Edge and divertor physics on JET: effect of toroidal field reversal

presented by **W. Fundamenski** on behalf of:

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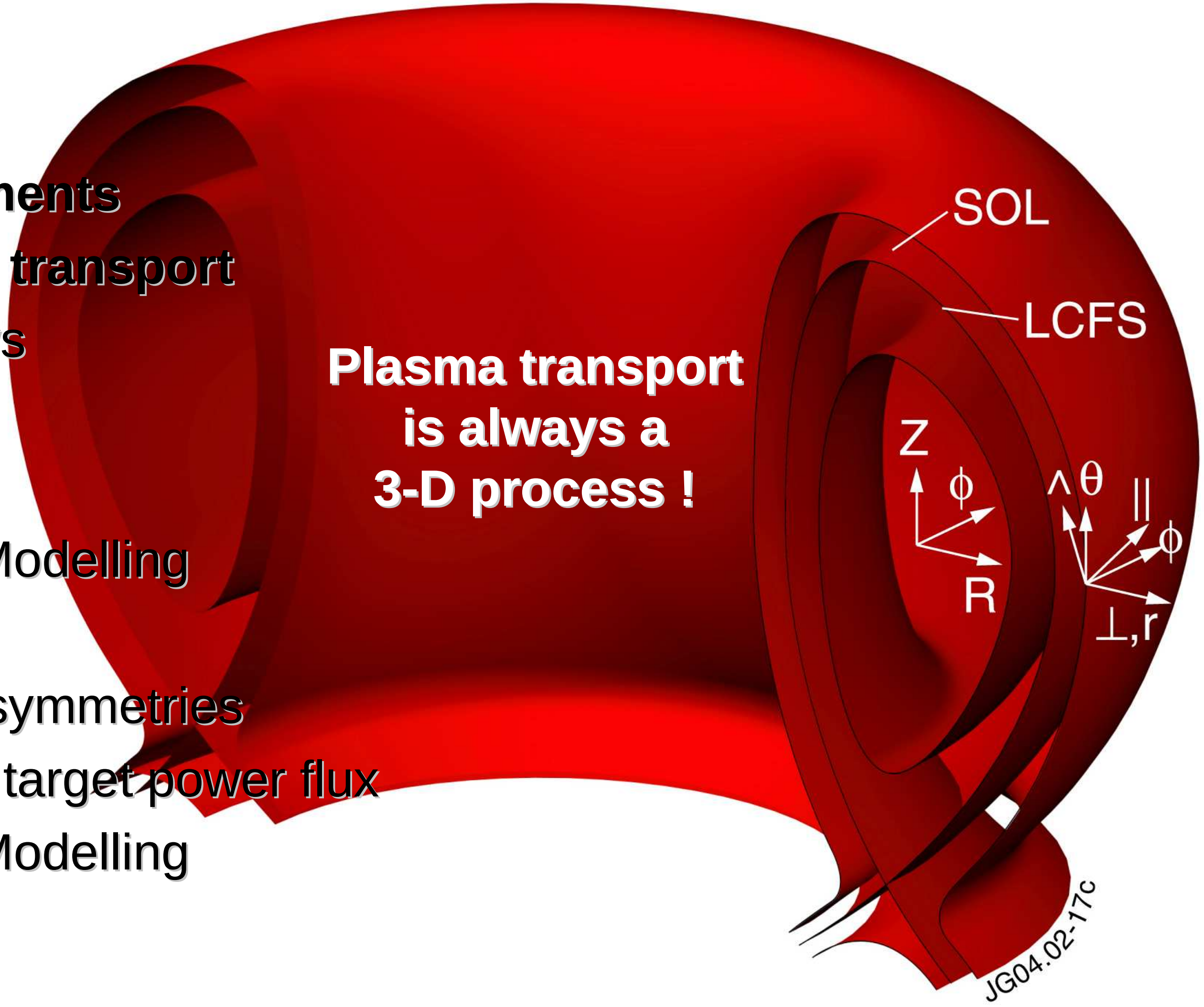
**See annex to J. Pamela, Fus. Energy 2002 (Proc. 19th Int. Conf. Lyon, 2002), IAEA, Vienna*

Outline

- **Motivation**
- **Basic Theory**
- **Recent JET experiments**
- **Mass & momentum transport**
    - Parallel SOL flows
    - Carbon migration
    - L- vs. H-mode
    - Interpretation & Modelling
- **Energy transport**
    - Divertor power asymmetries
    - Radial profiles of target power flux
    - Interpretation & Modelling
- **Conclusions**



Plasma transport is always a 3-D process !

Motivation: ITER

Issues	Physics
L-H & III-I transitions	**H-mode (ETB) barrier**
Magnitude of SOL flows: Tritium co-deposition Helium ash removal Carbon migration	**Mass & Momentum transport** Classical drifts, Mechanisms of $D_\perp$, $v_\perp$, $\eta_\perp$ (θ)
Power exhaust: L- & H-mode (inter-ELM & ELM) divertor tile power loading in-out asymmetries	**Energy transport** **Poloidal:** Classical drifts **Radial:** Mechanisms of $\chi_\perp$ (θ) Classical vs. Turbulent Ion Orbit Loss

Improve theoretical understanding

Experiments

Rev-B (B×∇B↑) campaign:

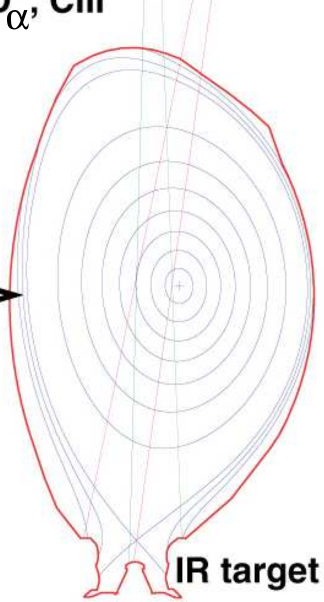
- attempt to match fwd-B plasmas
- MkIIGB SRP divertor
- Many pulses in DOC-L, SNL
- Both B_ϕ and I_p reversed, so helicity constant

Key observables:

- SOL flows & fluctuations
- Divertor asymmetries
- Impurity migration

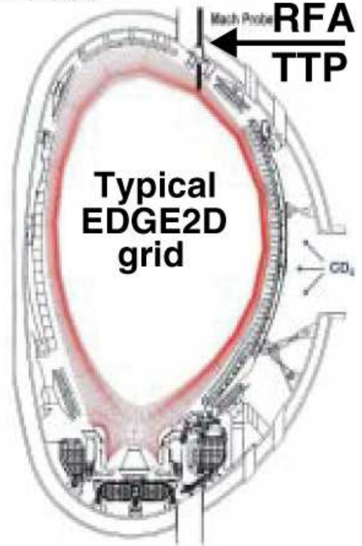
Principal diagnostic data used in this talk

Divertor spectroscopy D_α, CIII



IR target views

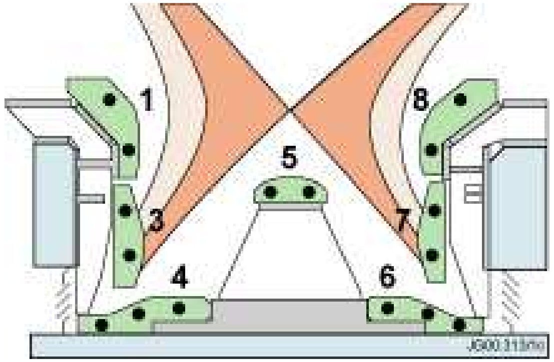
Reciprocating Mach probes



Divertor tile thermcouples

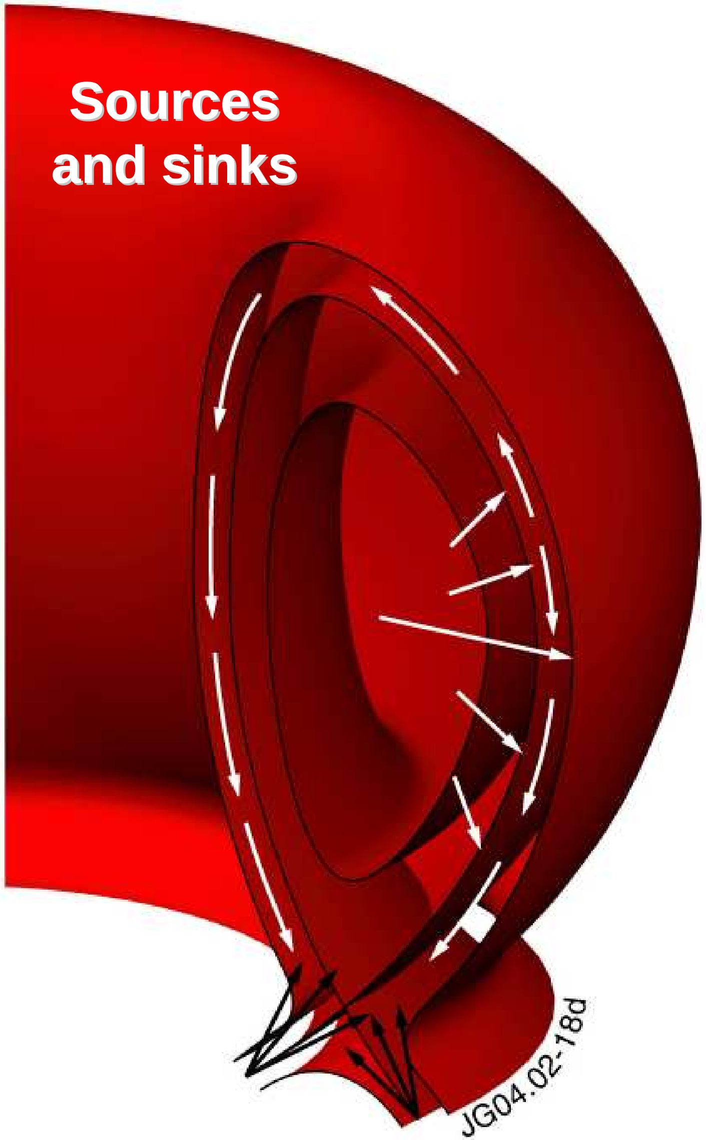
+

Langmuir probes



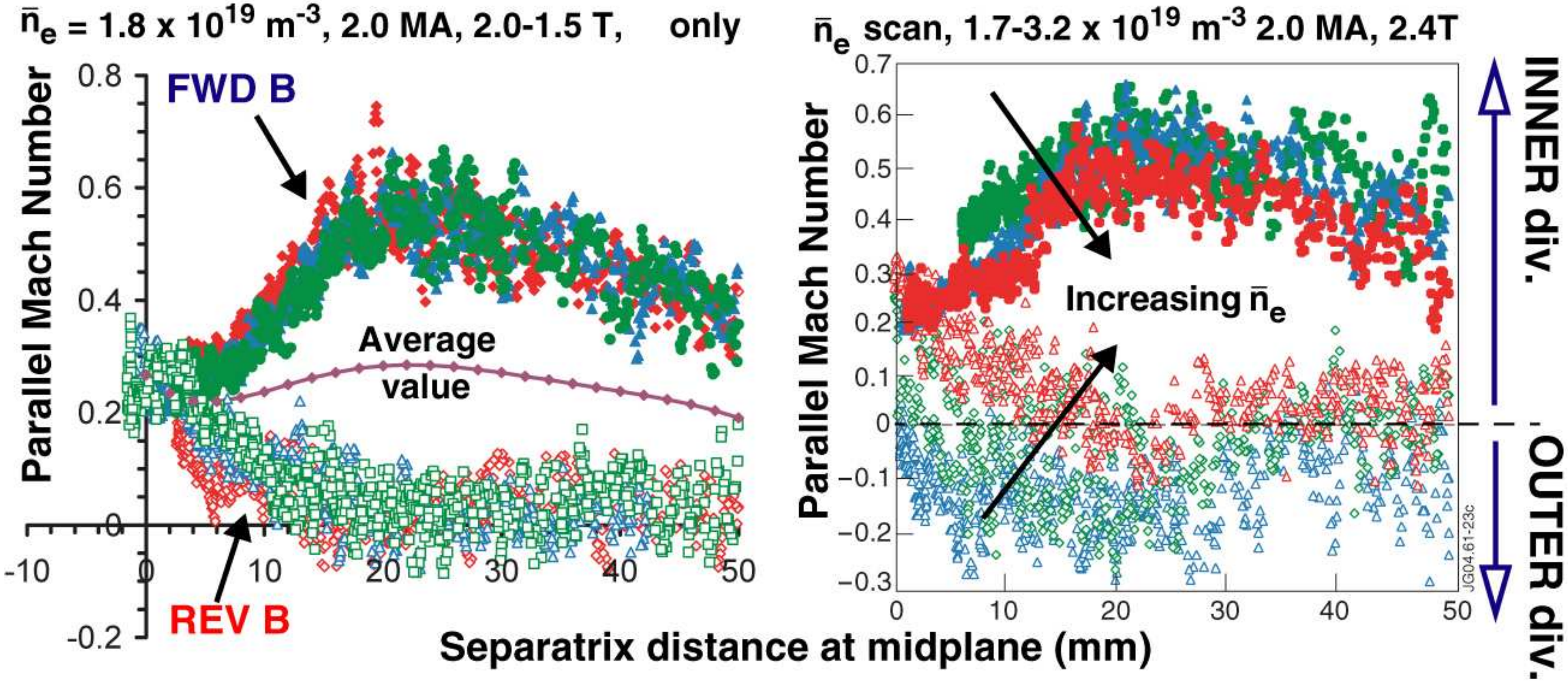
Mass & Momentum Transport

- Observation of large || SOL flows in nearly all tokamaks
- Not fully understood at present
- Complex interplay between three directions (||,∧,⊥)
  - Phirsch-Schluter flows
  - Ionization driven flows
- Classical drifts play a major role
- Overviews
  - *Chankin: PSI12,14,EFPW2003*



