \partial_r \Gamma_r(r, l_\parallel') \right\}$$

⇒

$$\frac{1}{\langle V_\parallel\rangle}\frac{\partial\langle V_\parallel\rangle}{\partial r} = \underbrace{-\frac{1}{\langle n\rangle}\frac{\partial \langle n\rangle}{\partial r}}_{①} + \frac{1}{\langle n\rangle\langle V_\parallel\rangle}\int_{l_0}^{l_\parallel} dl_\parallel' \left\{ \underbrace{\partial_r S(r,l_\parallel')}_{②} - \underbrace{\partial_r^2 \Gamma_r(r,l_\parallel')}_{③} \right\}$$

① $-\frac{1}{\langle n\rangle}\frac{\partial\langle n\rangle}{\partial r} > 0$ → usual profile

② $\partial_r S > 0$ → source stronger → well

③ $\partial_r^2 \Gamma_r < 0$ → { $\Gamma_\parallel$ ↔ likely parallel loss accum.; consistent with $\langle V_\parallel\rangle' > 0$ }

$$\underbrace{1/L_V = -7/L_n}_{①} + \frac{1}{\langle n\rangle\langle V_{\parallel}\rangle}\int_{l_0}^{l_{\parallel}} dl_{\parallel}' \{\underbrace{\partial_r S}_{②} - \underbrace{\partial_r^2 \Gamma_r}_{③}\}$$

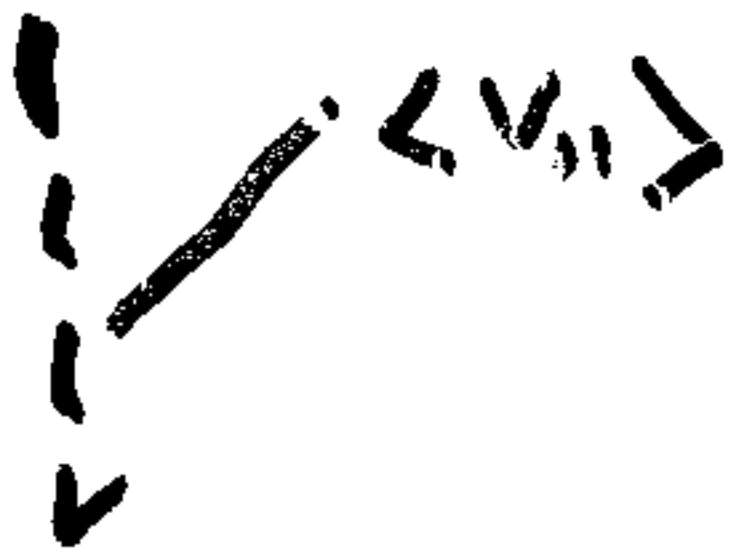
① > 0

② > 0; likely

③ > 0; quite possibly; consistent

⇒ $r > r_{LCFS}$ SOL, $\frac{1}{\langle V_{\parallel}\rangle}\frac{\partial\langle V_{\parallel}\rangle}{\partial r} > 0$

SOL flow speed increases with radius



{ asymptotic behavior at $r \gg r_{LCFS}$ unclear

∴ relaxation of $\langle V_{\parallel}\rangle_{SOL}$ by transport

⇒ inward viscous shear stress

Mechanisms:

→ generic ④ electrostatic turbulence

→ parallel shear flow

both $k_{\perp} \sim 1/L_{\perp}$

Either way:

$\rightarrow \langle \tilde{v}_r \tilde{v}_\parallel \rangle \cong -\chi_\phi \frac{\partial \langle v_\parallel \rangle}{\partial r}$ diffusive inward momentum transport

a la' QL; $\chi_\phi = \langle \tilde{v}_r^2 \rangle \tau_c$

no scale sep. ↳ whatever SOL turbulence ....
$\chi_\phi \sim D_B$; DWT

→ For parallel shear flow (minimal)
(Catto, MNR, Lin; Mattor, P.D)
- negative compression
- asymmetry in $k_\parallel$
- robust, fluid mechanism
- $\nabla_r \langle v_\parallel \rangle$ vs $\nabla_r \langle n \rangle$

$$\omega = -\frac{\omega_{*e}}{2} \pm \frac{1}{2}\left(\omega_{*e}^2 - k_\parallel \langle v_\parallel \rangle \omega_{*\langle v_\parallel \rangle}\right)^{1/2}$$
$$\omega_{*\langle v_\parallel \rangle} \sim \frac{\partial \langle v_\parallel \rangle}{\partial r}$$

- in SOL, expect:

$$\chi_\phi \sim \left(1/L_v - 1/L_{v,crit}\right)^\alpha \quad 1 \leq \alpha \leq 2.5$$
$$\sim \left(\frac{L_{v_0}}{L_v} - 1\right)^\alpha D_B \qquad k_\perp L_n \sim 1.$$

