Driving Toroidally Asymmetric Current Through the Tokamak Scrape-Off Layer to Control Edge Profiles and Stability

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OUTLINE

1. **Motivation:** non-axisymmetric divertor design can mitigate heat exhaust

1. **SOL convection:** potential for enhanced transport

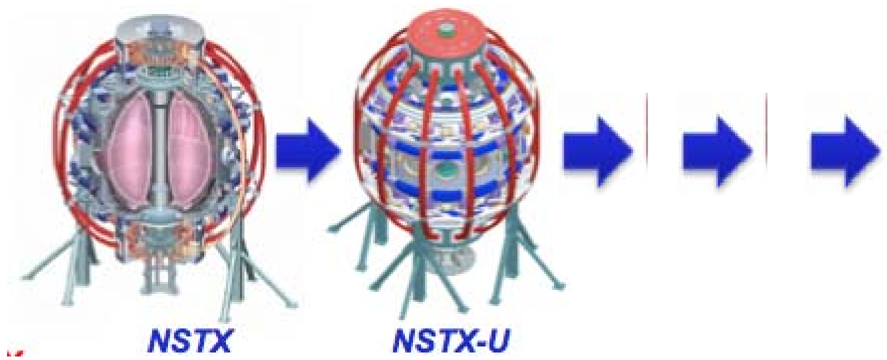
2. **SOL current:** magnetic perturbations for ELM pacing/control

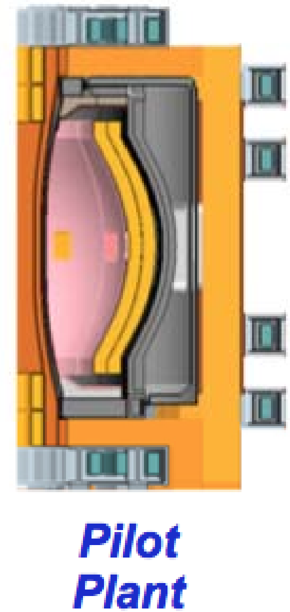
3. **Passive current drive:** reactor-relevant techniques

4. **Conclusion**

MOTIVATION: ST's need to solve a burning problem!

- **Steady-state and transient heat fluxes are large**
  - Smaller size implies larger P/R and P/R^2
  - Fluxes are difficult to exhaust and difficult to radiate away



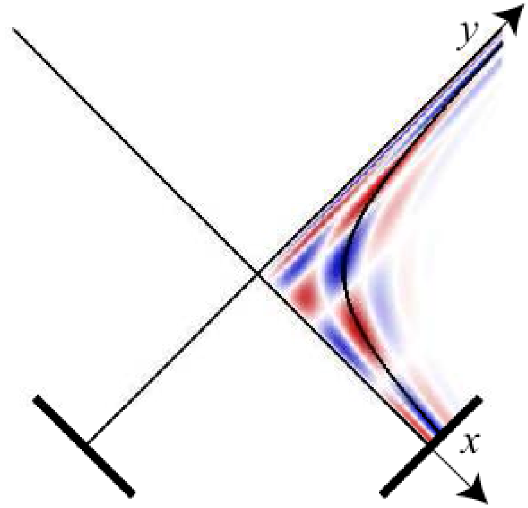


- **Demonstration that ST's are attractive power plants will require design principles and/or control techniques for mitigation of peak fluxes**
  - At full current, NSTX-Upgrade will need to utilize mitigation techniques to achieve planned 5 sec pulse length

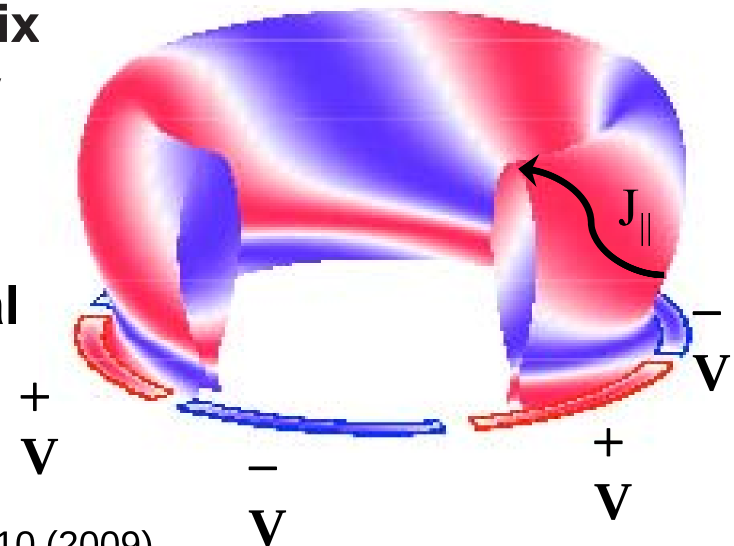
- **NSTX Mission to confront high heat flux issues presents an opportunity to prototype new control methods for SOL, divertor, & PMI**