Parallel SOL flow near top of vessel

$M_{||}$ ~ 0.5 ($B\times\nabla B\downarrow$) vs. $M_{||}$ ~ 0 ($B\times\nabla B\uparrow$)



$B\times\nabla B\downarrow$ strong parallel flow towards inner divertor at RCP

$B\times\nabla B\uparrow$ flow stagnates at RCP

Near separatrix $M_{||}$ ~ average $M_{||}$ ~ 0.2 - 0.3

SOL flow confirmed by RFA T_i data

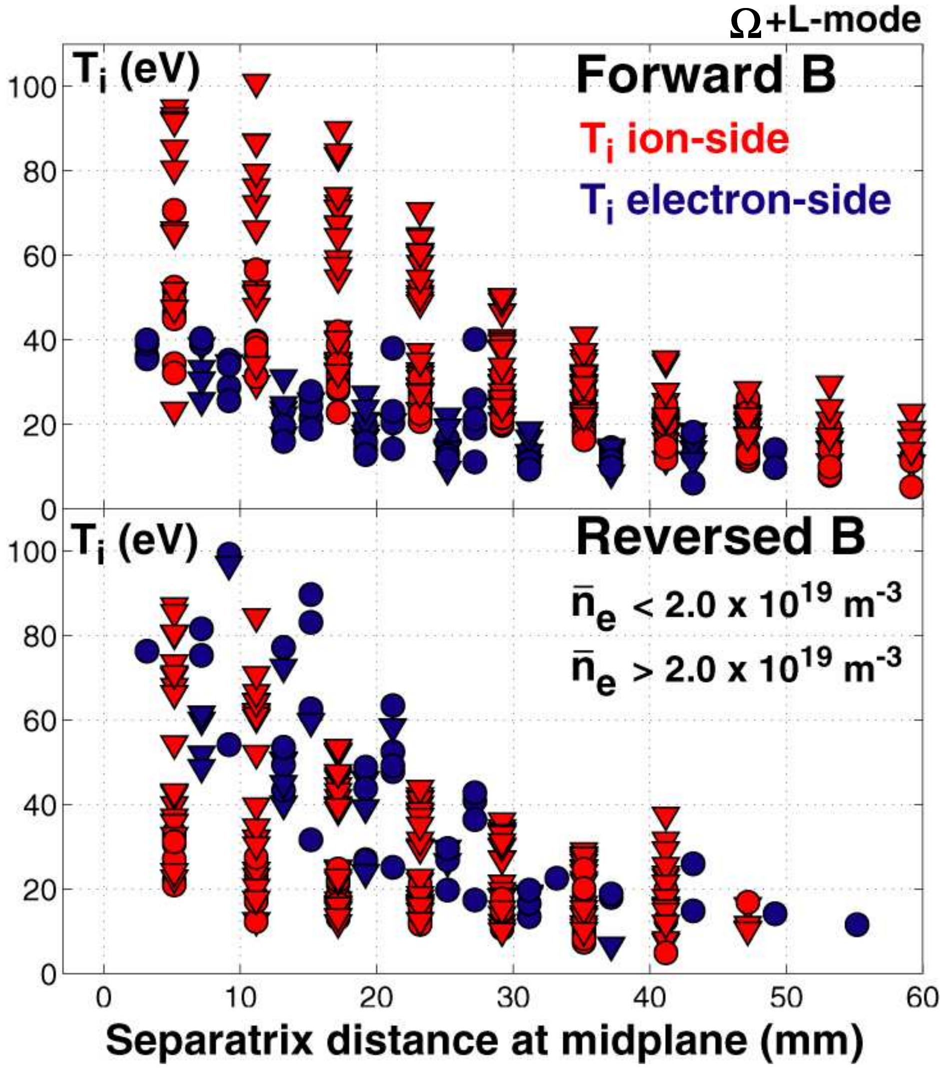
Retarding Field Analyser (RFA)

- j_{sat} and T_i on both sides of probe
- j_{sat} ratio gives $M_{||}$ (previous slide)
- T_i ratio consistent with $M_{||}$

$B\times\nabla B\downarrow$: $T_{i,i\text{-side}} / T_{i,e\text{-side}} > 1$

$B\times\nabla B\uparrow$: $T_{i,i\text{-side}} / T_{i,e\text{-side}} \sim 1$

Ions depleted on downstream side in ~ agreement with theory

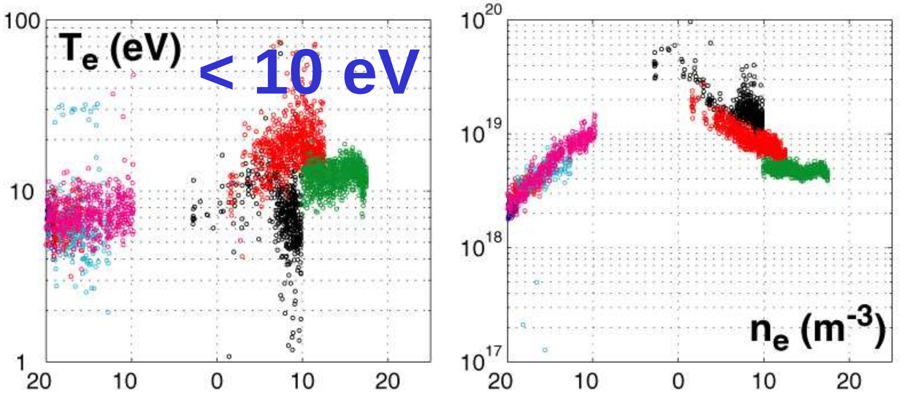


Target T_e, n_e profiles in matched L-modes

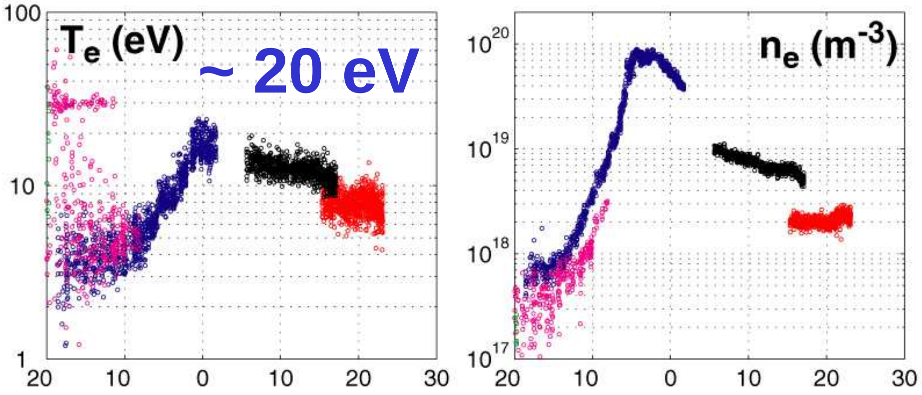
Inner Target

Outer Target

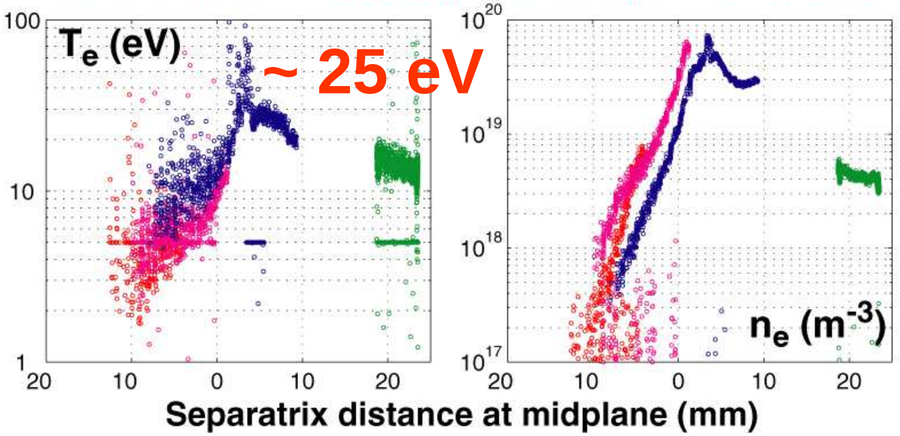
Forward B #50414, L-mode, t = 55.5-59.5s



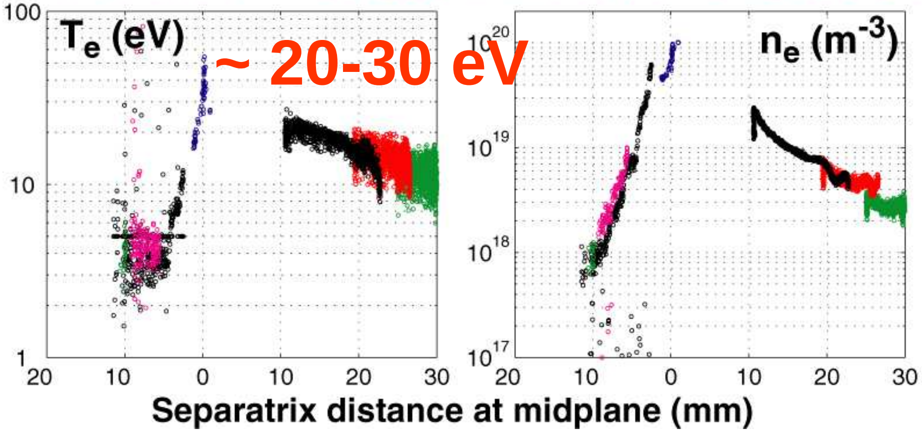
Forward B #50414, L-mode, t = 55.5-59.5s