→ Consider $\chi_\phi = \chi_\phi^{amb} + \chi_\phi^{PSF}$

Some Comments

- need revisit with:
  - → serious geometry ⇒ ⊥ dependence of flux compression factor
  - → SOL flow effect on $\Gamma_\perp(r,\theta)\Big|_{SOL}$ (cross phase in SOL)

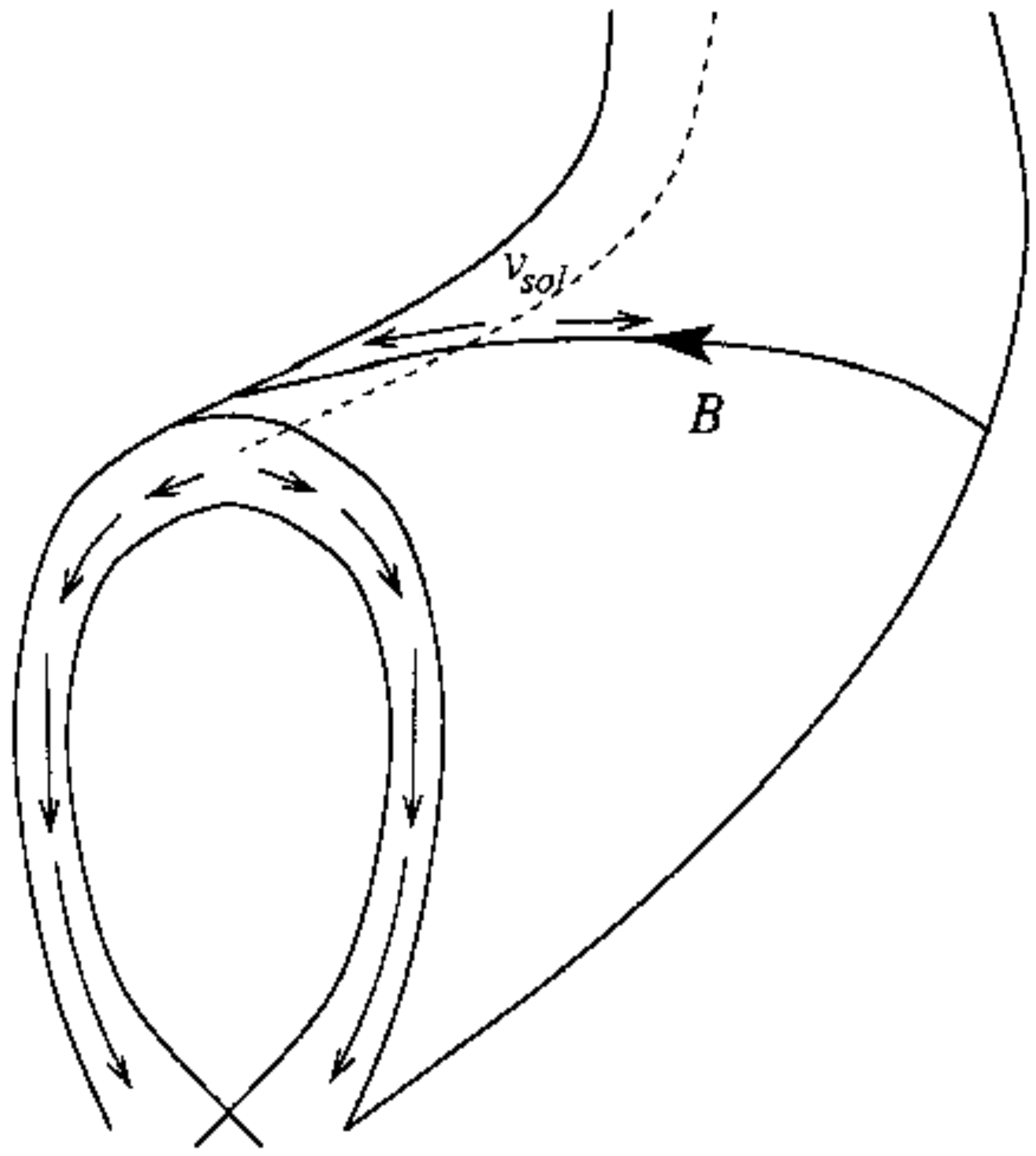
- structure of SOL momentum flux

⟺ does viscous stress exerted by SOL really beat momentum outflux at $\theta \sim 0$ due $\begin{cases} \text{RBM} \\ \text{blobs (Myra et. al.)} \end{cases}$?

→ poloidal structure of SOL turbulence (?)

→ PSF analysis must treat curvature, shaping, null (shear), ∇P_{SOL} coupling kinetics ....
(XGC1 ?)