SOLUTION: Toroidal variations of divertor plasma can be used to mitigate target exhaust

- **Non-axisymmetric variations in the electrostatic potential drive both ExB convection and parallel current $J_{||}$**



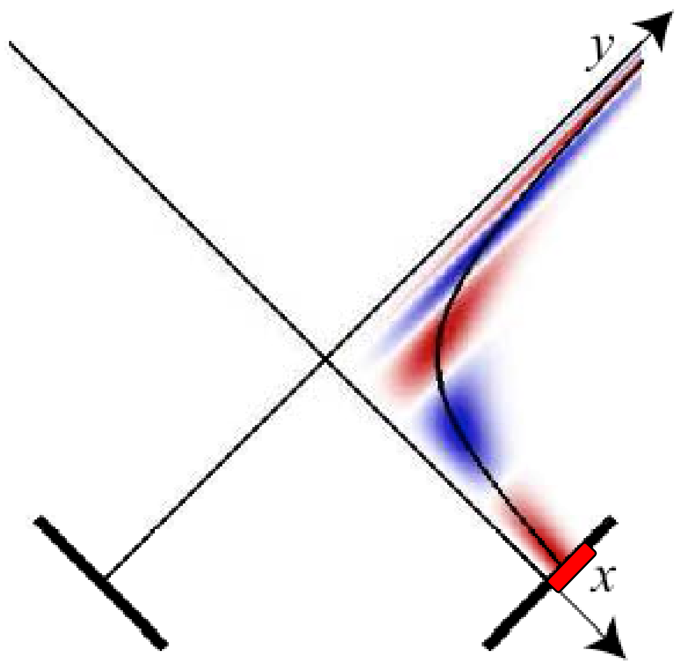
- **SOL convection[1] can be used to spread particle and heat fluxes in the divertor**
- **SOL current[2] can be used to generate magnetic perturbations inside the separatrix that controls pedestal transport & stabillity**
- **Can be driven either by direct electrical biasing or by passive generation of toroidal divertor asymmetries**



[1]R. H. Cohen and D. D. Ryutov, Nucl. Fusion **37** 621 (1997)
[2]I. Joseph, R. H. Cohen and D. D. Ryutov, Phys. Plasmas **16** 052510 (2009)

Phasing at the target plate determines the effect in the SOL

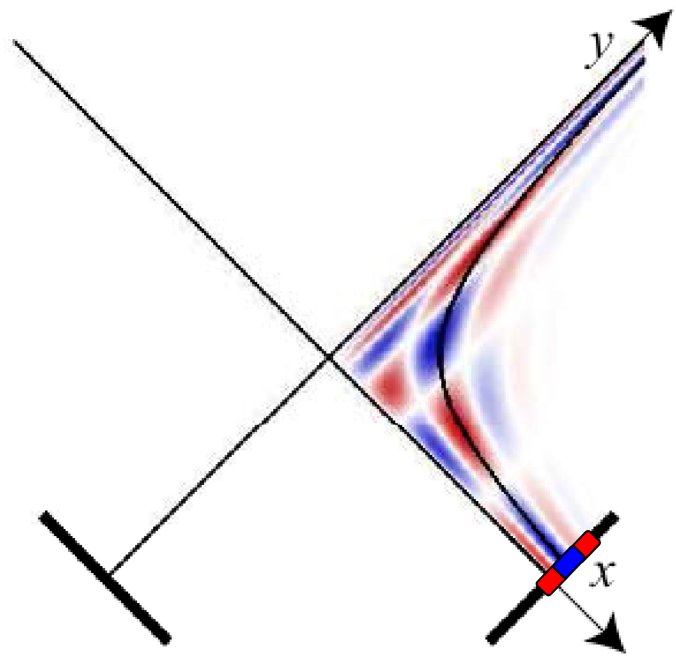
- Perpendicular current is smaller than parallel current by $O(\rho/\lambda)$ – neglect to 0th order
- Parallel current conserved along field lines $0 = \nabla\cdot \mathbf{J} \approx \nabla\cdot J_{\|}\mathbf{b} = \mathbf{B}\cdot \nabla J_{\|} / B$
- Potential develops similar spatial structure $\Phi = \Phi_{\text{target}} - \int \eta_{\|} J_{\|} dl \approx \Phi_{\text{target}}(1 - l / L_c)$