Reversed B #59589, L-mode, t = 54.0-60.0 s

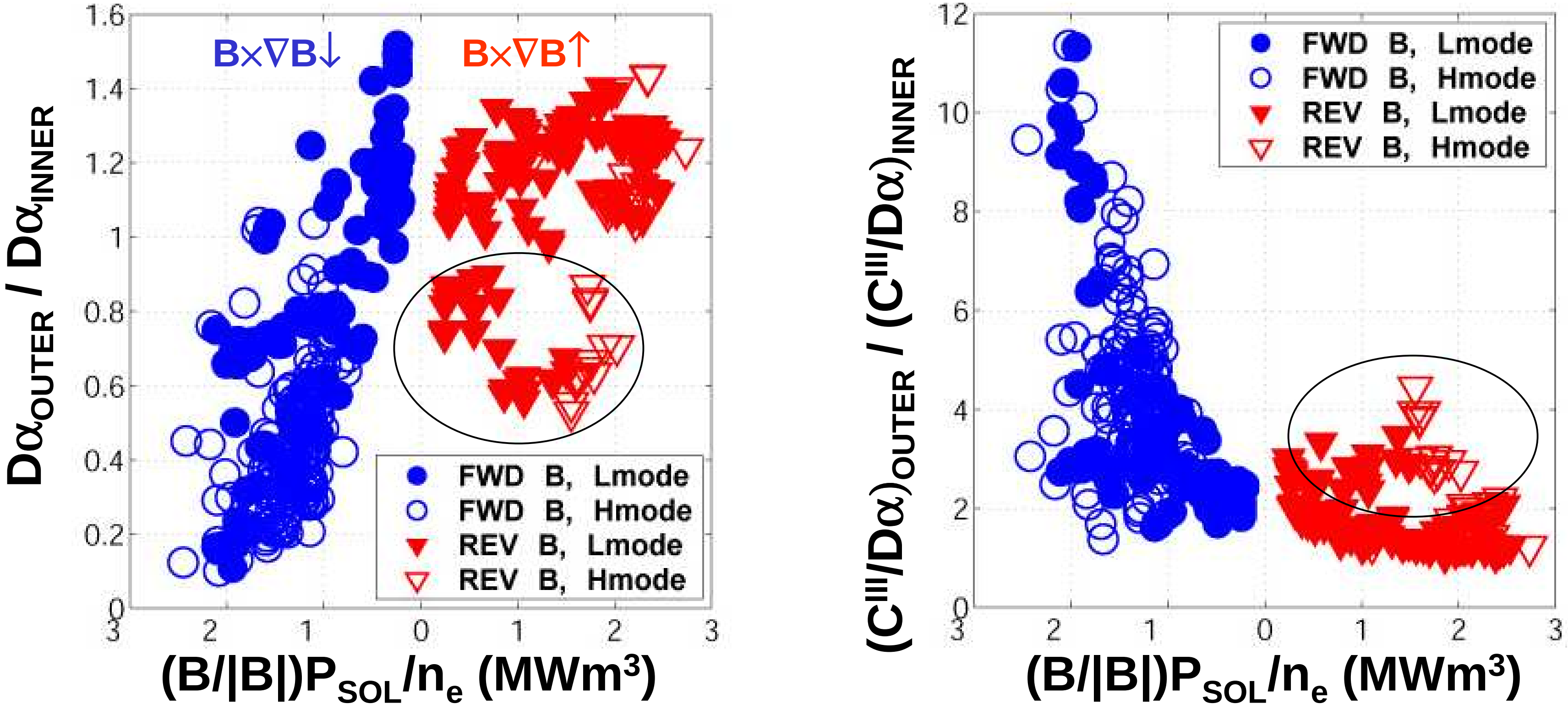


Reversed B #59589, L-mode, t = 54.0-60.0 s



D_α and C^{III} out-in asymmetries

Large database of shots with a range of B, I, P, ne

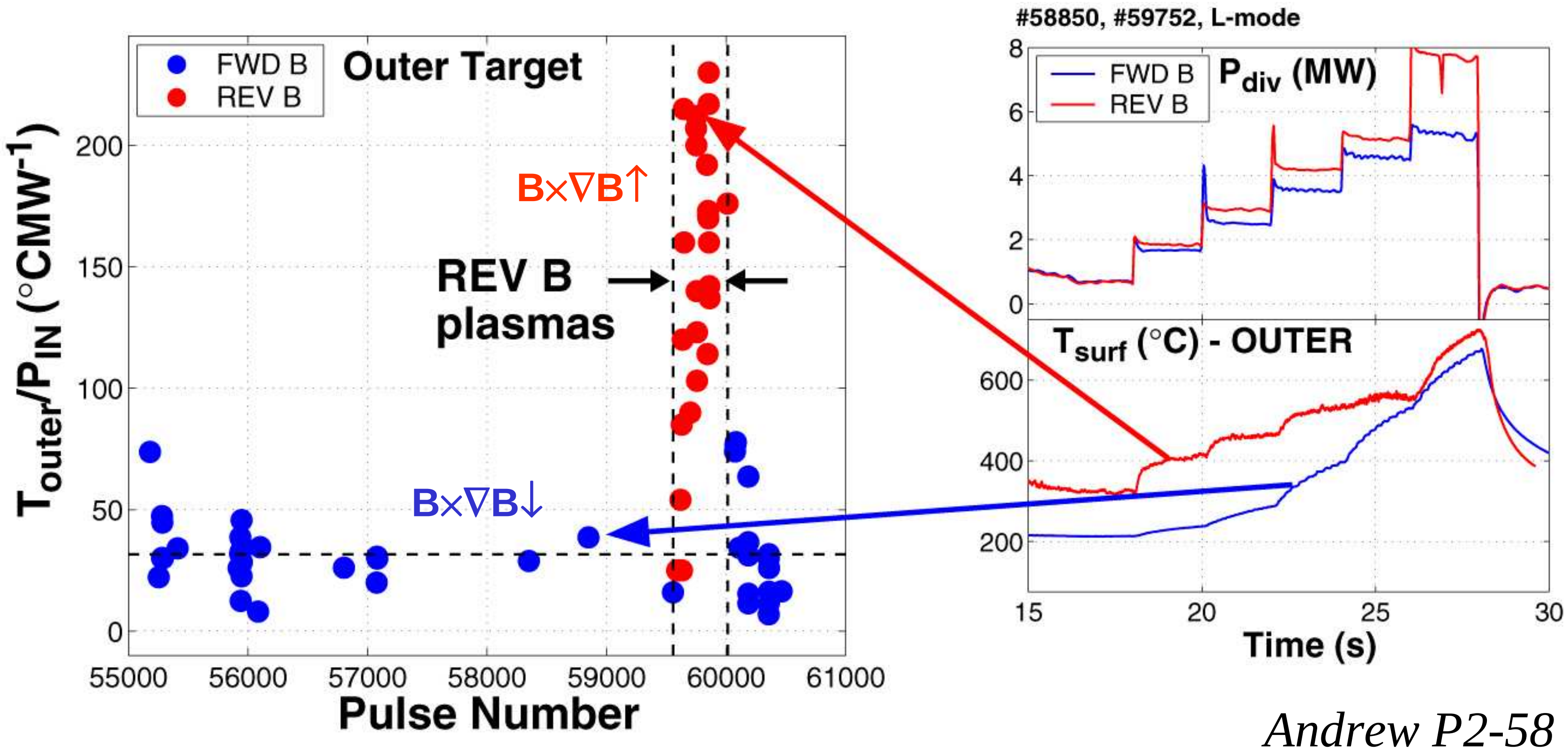


B×∇B↓ More D_α and less C^{III} in inner divertor, both Ω, L & H

B×∇B↑ Balanced D_α and C^{III} in both Ω, L & H

Surface layers on outer target (IR data)

High ΔT_{surf} indicates poorly adhered target surface layers



Andrew P2-58

B×∇B↓ Surface layers only on inner target

B×∇B↑ Layers grow on outer target, still present on inner target

Modelling with 2-D fluid codes + drifts

EDGE2D/NIMBUS with

- Classical drifts in core and SOL
- Radial profiles $D_\perp$, $\chi_\perp$ to best match target probe
- Gas puff from top of torus (as in experiment)

$B\times\nabla B\downarrow$

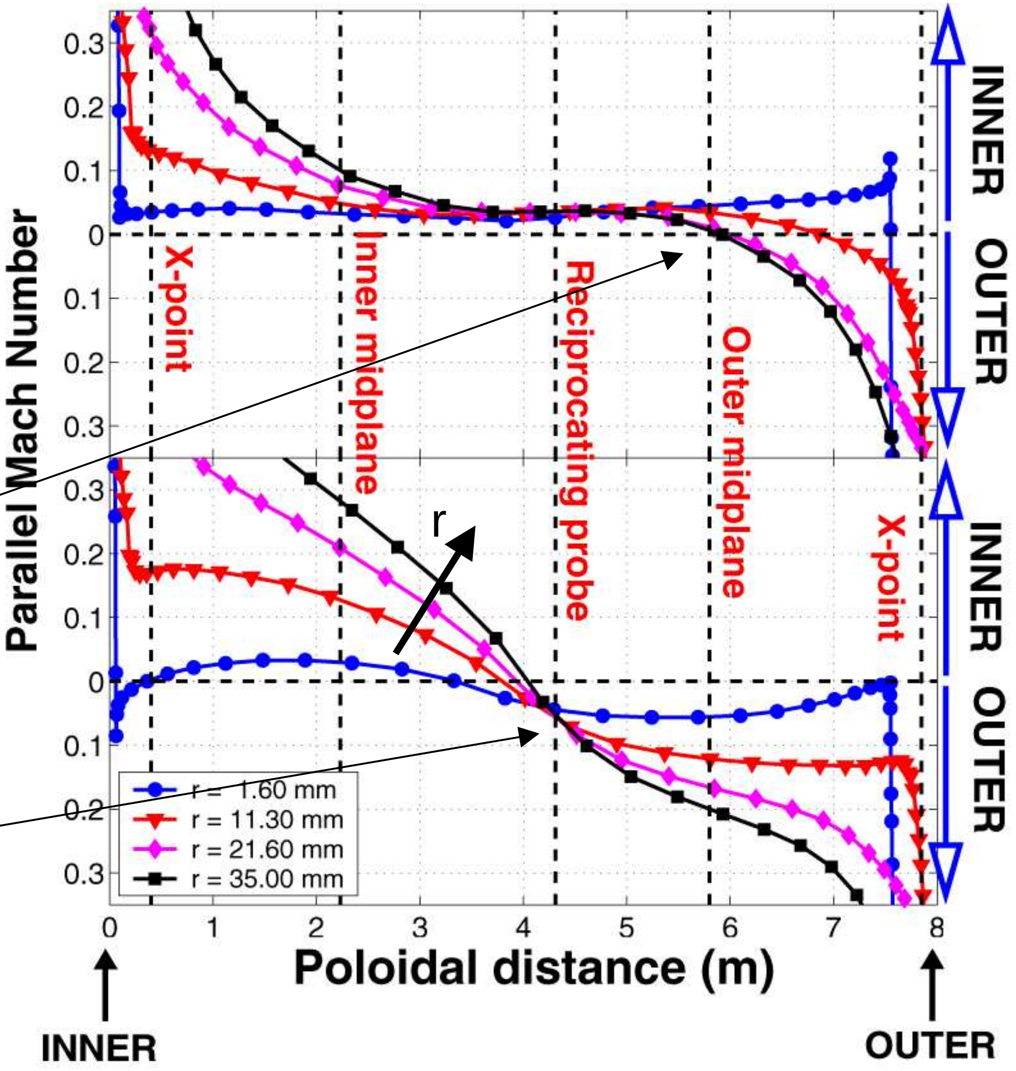
Stagnation point on LFS

$M_{||}$ < 0.1 over most of the SOL, from IMP to OMP

$B\times\nabla B\uparrow$

Stagnation point near top

$M_{||}$ > 0.1 over most of the SOL from IMP to OMP



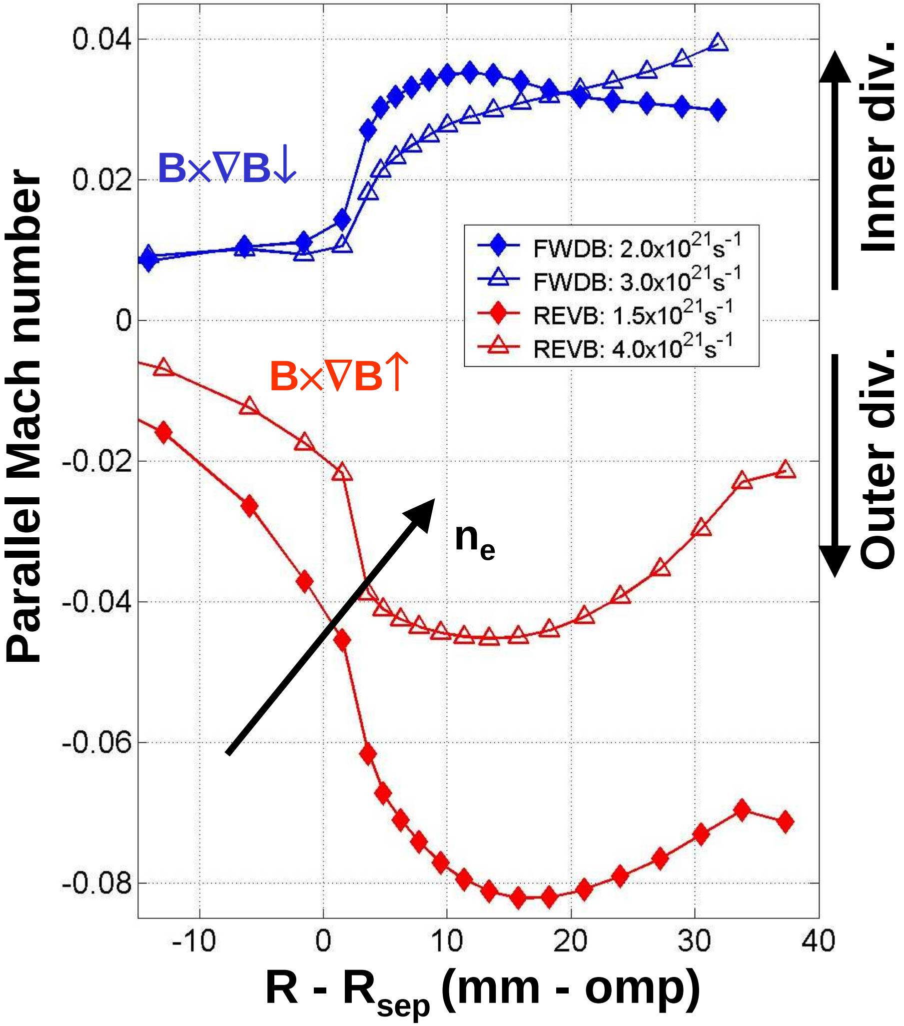
Radial variation of Mach number at RCP

Right trends in profile shape and density variation, but magnitude too low by 5-10x ?!

Poloidal/Radial drifts give rise to a return || SOL flow, in the opposite direction to ExB

∴Drift + ionisation driven flows can account for part of C migration

Chankin, EFPW-2003



Other SOL flow modelling approaches

Active area of research !!!

Kirnev, Strachan, Huber, Coster, Matthews...