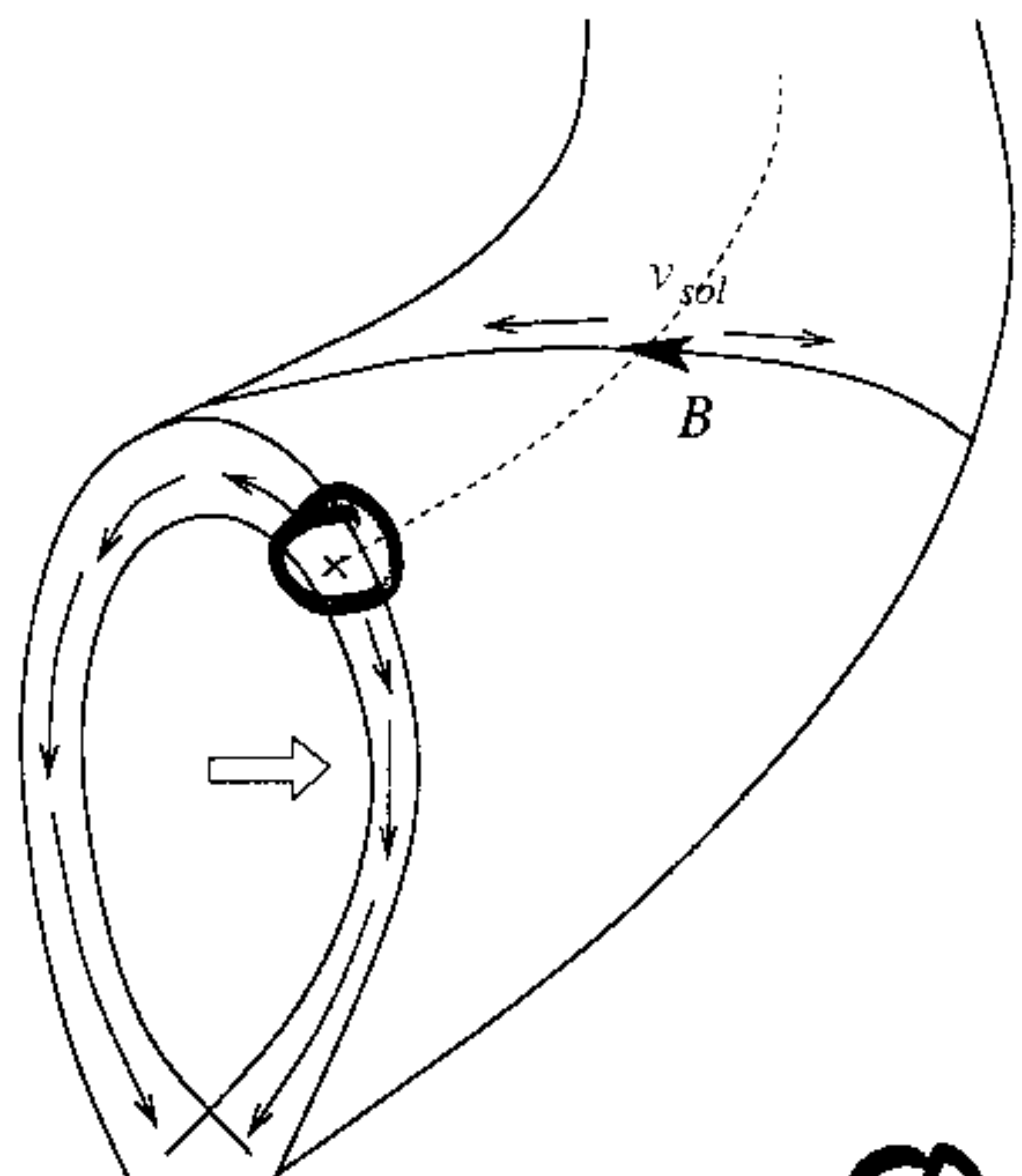
Mechanisms of Symmetry Breaking



no ballooning (left-rt symm, flux)

Figure 1: Basic flow structure in the absence of symmetry breaking. The profile given here is for $\partial\Gamma_r/\partial r > 0$. Note that there would be no flow if $\partial\Gamma_r/\partial r = 0$.

imposing ballooning on ambient flow



$V_{\parallel}$ amb ⟺ symm brk. ⟺ strong ballooning

Figure 2: Flow structure with ballooning to provide symmetry breaking. Due to ballooning the left-right symmetry is broken. Still $\partial\Gamma_r/\partial r > 0$, so that the aymmetry induced poloidal flow is imposed on top of the basic background flow.