Constant phase on target

can be used to drive coherent perturbation to midplane

$$\Phi \propto \cos n(\zeta - q\theta)$$



Sinusoidal phase on target

best for driving radial convection cells in divertor

$$\Phi \propto \cos(k_\psi \psi)\cos n(\zeta - q\theta)$$

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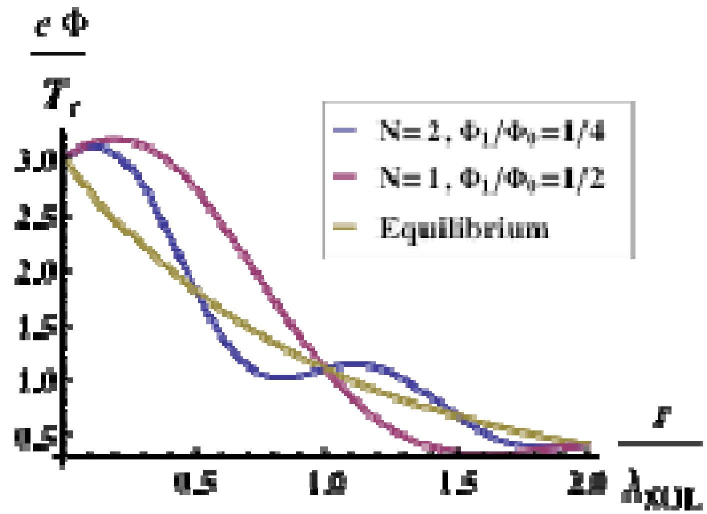
SOL POTENTIAL: possible generation of convection cells that enhance radial transport

- **Electrostatic convection can be used to control fluxes if the potential generates enough vorticity to entrain turbulent structures**



- **Equilibrium SOL potential is on the order of the floating potential**

  $\Phi_0 \sim \Lambda T_e \qquad \Lambda \sim 2-4$

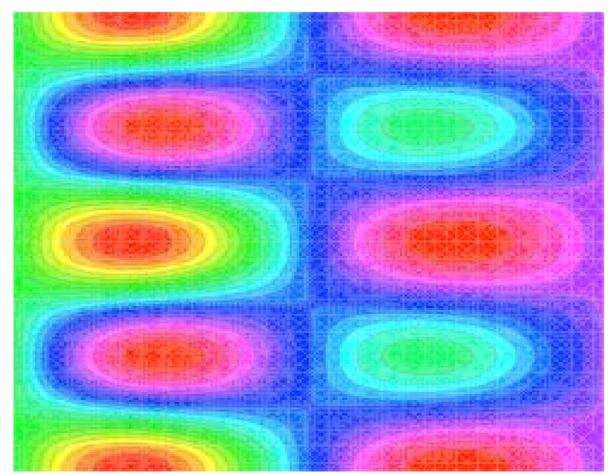
  – Radial decay lengths are comparable

  $L_\Phi = \Phi_0 / \Phi_0' \sim T_e / T_e' = L_T$

- **Generating a convection cell requires both an *O*-point and an X-point**

  $\Phi_1 / \Phi_0 > 1/k_x L_\Phi \qquad e\Phi_1 / T_e > \Lambda / k_x L_T$

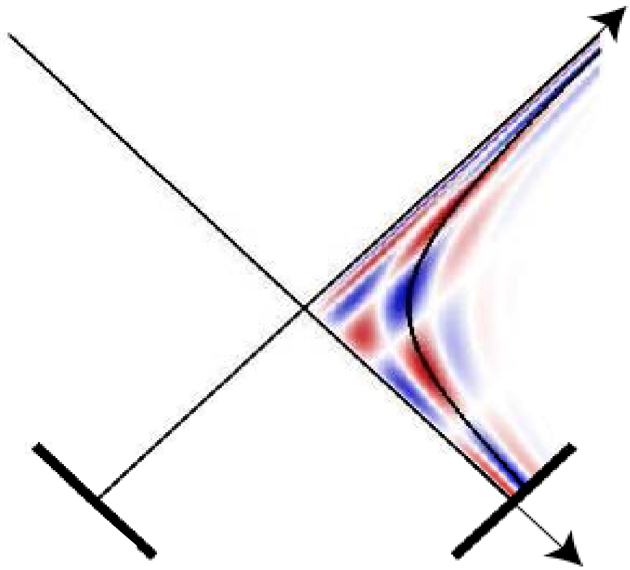
  – There are $N = k_x L_{Te}/\pi$ cells within a single L_T width



Convection cell transport can dominate both parallel transport and anomalous transport

- **Maximum rotation frequency at cell center**

  $\Omega_0 = k^2\Phi/B$



- **Parallel transport**
  - Time-scale $\tau_{\|} = L_c/V_T$ where $V_T = (T/m)^{1/2}$
  - Convection dominates conduction when $\Omega_0\tau_{\|} > 1$

    $e\Phi/T > 1/k^2\rho L_c$
  - Assume T~25 eV, L_c=10 m, and $e\Phi/T \sim 1$ then

    $\lambda_x < 2\pi(\rho L_c)^{1/2} \sim$ 50 cm for D^+ and ~ 7 cm for e^-
- **Anomalous transport**
  - Anomalous diffusion D_a yields transport time-scale $\tau_a = 1/k^2D_a$
  - Convection dominates when the Peclet # $Pe = \Omega_0\tau_a = \Phi/BD_a > 1$ which requires

    $e\Phi/T_e > D_a/\rho_s V_T$
  - Convection dominates Bohm transport $D_B = \rho_s V_T/16$ when