1) Effect of carbon plume on probe $M_{||}$ measurement

2) External momentum source

3) Poloidal variation of D⊥, χ⊥

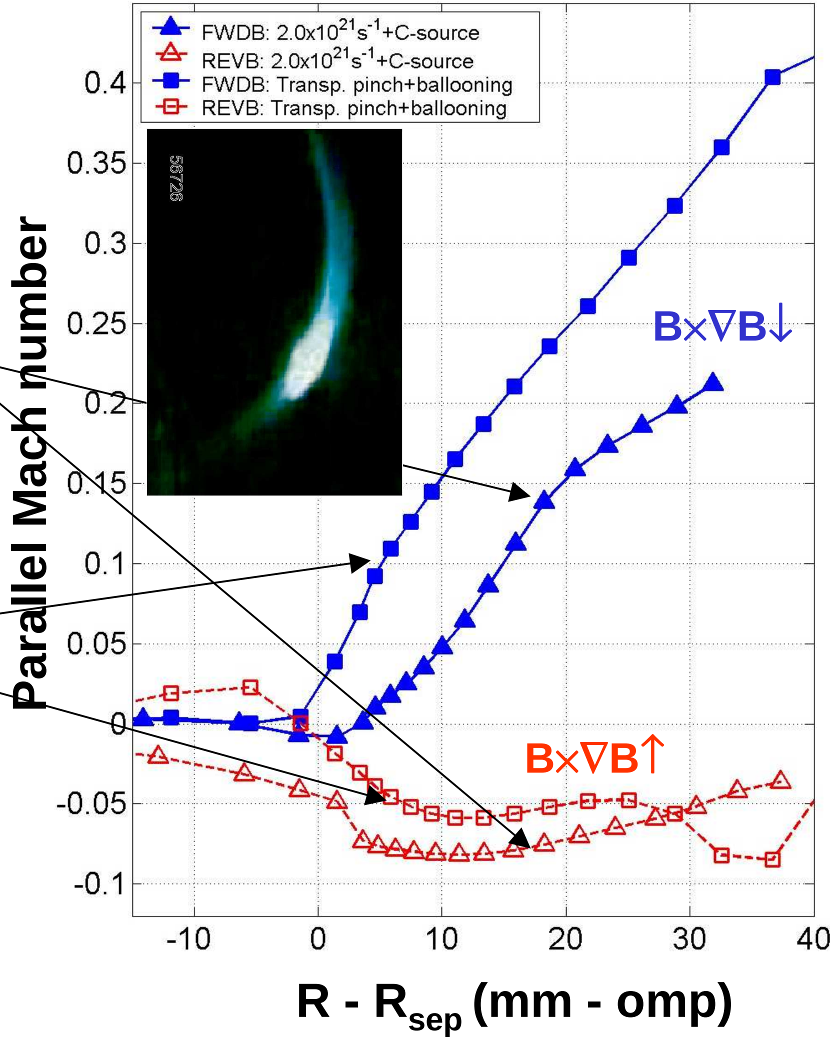
Radial pinch

HFS → LFS for fwd-B

HFS ← LFS for rev-B

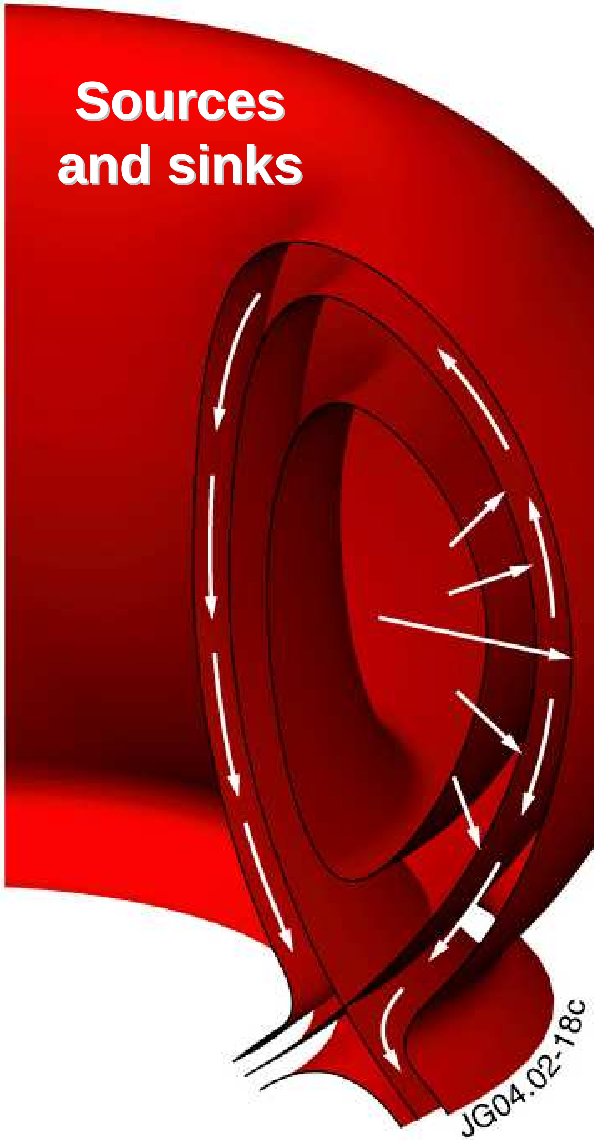
No drifts

Increase in flow magnitude



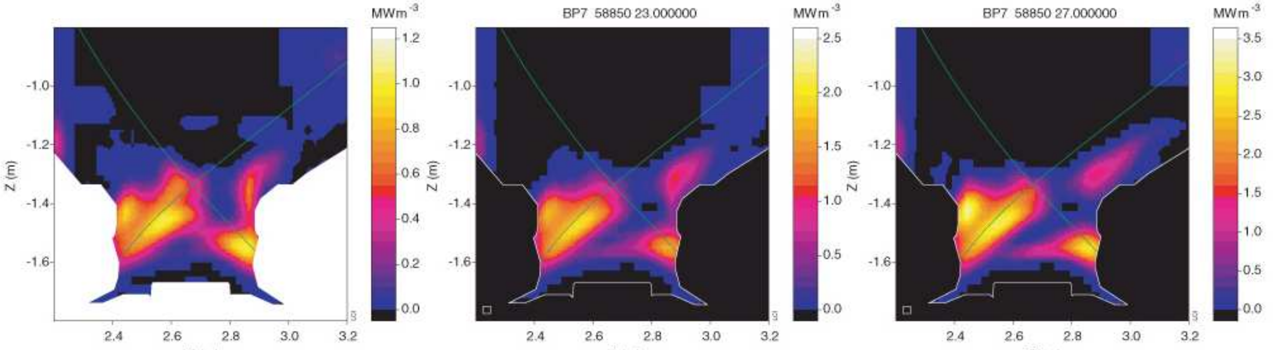
Energy Transport

- Sources and Sinks
  - Power deposited in core
  - Exhaust via SOL to div./wall
- Most energy flows out on LFS
  - Large surface area ~ R
  - Shafranov shift
  - LFS bad curvature,
    - higher level of fluctuations and MHD turbulence



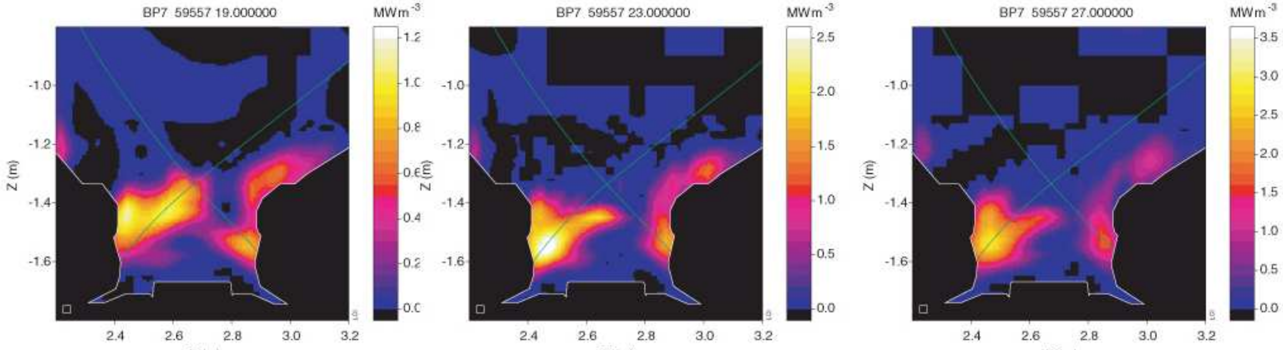
Matched L-mode power scans: 2-D radiation

Forward B

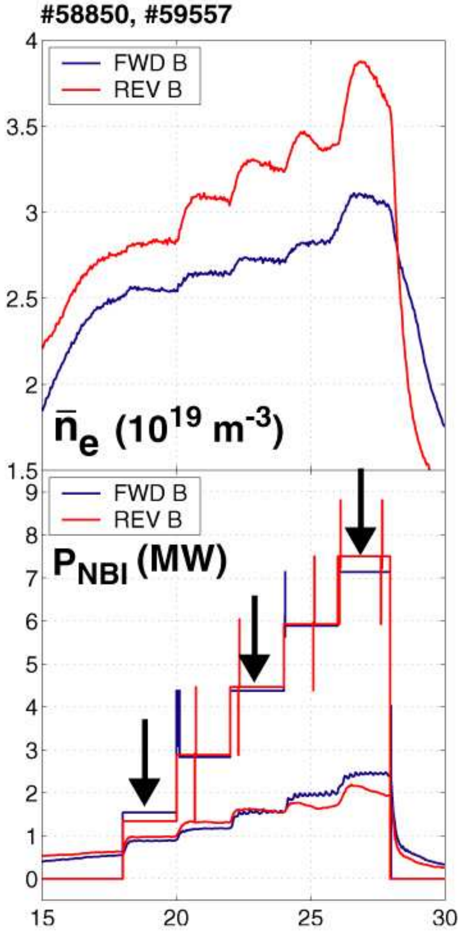


t = 19 s t = 23 s t = 27 s

Reversed B



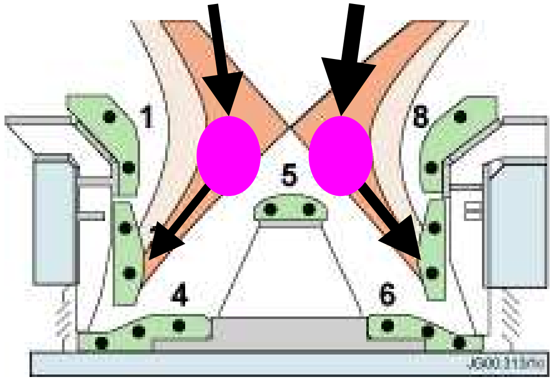
t = 19 s t = 23 s t = 27 s



Example: NBI L-mode, I_p = 2.0 MA, B = 2.4 T

Huber P3-22

$P_{div}^{outer}/P_{div}^{inner}$ modified by B×∇B direction



$P_{target} = P_{div} - P_{rad}$

Huber P3-22

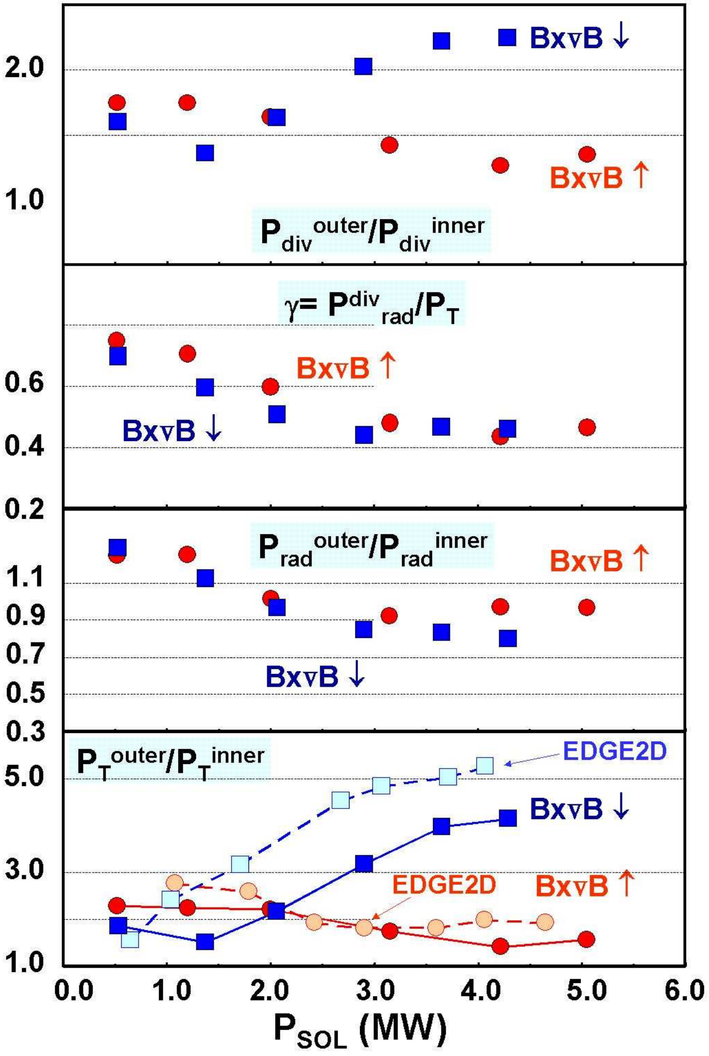
JT-60U: P_{div} balanced and insensitive to B×∇B caused by radiation asymmetries

On JET, this only the case at high density/low power

$P_{div}^{outer}/P_{div}^{inner}$ increases with P_{SOL}

Effect of B×∇B increases with P_{SOL}

What is happening ?!



Classical drifts in ∧ dir. with B×∇B ↓ vs. ↑

Fluid drift velocity:

$$\mathbf{v}_\sigma = v_{||\sigma}\mathbf{b} + \mathbf{v}^E + \mathbf{b}\times(\nabla p_{\perp\sigma} - \mathbf{R})/m_\sigma n_\sigma \Omega_\sigma$$
$$+ \{(v_{t||\sigma}^{2} - v_{t\perp\sigma}^{2} + v_{||\sigma}^{2})/\Omega_\sigma\}\mathbf{b}\times\mathbf{b}\cdot\nabla\mathbf{b}$$

$$\mathbf{v}^E \sim \mathbf{E}\times\mathbf{b}/B, \quad \mathbf{b} = \mathbf{B}/B, \quad \Omega_\sigma = e_\sigma B/m_\sigma, \quad v_{t\sigma} = (T_\sigma/m_\sigma)^{1/2}$$