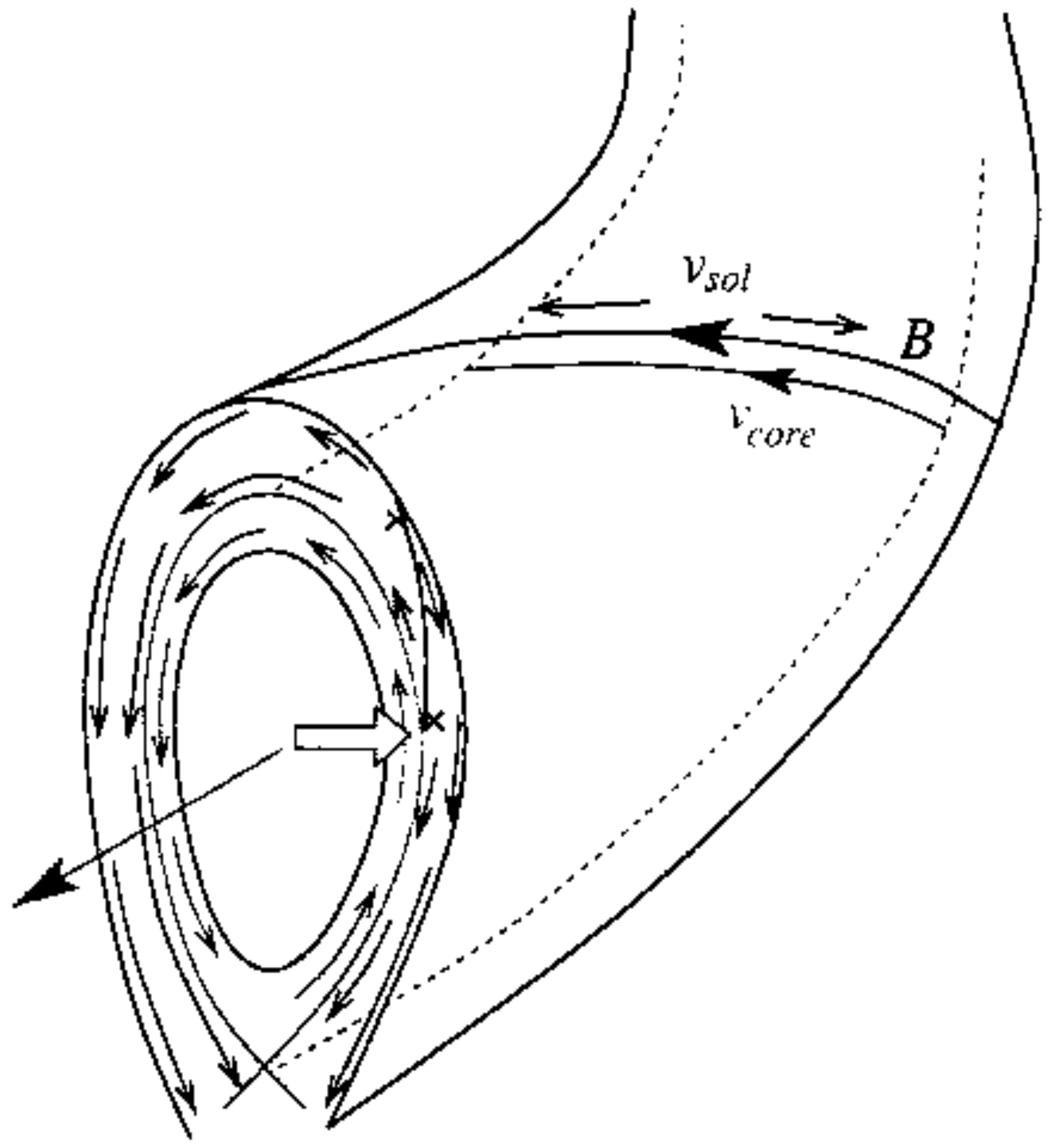


Figure 3: Flow structure with ballooning and "core rotation" to provide symmetry breaking. Assuming the flow at the last closed flux surface is mostly parallel. The core rotation "also" provides a boundary condition for the SOL flows as well as vice versa. In other words, we need a "dynamic matching condition".

with core rotation : { core ⟺ b.c. for SOL
SOL ⟺ b.c. for core }

net symm brk → { ballooning asymm.
ambient rotation }

(①III-case ?!)

Future Work

→ solidify calculation, as noted above

→ match to inside LCFS, with $\langle V_E \rangle' \neq 0$ but sub-crit.

- parametrize out flux strength, localization
- match stresses
- implication for core flows
  ⇝ $V_{\phi_{in}}(r)$ from match

Particle
Flux → SOL flow → edge flow → V_0
Heat symmetry breaking. (influx; $\langle V_E \rangle'$!?) Mach

→ Key: symmetry breakings of
competition $\langle V_E \rangle'$ vs SOL structure.