    $e\Phi/T_e > 1/16$
  - Convection dominated regime yields large effective diffusion[1]

    $D_* \sim Pe^{1/2}D_a = (D_a\Phi/B)^{1/2} \sim 4\,(D_aD_B)^{1/2}$

[1]M.N. Rosenbluth, Phys. Fluids **48** 024003 (1987)

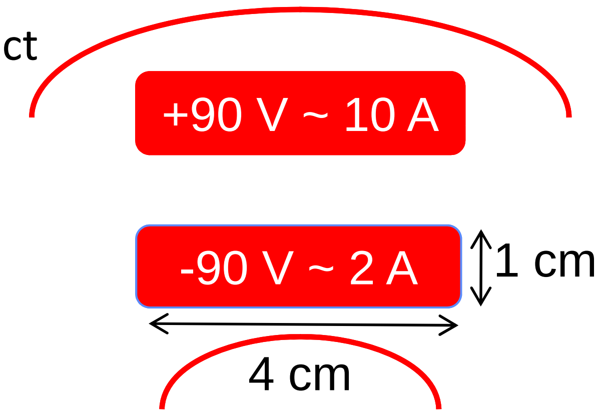
Electrode biasing experiments on NSTX have demonstrated a local interaction with SOL plasma & filamentary structures[1]

- Two pairs of biasable electrodes were installed in the NSTX divertor

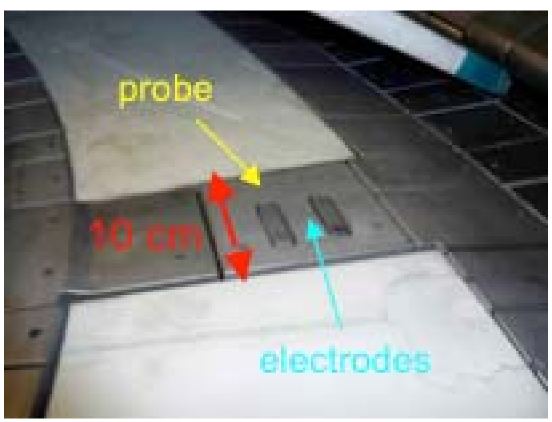
- When biased to +/- 90 V electrodes are observed to locally deflect plasma filaments near the divertor surface by ~ 1 cm

- Previous midplane electrode experiments demonstrated local control over SOL profiles consistent with ExB convection[2]

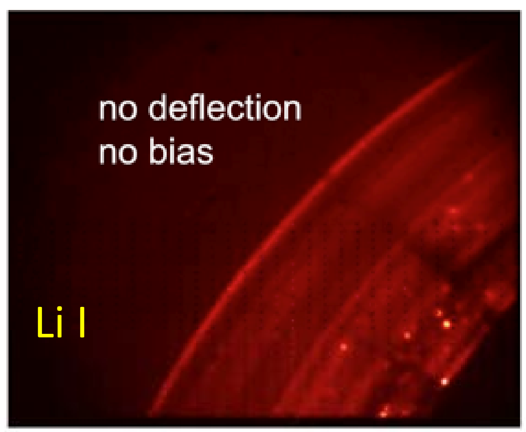
- **Comparison with theory is currently in progress**



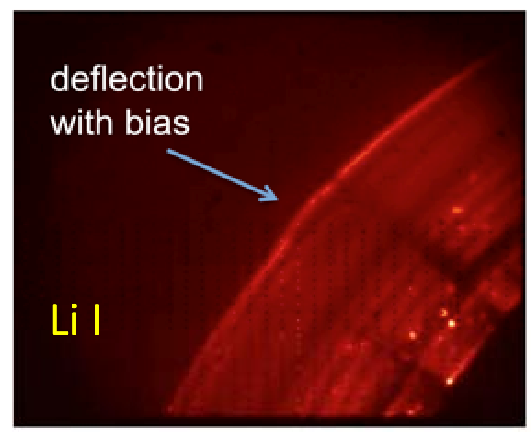
Bay E electrodes



Without bias



With ±90 V bias



[1]S. J. Zweben, et al., private communication (2010)

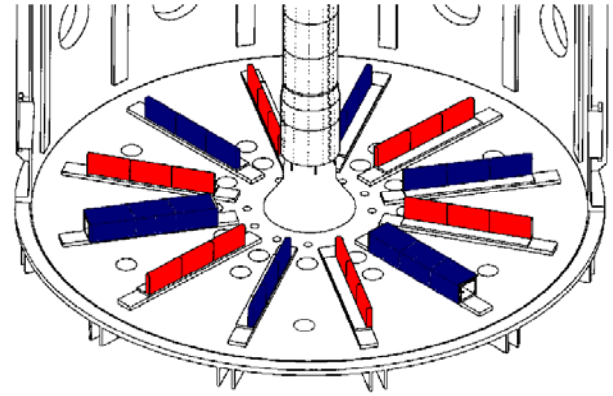
[2]S. J. Zweben, et al., Plasma Phys. Controlled Fusion, **51** 105012 (2009)