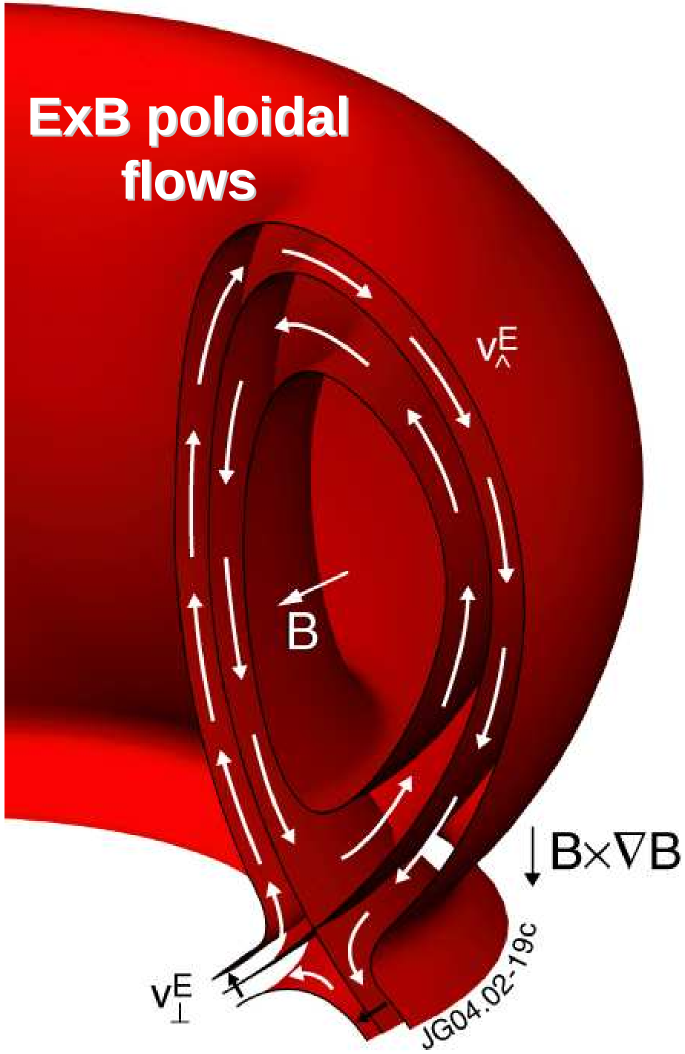
Energy flux due to drifts:

$$\mathbf{q}_\sigma = 2.5 p_\sigma \langle\mathbf{v}^{gc}\rangle_\sigma - \nabla\times(2.5 p_\sigma T_\sigma \mathbf{b}/e_\sigma B)$$
$$\approx 2.5 p_\sigma \mathbf{v}_\sigma + 2.5 p_\sigma v_{t\sigma}\rho_\sigma \mathbf{b}\times\nabla T_\sigma/T_\sigma$$

Radial E-field in SOL = $E_{\perp,SOL} \sim 3\nabla_\perp T_{e,t}$

Relative strength of drifts increases with power

$$q_{\theta i}^{E}/q_{\theta i} \sim 3\,\rho_{\theta s}/\lambda_{Te,t}$$
$$q_{\theta i}^{\nabla T}/q_{\theta i} \sim \pm\,\rho_{\theta s}/\lambda_{Ti}$$



Matched pairs of Z-swept shots

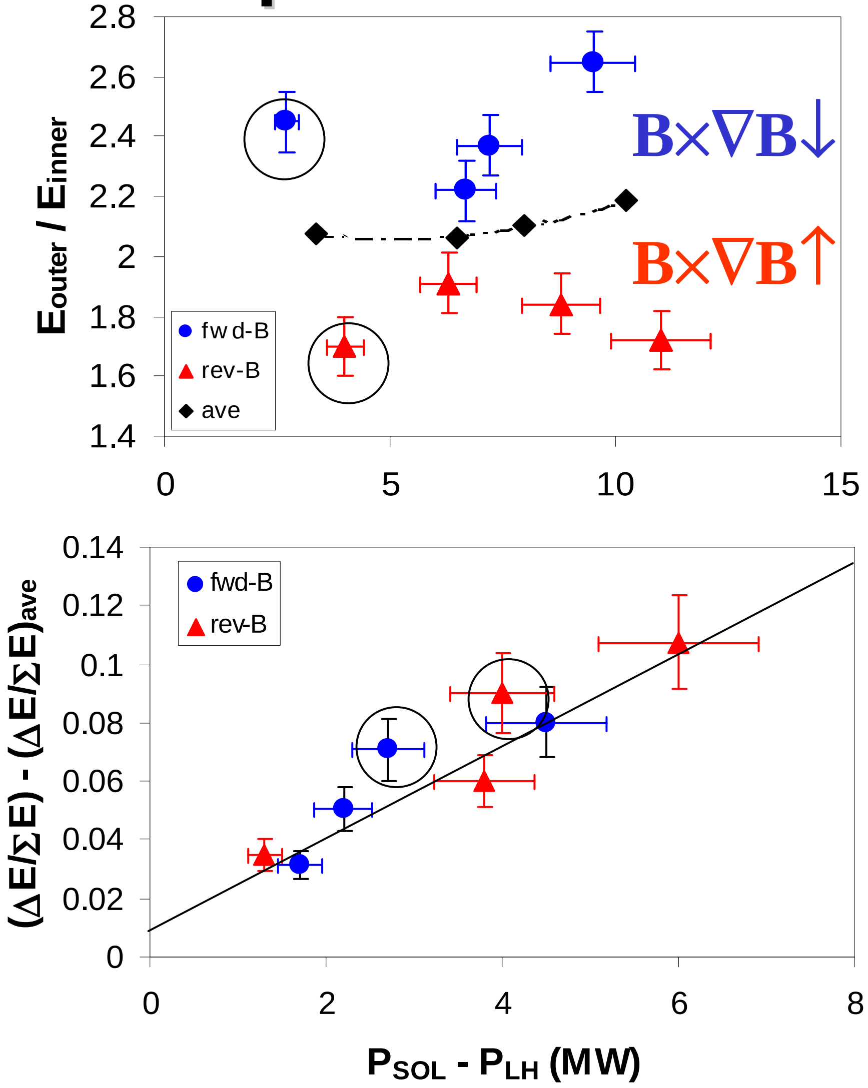
Variation in B, I and P_{heat}

Average asymmetry ~ 2.2

E_{outer} / E_{inner} and ΔE / Σ E increase with P_{SOL}

Larger effect in L-mode, unless use P_{SOL} - P_{LH}

Fundamenski P3-15



Radial profiles insensitive to $B\times\nabla B$ dir.

Peak heat flux for both fwd-B and rev-B points, agree well with fwd-B scaling for outer target,

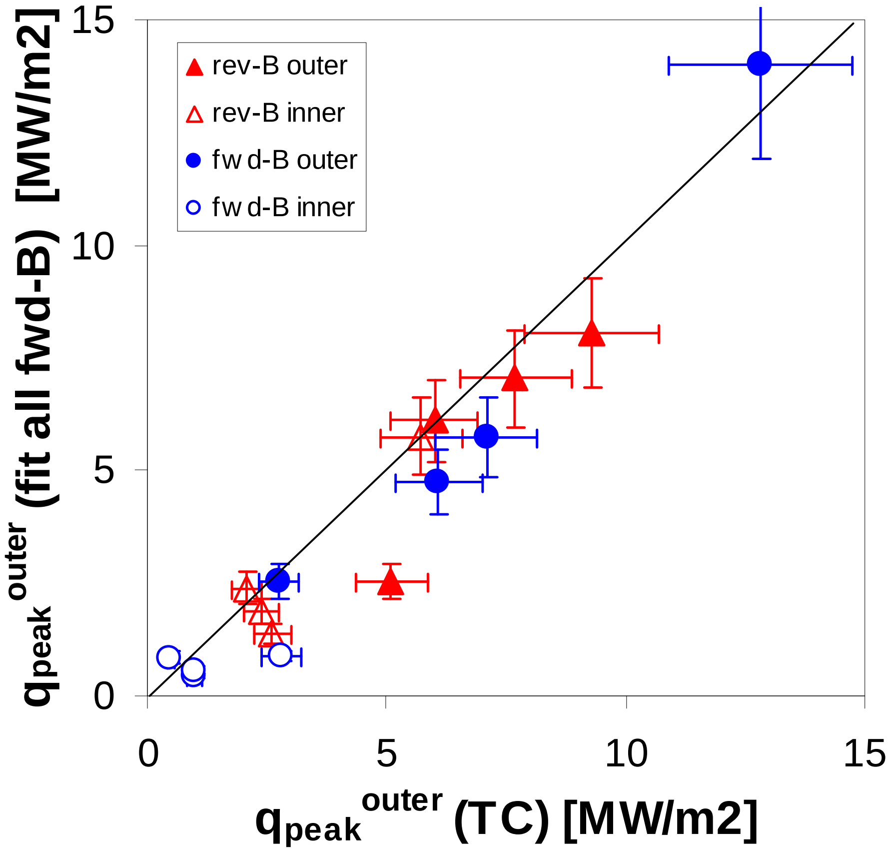
$$\lambda_q \propto A(Z) B_\phi^{-1} q_{95}^{0.6} P_t^{-0.4} n_{e,u}^{0.25}$$

This scaling best matched by (neo)-classical ion conduction

Fundamenski, NF (2004)

$$\therefore\ q_{\theta i}^{E} / q_{\theta i} \sim \rho_{\theta s}/\lambda_{Te} \sim T_{i,t}^{1/2} P_{SOL}^{1/2} n_{e,u}^{-0.2}$$

The B dependence cancels !



Ion orbit loss (IOL) modelling with ASCOT

ASCOT is a guiding centre Monte-Carlo code

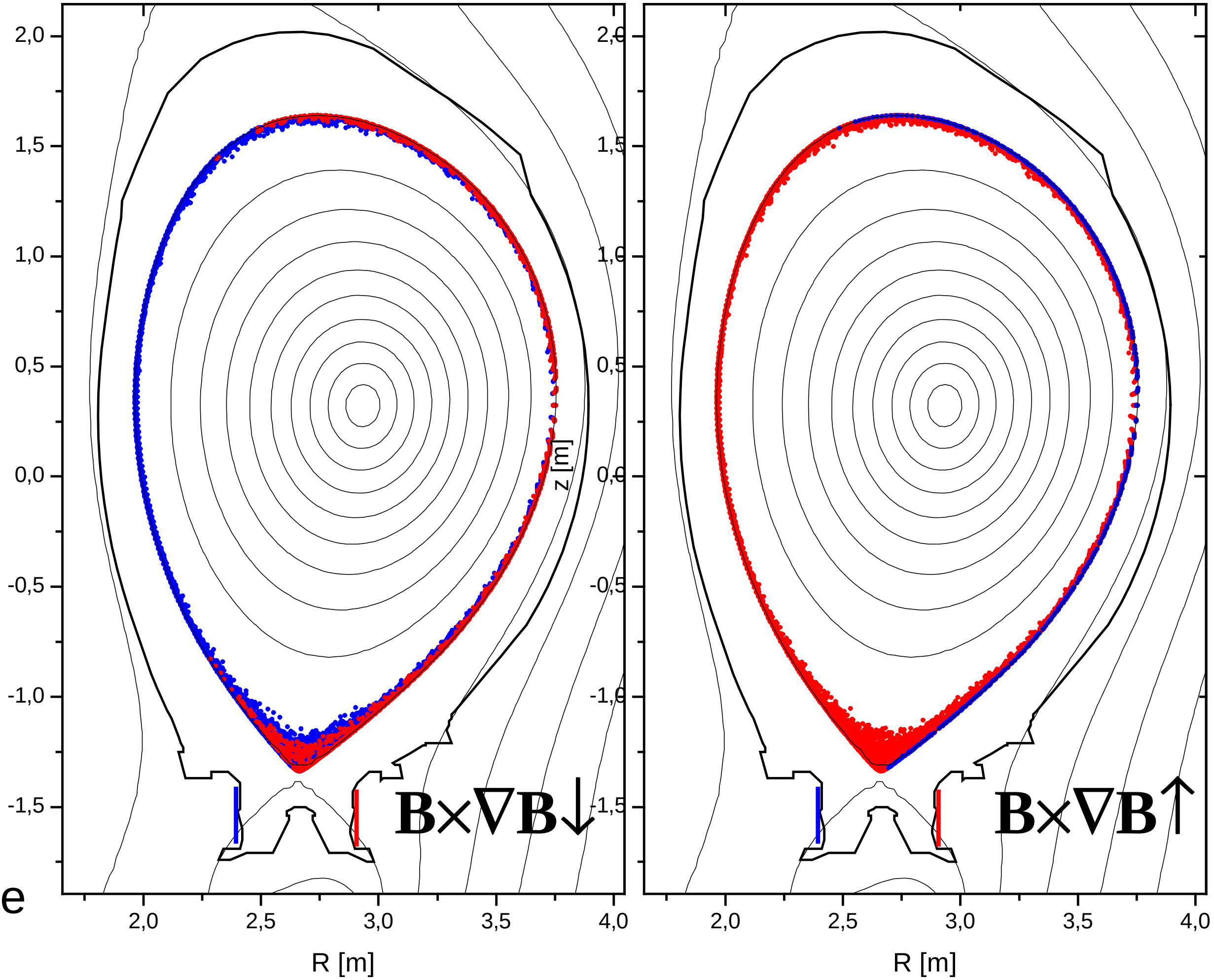
All collisions and drifts

Launch particles in ETB, follow until hit targets

With B×∇B↓ more ion orbits strike inner target

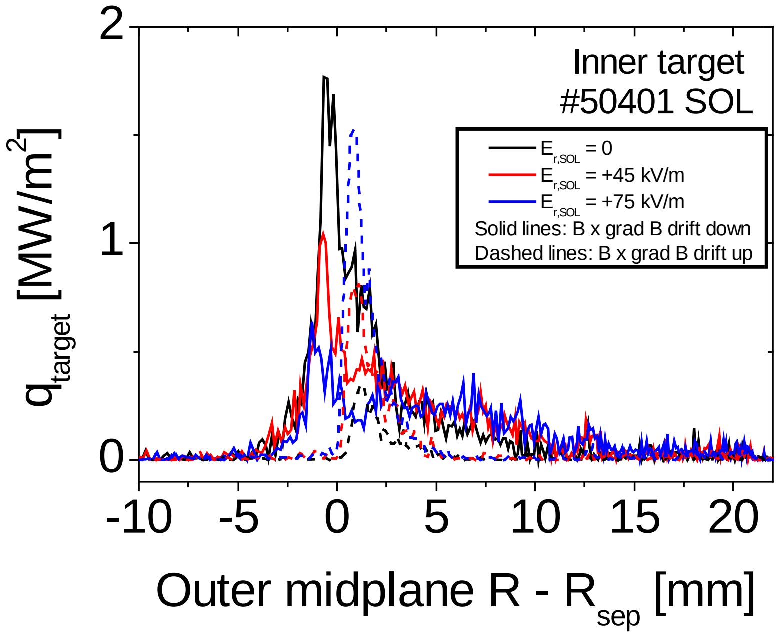
With B×∇B↑ most ion orbits strike outer target