Full divertor biasing experiments on MAST were able to demonstrate broadening of strike point flux profiles[1]

- **Six graphite ribs electrically isolated from the vacuum vessel and directly biased with 1 MW power supply**

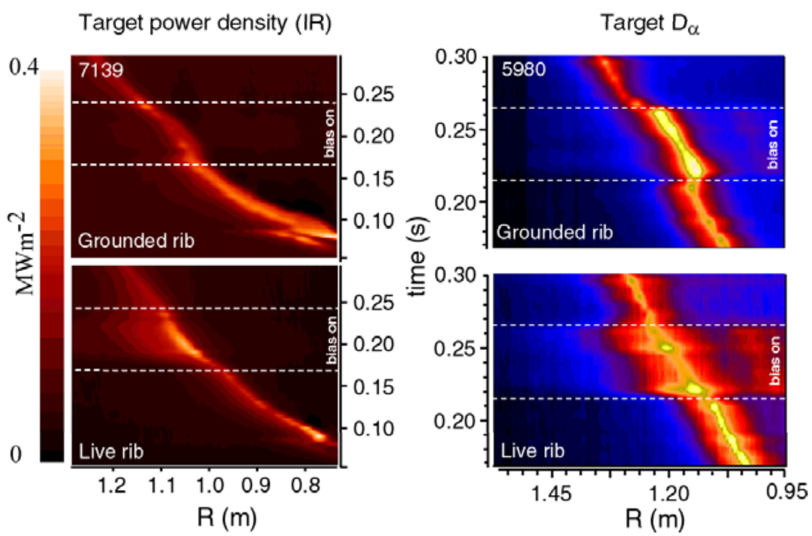
- provides 5 kA at 200 V (DC)

- effectively n=6, I=2.5kA perturbation



- **Strike-points observed to broaden & shift in opposite directions**

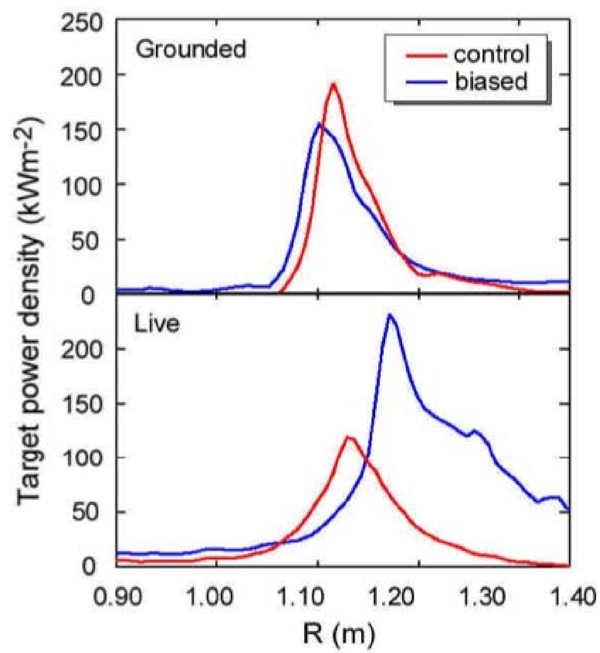
-width could be enhanced up to ~4x



- **Peak heat fluxes significantly modified**

-**Grounded ribs:** peak decreased (by up to ~4x) due to enhanced SOL width

-**Live ribs:** peak was still increased due to the additional P_{SOL}



[1]G. F. Counsell, et al., Nucl. Fusion **43** (2003) 119
G. F. Counsell, et al., EPS St. Petersburg 2003 ECA Vol. 27A, P-3.202

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4. **Conclusion**

SOL CURRENT: possible generation of magnetic perturbations for ELM pacing and/or ELM control[1]

- **Resonant threshold is rather small**

  $$\left|B_{m=qn}/B\right| \sim 2-5\times10^{-4}$$

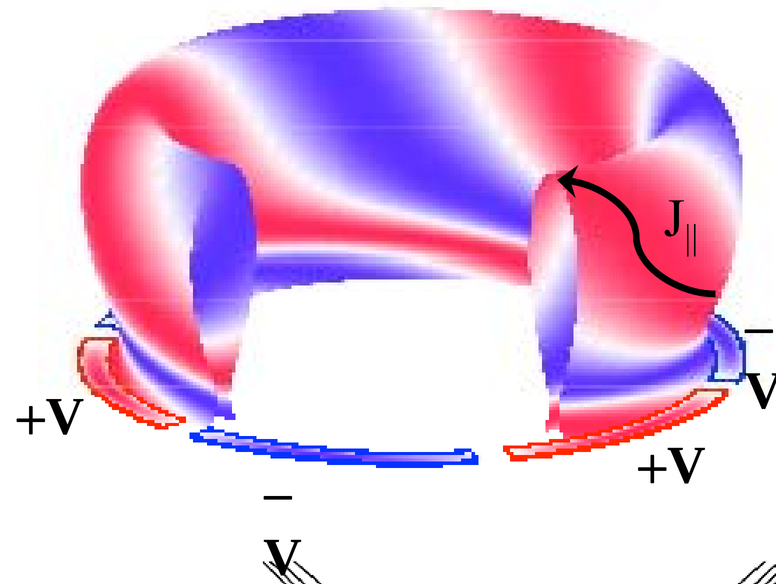
- **SOL currents are primarily parallel to B**
  - Generates naturally resonant spectrum for $\delta A_{||}$ and δB_{perp}
- **The net surface current determines the perturbation amplitude δB**
  - Net parallel surface current density

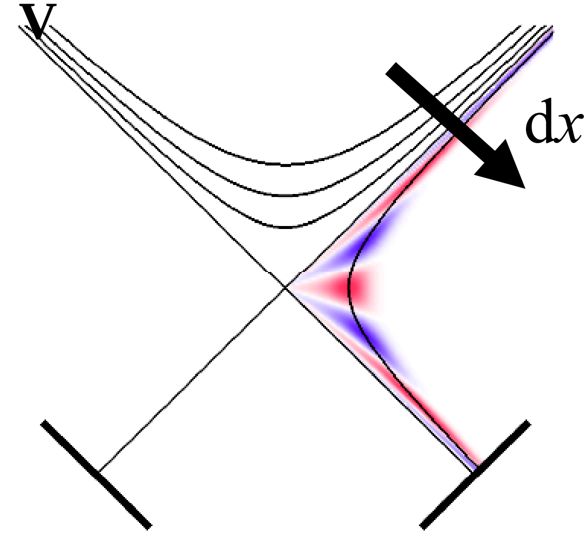
    $$K_{||} = \int J_{||} dx$$

  - Determines the tangential discontinuity

    $$[\delta \mathbf{B}]_{tang} = \mu_0 \mathbf{K} \times \mathbf{n}$$

  - Yields estimate $\delta B_{\mathrm{normal}} \sim [\delta B]_{\mathrm{tang}}/2 = \mu_0 K_{||}/2$





[1] I. Joseph, R. H. Cohen and D. D. Ryutov, Phys. Plasmas **16** 052510 (2009)
I. Joseph, Phys. Plasmas **16** 052511 (2009)
I. Joseph, Contrib. Plasma Phys. **50** 311 (2010)

Upper limit for target field perturbation strength can exceed threshold $B_{mn}/B \sim 2\text{-}5 \times 10^{-4}$ by a wide margin

Upper limit based on full saturation current assumes 100% efficiency

- Entire target plate is used to drive ion saturation current
- Field near target plate is equal to field at midplane

	λ_{sat} (cm)	J_{sat} (A/cm^2)	K_{sat} (A/cm)	δB (G)	$\delta B/B$ ($\times 10^{-4}$)
ITER	2-3	100-400	200-1000	100-800	20-200
DIII-D	2-3	5-40	10-100	6-80	3-40
NSTX	5	2-4	10-40	6-20	10-40
MAST	5	0.4-2	2-10	1-6	2-10