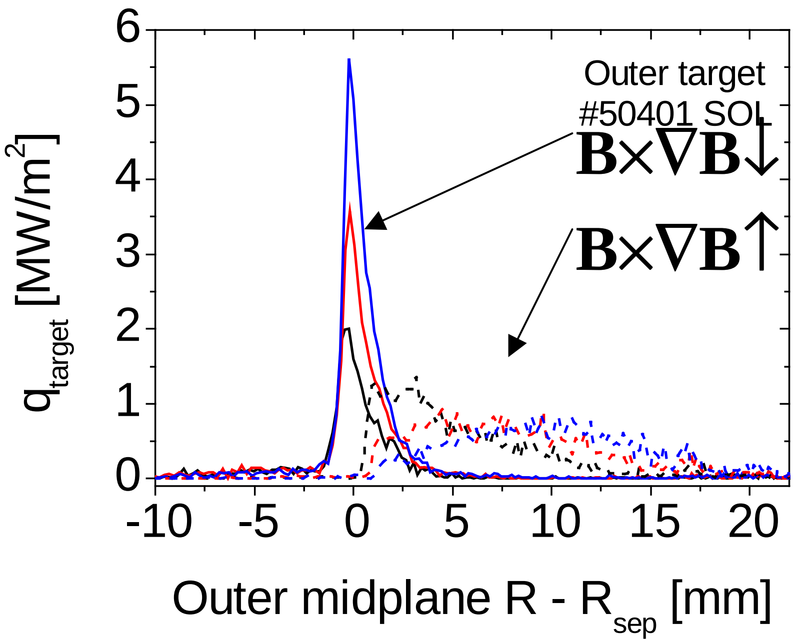
IOL is partly consistent with fwd-B data, for fairly large $E_{r,SOL}$ values > 30 kV/m



IOL target power profiles from ASCOT

JET 2.4 MA/2.5T, 12MW NBI,
15mm T-pedestal with T_{sep} = 0.41 keV, T_{ped} = 1 keV





Both inner and outer target power profiles, strongly affected by B×∇B dir

Not consistent with experiment ⇒ IOL not dominant in the SOL

Fundamenski P3-15

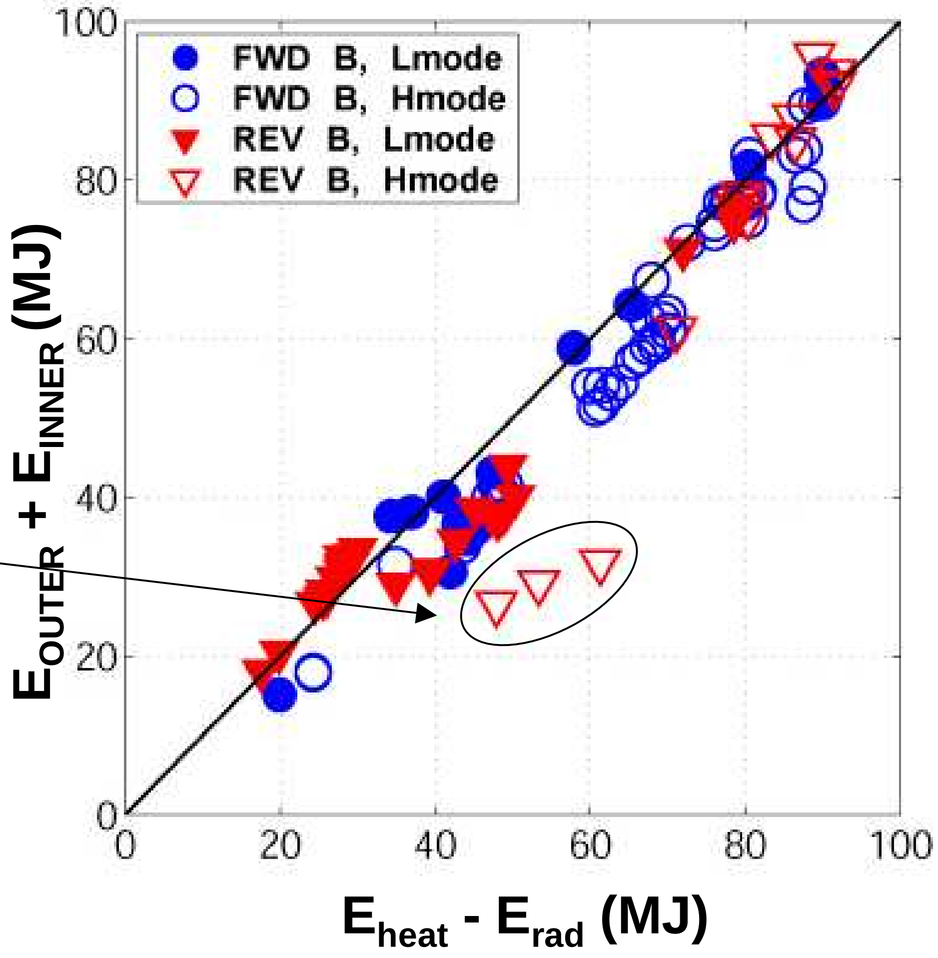
Global power balance

Large database of shots with a range of B, I, P, n_e (110 shots)

Deposited power based on divertor tile thermocouples

Generally good energy accounting in both fwd-B and rev-B

Exception: rev-B, 1.2 T with strong LFS wall interaction (prompt NBI CX losses)



Deposited power asymmetries

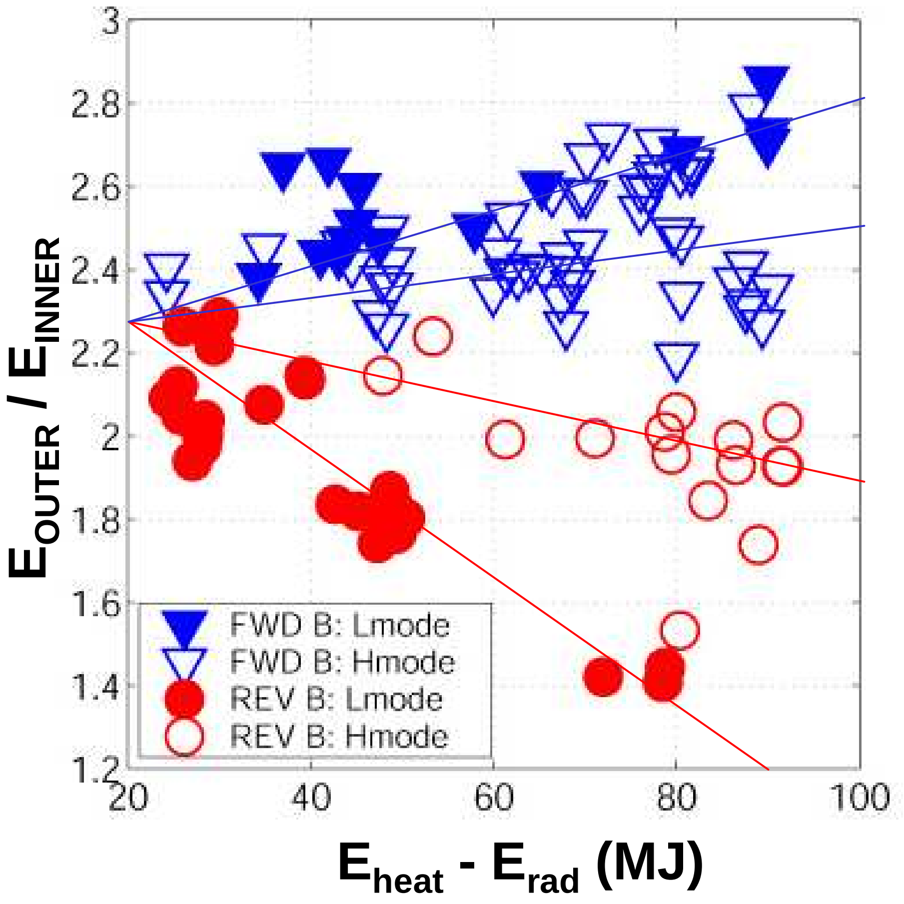
Large database of shots with a range of B, I, P, n_e (110 shots)

Deposited power asymmetry based on vertical tiles only

Average asymmetry ~ 2.2

Effect of B×∇B grows with power, as expected for classical drifts

Effect stronger in L-mode (ELMs vs. inter-ELM)



Power asymmetry scaling consistent with classical drift effects

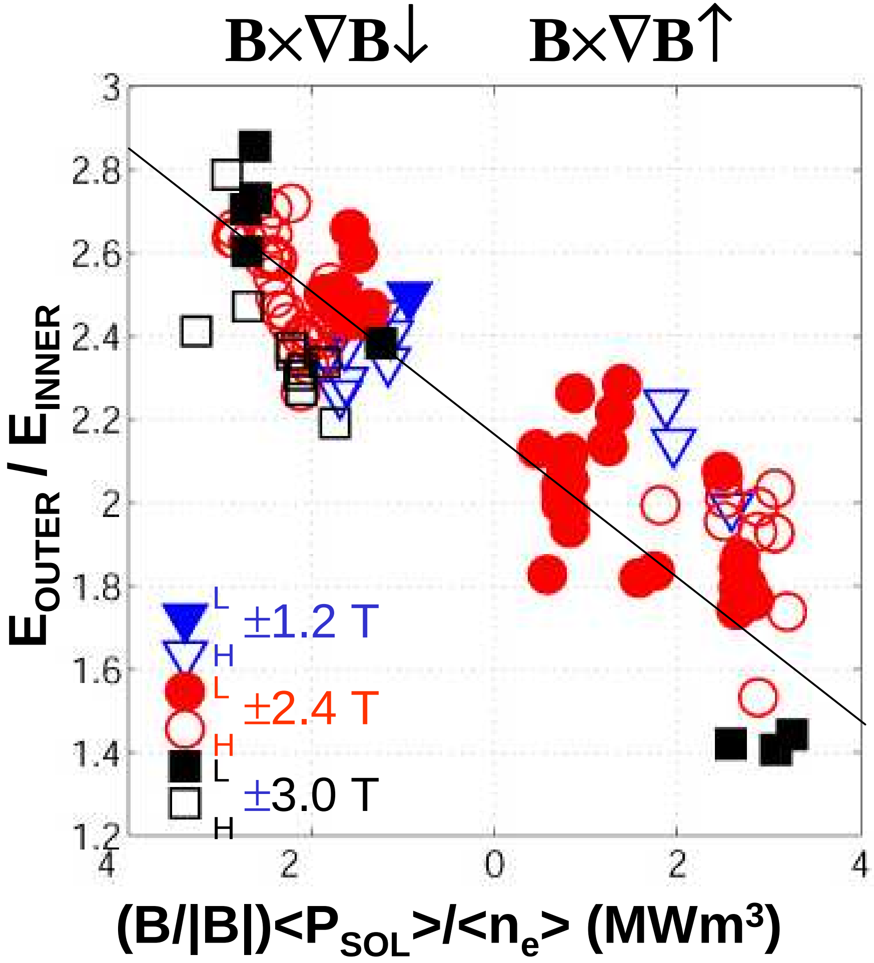
Linear scaling with power / density

Weak, if any, B scaling

Consistent with predictions based on classical drifts and measured SOL width scaling,

$$\therefore\ q_{\theta i}^{E} / q_{\theta i} \sim T_{i,t}^{1/2}\, P_{SOL}^{1/2}\, n_{e,u}^{-0.2}$$