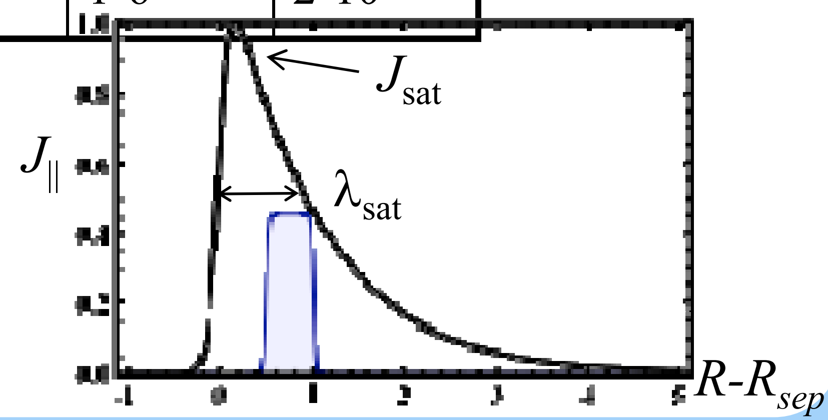
Definitions

J_{sat} = peak value of ion saturation current

λ_{sat} = perp. e-folding length of J_{sat} across target

$K_{sat} = J_{sat}\,\lambda_{sat}$ = integrated surface current density

$B_{sat} = \mu_0 K_{sat}/2$ = amplitude near target plate



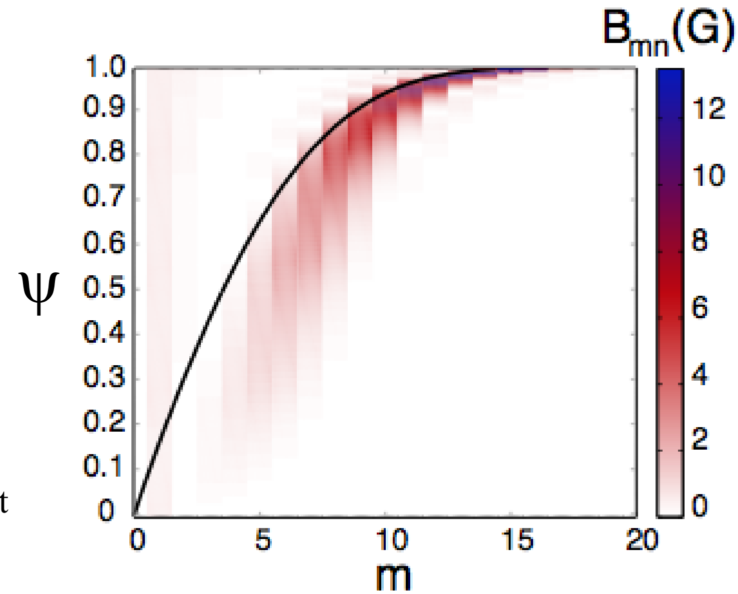
δB generated by the SOL current has a naturally edge-resonant helicity spectrum

$k_{\|} \propto m - qn = 0$

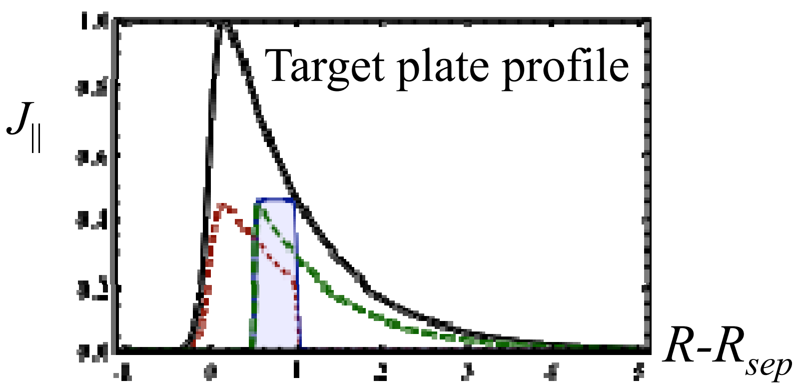
- **Spectrum is naturally edge-resonant**

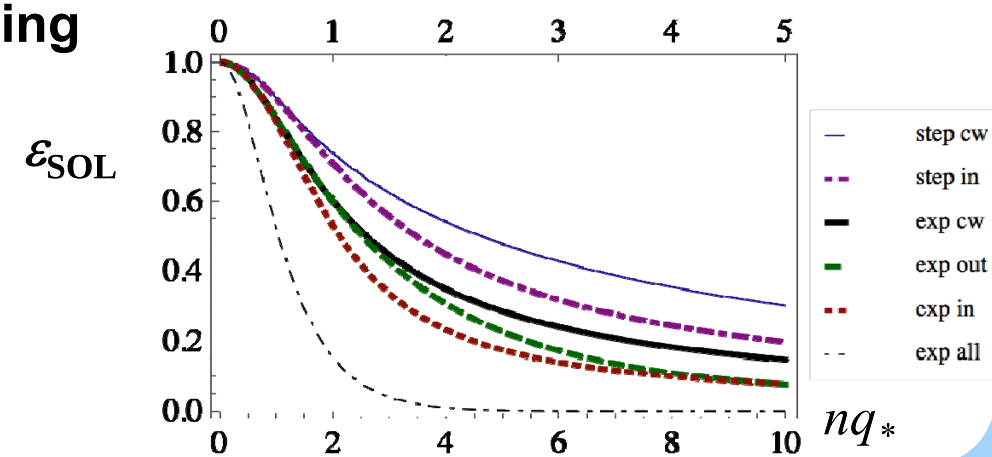
$$B_{m=qn} = \varepsilon_{SOL} B_{sat} (l/a) \log(a/nq_* d)$$

d = distance from flux surface to surface current
$q_* = B_T/RB_P$' quantifies X-point shear (4-5 NSTX)
ε_{SOL}= current drive efficiency $(RB_pK)_{mid}/(RB_pK)_{target}$



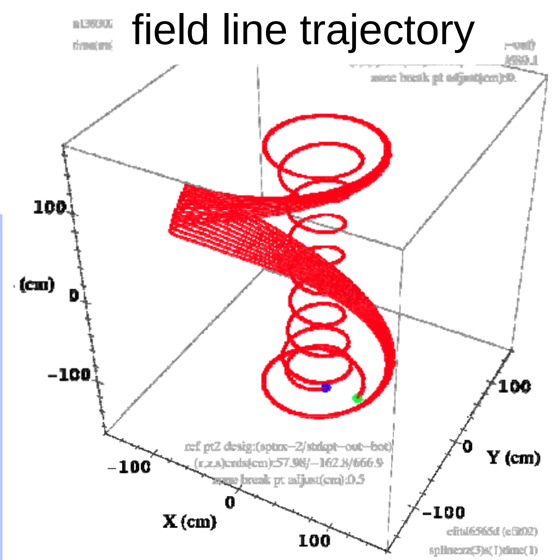
- **Efficiency can be controlled by optimizing location & width of current profile to reduce phase mixing**