Strong evidence for drift effects in JET power exhaust



Modelling with 2-D fluid codes

EDGE2D/NIMBUS with

D⊥, χ⊥(θ) larger on LFS, and

1) Classical drifts in SOL

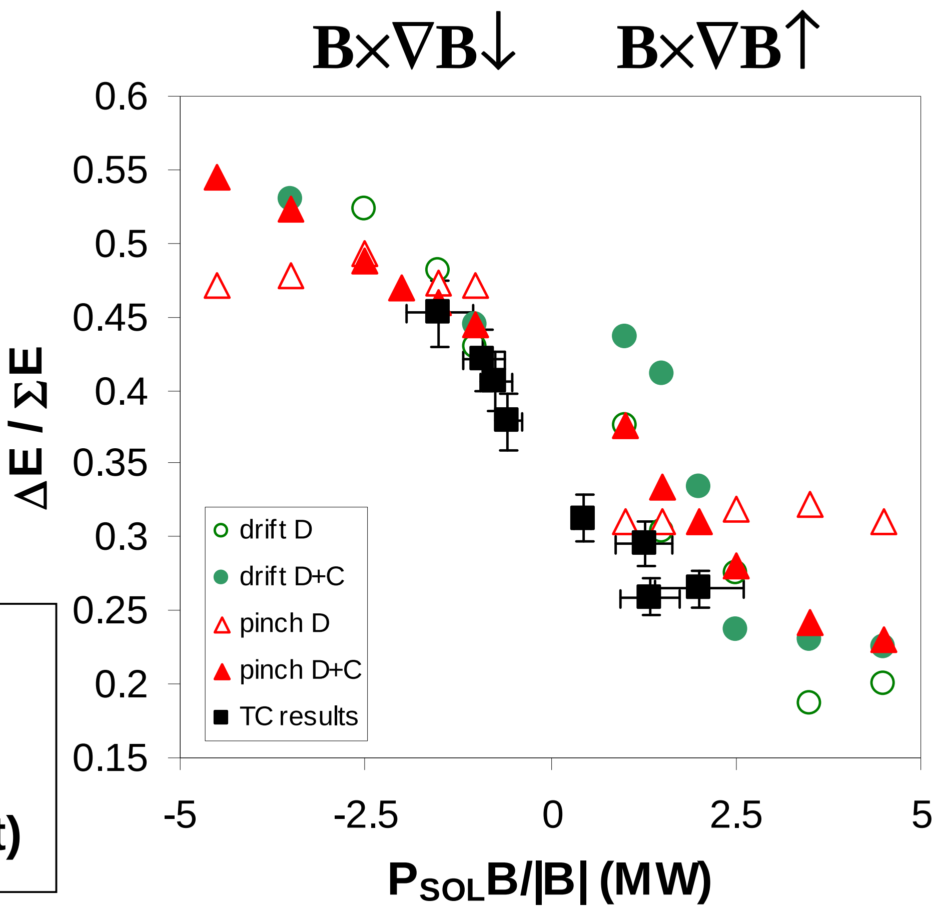
No pinch velocity

2) No drifts

Radial pinch velocity ~ 10 m/s

HFS → LFS for fwd-B

HFS ← LFS for rev-B



Two approaches give similar results

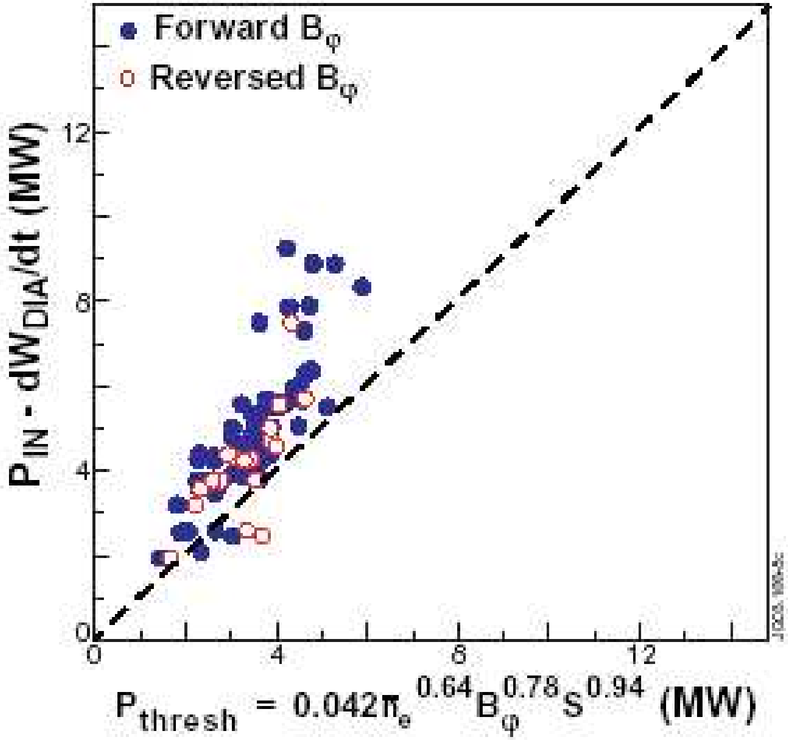
Fair agreement with experiment

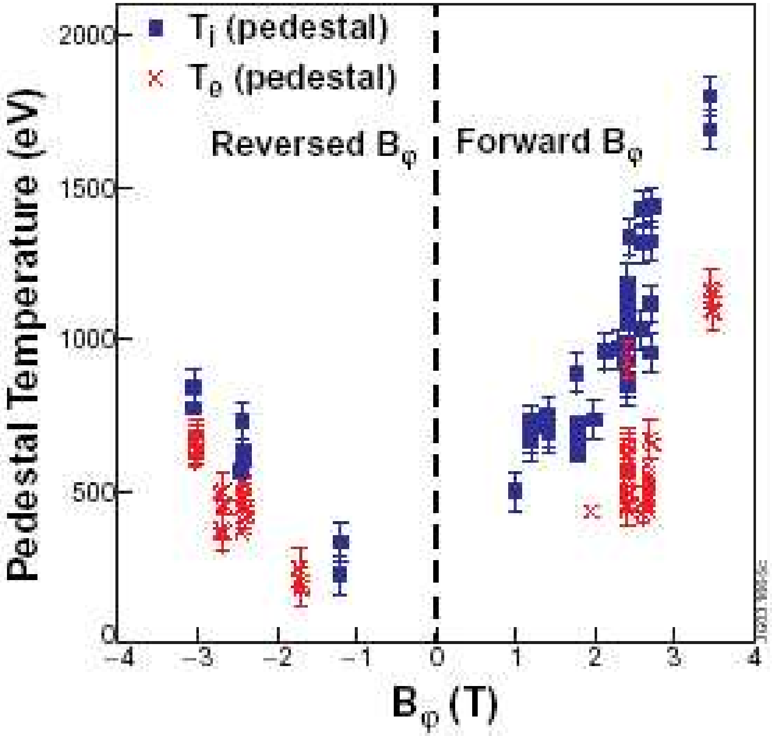
Effect of Carbon (radiation, transport)

Conclusions

- **Strong evidence for classical drift effect in SOL transport**
  - qualitatively explains SOL flows and C migration
    - active area of research !
  - quantitatively explains power asymmetries
  - transport, rather than radiation, responsible
- **Radial energy transport insensitive to $B\times\nabla B$ dir**
  - consistent with classical ion conduction: fits all JET data !!!
  - ion orbit loss ruled out as dominant mechanism in inter-ELM
- **Stronger drift effects in L-mode and during ELMs**
  - under investigation
- **More in the following presentations**
  - Orals: Matthews R-1, Strachan O-2, Kirnev O-8
  - Posters: Andrew P2-58, Fundamenski P3-15, Huber P3-22

L-H and III-I transitions





- L-H power threshold **independent** of B×∇B direction (↓ vs. ↑)
- III-I power threshold ~2x higher with B×∇B↑

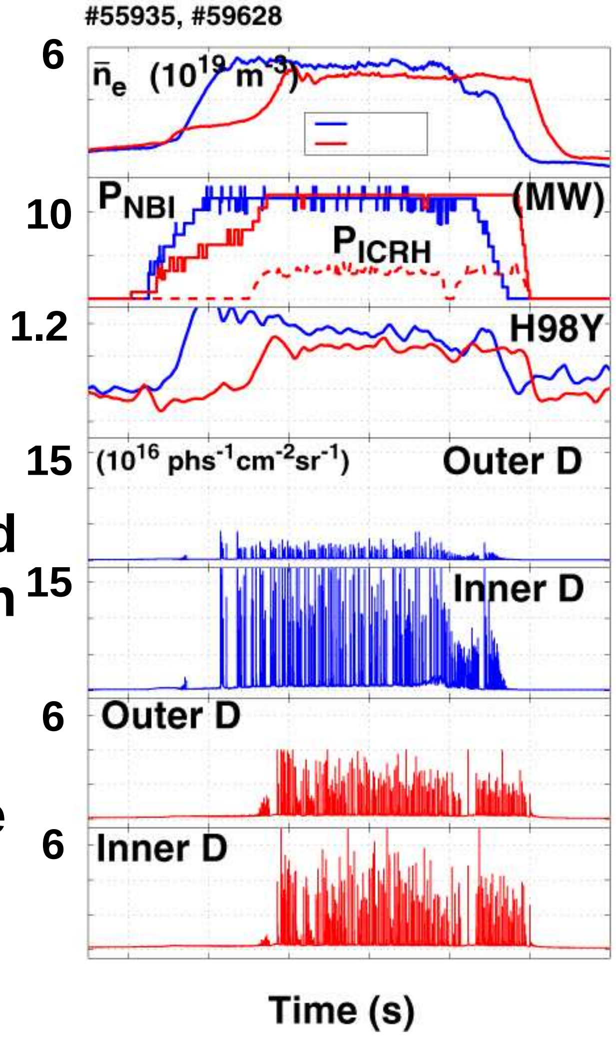
ELM $D_\alpha^{outer}/D_\alpha^{inner}$ in matched Type-I H-modes

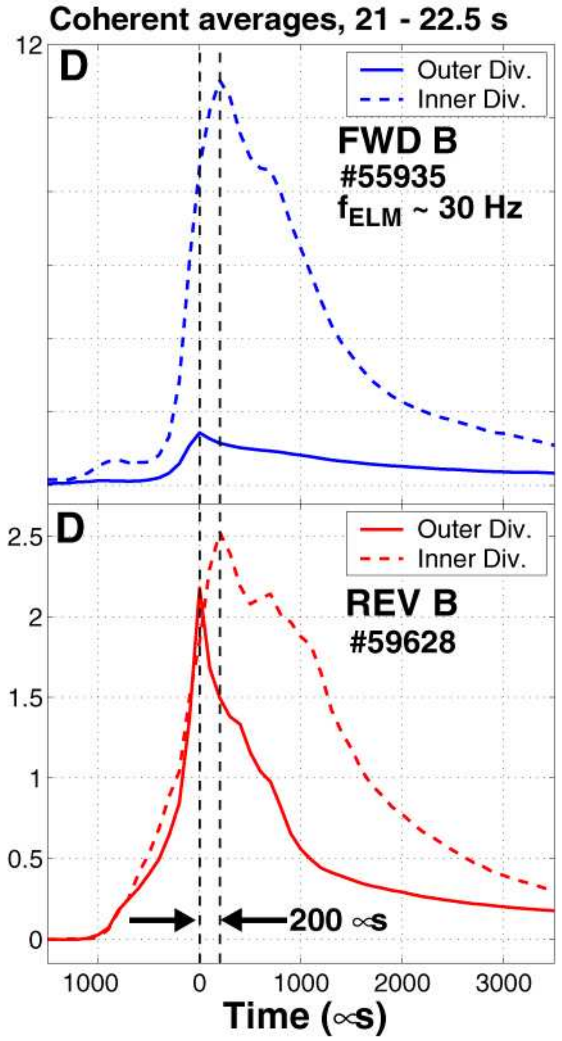
B×∇B↓ ELM D_α much larger at inner target

B×∇B↑ ELM D_α balanced

Consistent with in-out density asymmetry and with SOL flow direction

IR analysis complicated by presence of surface layers





SOL flow confirmed by TTP v_θ data

Turbulent Transport Probe (TTP)

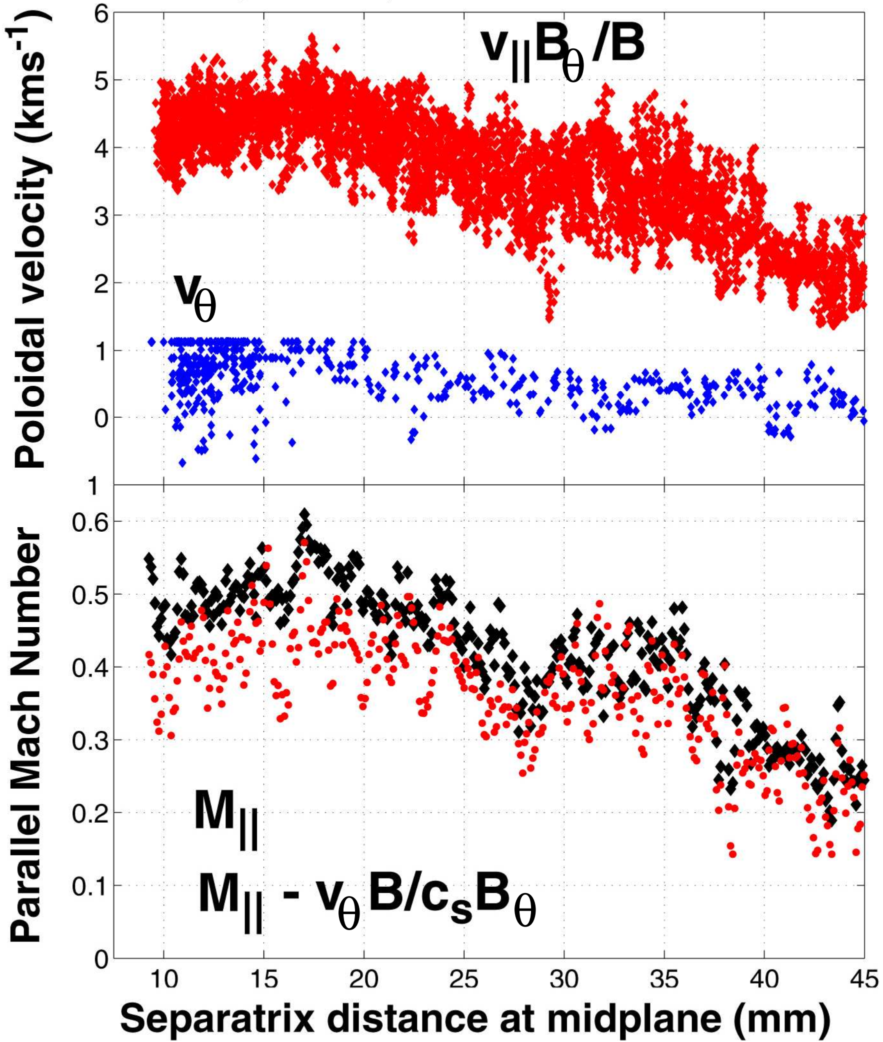
- measures j_{sat} ,T_e and v_θ
- j_{sat} ratio gives $M_{||}$
- T_e gives c_s
- v_θ poloidal phase vel. of fluctuations

$M_{||}$ (TTP) ~ $M_{||}$ (RFA)

$v_\theta << M_{||} c_s B_\theta / B$

SOL flow on JET not an artefact of toroidal rotation, as reported from C-mod (LaBombard et al.)

#56893, t = 60 s, Forward B



Deposited power profiles for matched pairs

Thermocouple method of reconstructing power profiles

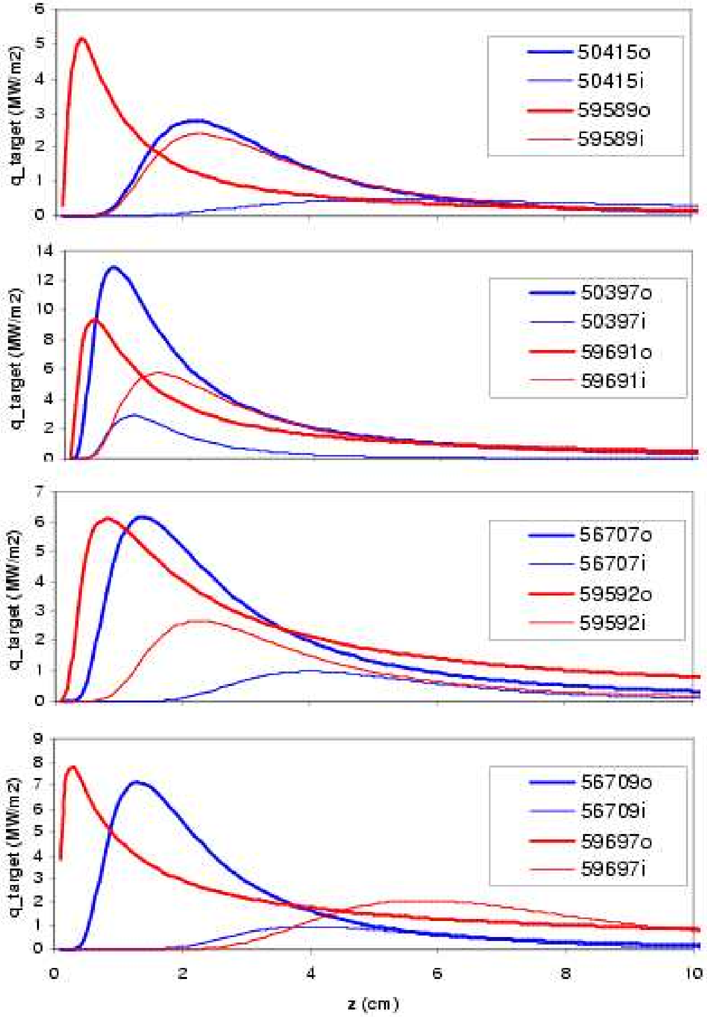
Larger effect on inner than outer profiles, consistent with Langmuir probes

Parametrise in terms of peak heat flux and power widtrh

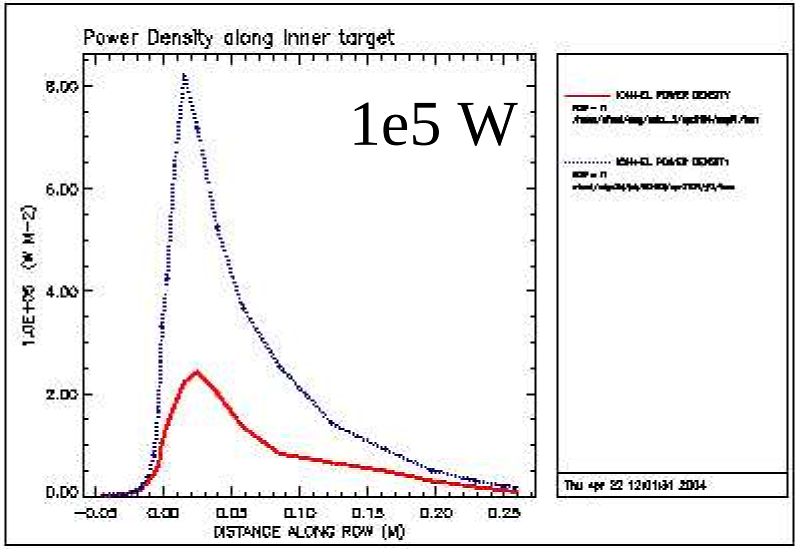
To assess effect of B×∇B must plot both vs. fwd-B scaling (next slide)

B×∇B↓

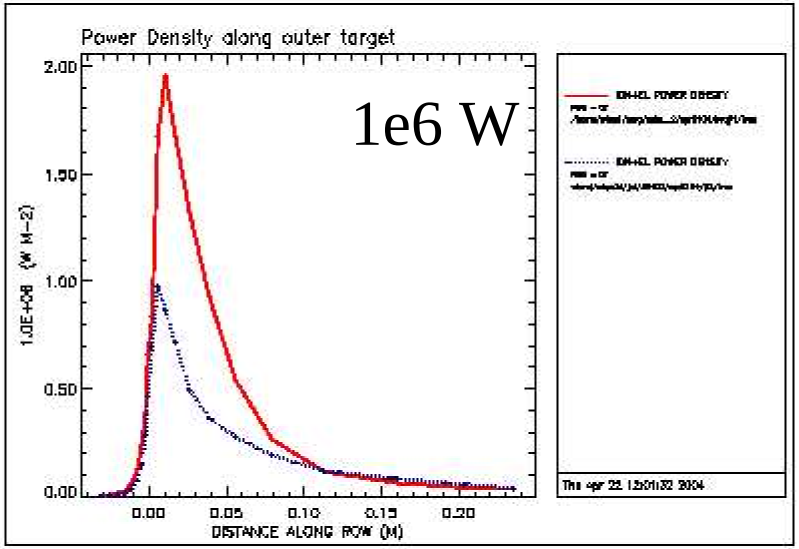
B×∇B↑



0.2 m2/s (flux space), 4 MW, 2e19 m-3, D+C, SOL+core drifts



1e5 W



1e6 W

Bx∇B ↓ vs. Bx∇B ↑

Classical drifts in ∧ dir. with B×∇B ↓ vs. ↑

Guiding centre picture:

$$\langle v^{gc}\rangle_\sigma = \langle v_{||}^{gc}\rangle_\sigma \mathbf{b} + \mathbf{v}^E$$
$$+ (v_{t\perp\sigma}^2/\Omega_\sigma)\{\mathbf{b}\times\nabla B/B + \mathbf{b}(\mathbf{b}\cdot\nabla\times\mathbf{b})\}$$
$$+ \{(v_{t||\sigma}^2 + v_{||\sigma}^2)/\Omega_\sigma\}\mathbf{b}\times\mathbf{b}\cdot\nabla\mathbf{b}$$

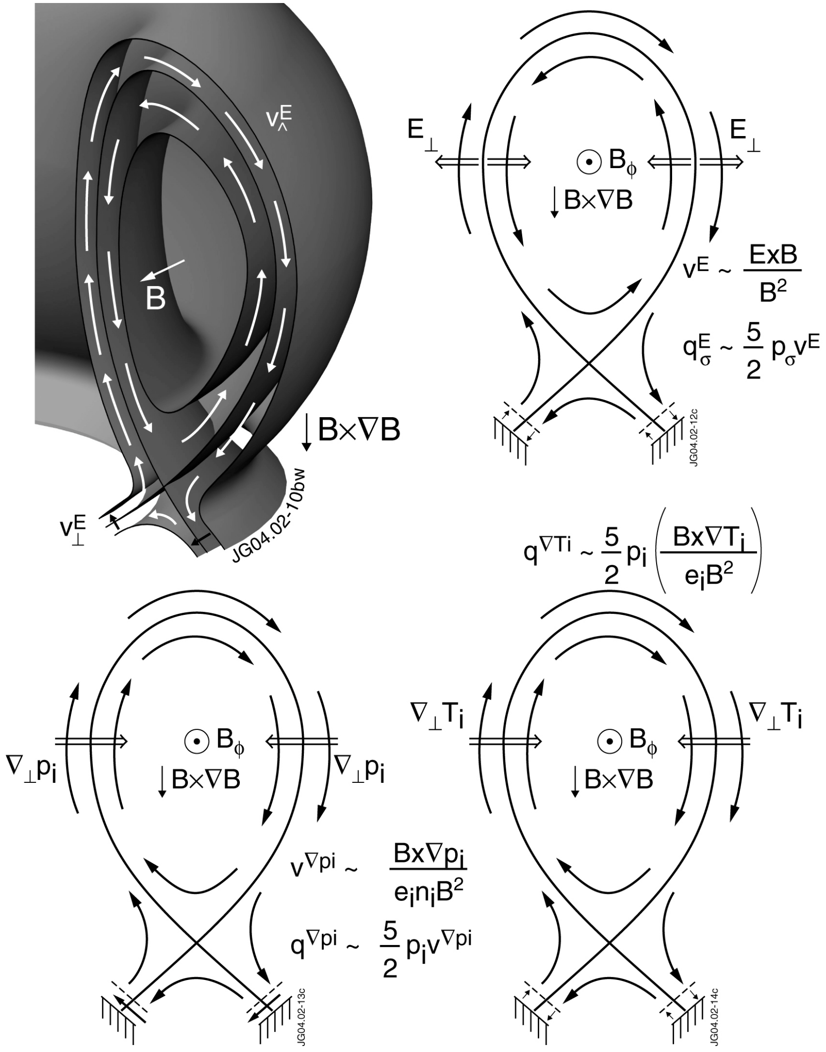
Fluid picture:

$$\mathbf{v}_\sigma = v_{||\sigma}\mathbf{b} + \mathbf{v}^E + \mathbf{b}\times(\nabla p_{\perp\sigma} - \mathbf{R})/m_\sigma n_\sigma \Omega_\sigma$$
$$+ \{(v_{t||\sigma}^2 - v_{t\perp\sigma}^2 + v_{||\sigma}^2)/\Omega_\sigma\}\mathbf{b}\times\mathbf{b}\cdot\nabla\mathbf{b}$$

$$\mathbf{v}^E \sim (1+0.25\rho_\sigma^2\nabla^2)\mathbf{E}\times\mathbf{b}/B \sim \mathbf{E}\times\mathbf{b}/B$$
$$\mathbf{b} = \mathbf{B}/B,\ \Omega_\sigma = e_\sigma B/m_\sigma,\ v_{t\sigma} = (T_\sigma/m_\sigma)^{1/2}$$

Energy flux due to drifts:

$$\mathbf{q}_\sigma = 2.5 p_\sigma \langle \mathbf{v}^{gc}\rangle_\sigma - \nabla\times(2.5 p_\sigma T_\sigma \mathbf{b}/e_\sigma B)$$
$$\approx 2.5 p_\sigma \mathbf{v}_\sigma + 2.5 p_\sigma v_{t\sigma}\rho_\sigma \mathbf{b}\times\nabla T_\sigma/T_\sigma$$



Relative strength of drift terms

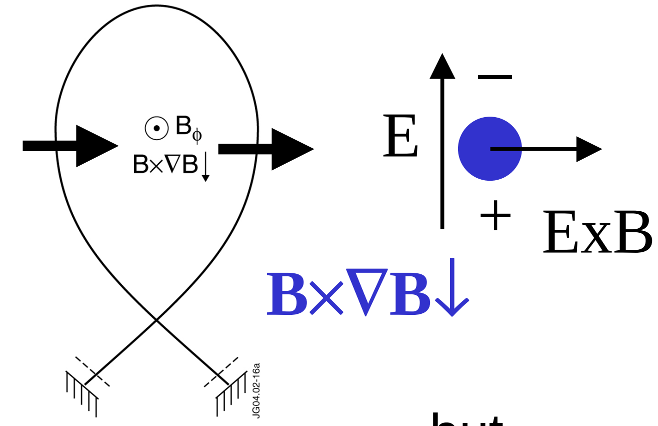
Radial E-field in SOL due to $\nabla_\perp T_e$	$E_\perp \sim 3\nabla_\perp T_{e,t}$
Poloidal component of heat flux	$q_{\theta\sigma} = (B_\theta/B)q_{\|\|\sigma}$ $q_{\|\|\sigma} \sim p_\sigma L_{\|\|}/\tau_{\|\|\sigma}$ $\tau_{\|\|i} \sim L_{\|\|}/c_s$, $\tau_{\|\|e} \sim L_{\|\|}^2/\chi_{\|\|e}$
The ratio of poloidal components: ExB	$q_{\theta i}^E/q_{\theta i} \sim 3\rho_{\theta s}/\lambda_{Te}$ $q_{\theta e}^{E}{}_{/\theta e} \sim \nu^*_e \rho_{\theta s}/\lambda_{Te}$
diamagnetic (conductive)	$q_{\theta i}^{\nabla T}/q_{\theta i} \sim \pm \rho_{\theta s}/\lambda_{Ti}$ $q_{\theta e}^{\nabla T}/q_{\theta e} \sim \nu^*_e \rho_{\theta s}/\lambda_{Te}$
with fwd-B power width scaling $\lambda_q \propto A(Z)B_\phi^{-1}q_{95}^{0.6}P_t^{-0.4}n_{e,u}^{0.25}$	$q_{\theta i}^E/q_{\theta i} \sim q_{\theta i}^{\nabla T}/q_{\theta i} \sim$ $T_{i,t}^{1/2} P_{SOL}^{1/2} n_{e,u}^{-0.2}$

Other SOL flow modelling approaches

Active area of research !!!

See Kirnev, Strachan, Huber, Coster, Matthews, Chankin

1) Effect of carbon plume on probe
   $M_{||}$ measurement
2) External momentum source
3) Poloidal variation of D⊥, χ⊥
   Radial pinch
      HFS → LFS for fwd-B
      HFS ← LFS for rev-B
   No drifts
   Better match to experiment
   Physical basis? Not polarization.



but…