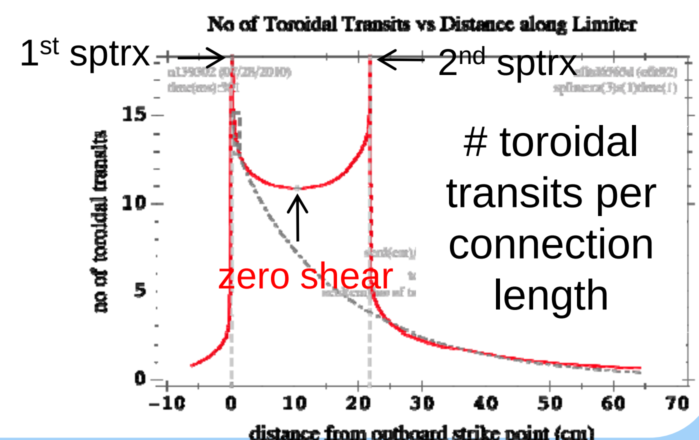
Narrow current filaments can also efficiently generate magnetic perturbations[1]

- **Magnetic field due to current filament**
  - Yields estimate $\delta B \sim \mu_0 I_{||}/2\pi d$
  - Resonant harmonic $<\delta B_{m=qn}> \sim \delta B\ d/a \sim \delta B/10$



	A_{tot} (cm^2)	I_{tot}	J (A/cm^2)	δB (G)	$\delta B/B$ (B=0.5 T)
BEaP electrode +90V	6=4x1.5	20-40 A	3-6	1-2	2-4×10^{-3}
Entire BEaP tile x 25 area	150=15x10	0.5-1 kA	3-6	25-50	0.5-1×10^{-2}
Far SOLC sensor ELM event		1-10 kA	3-4	50-500	10^{-2}-10^{-1}

- **Will δB decay due to phase mixing?**[1]
  - Low shear regions narrow width & reduce phase mixing of current paths[2]



[1] H. Takahashi, et al., Nucl. Fusion **44** 1075 (2004)
[2] H. Takahashi, et al., NSTX research proposal (2010)

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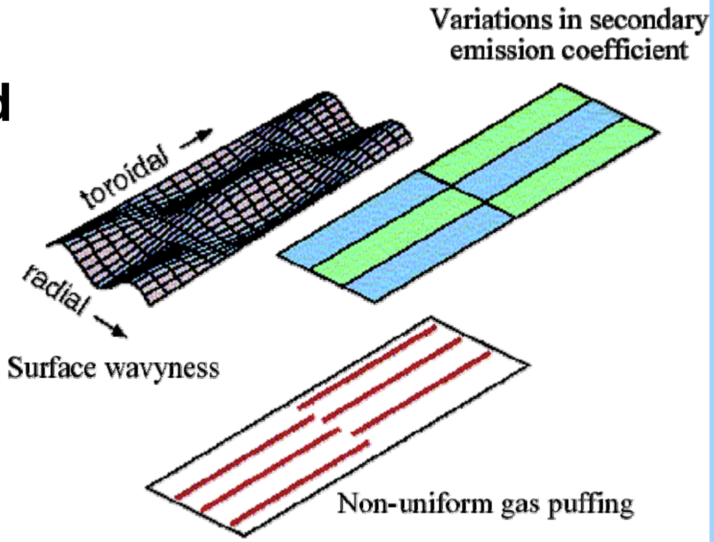
PASSIVE DRIVE TECHNIQUES: need further development

- **Direct electrical biasing has advantages**
  - Active control with high rep. rate & real time response to plate overloading
  - Could also be used to actively sweep strike point
- **But, hardware is severely constrained inside reactor vacuum vessel**
  - High neutron fluxes damage insulators needed for electrical isolation
  - Possibly substantial biasing power supply; power delivered directly to SOL
  - Large magnetic forces can damage supporting structures
- **Reactor-relevant proposals[1] could be tested for the first time on NSTX-Upgrade**
  - Drive through asymmetries in Te
    - neutral gas pumping and/or fueling
    - neutral and/or impurity radiation
  - Variation in plate angle
    - Can control fueling or angle wrt. field lines
  - Variation in materials that control ion recycling, secondary electron emission, & conductivity



[1]R. H. Cohen and D. D. Ryutov, Nucl. Fusion **37** 631 (1997)

Fusion Energy Program

UEDGE flux-tube model showed that ion or neutral pumping could generate much more current drive than gas-puffing[1]

- **Flux-tube model** (DIII-D params)

  $B_P/B_T=10$, $L_c=30$ m

  $P_{inj} = 0.1$ MW/m x 10 m = 10 MW

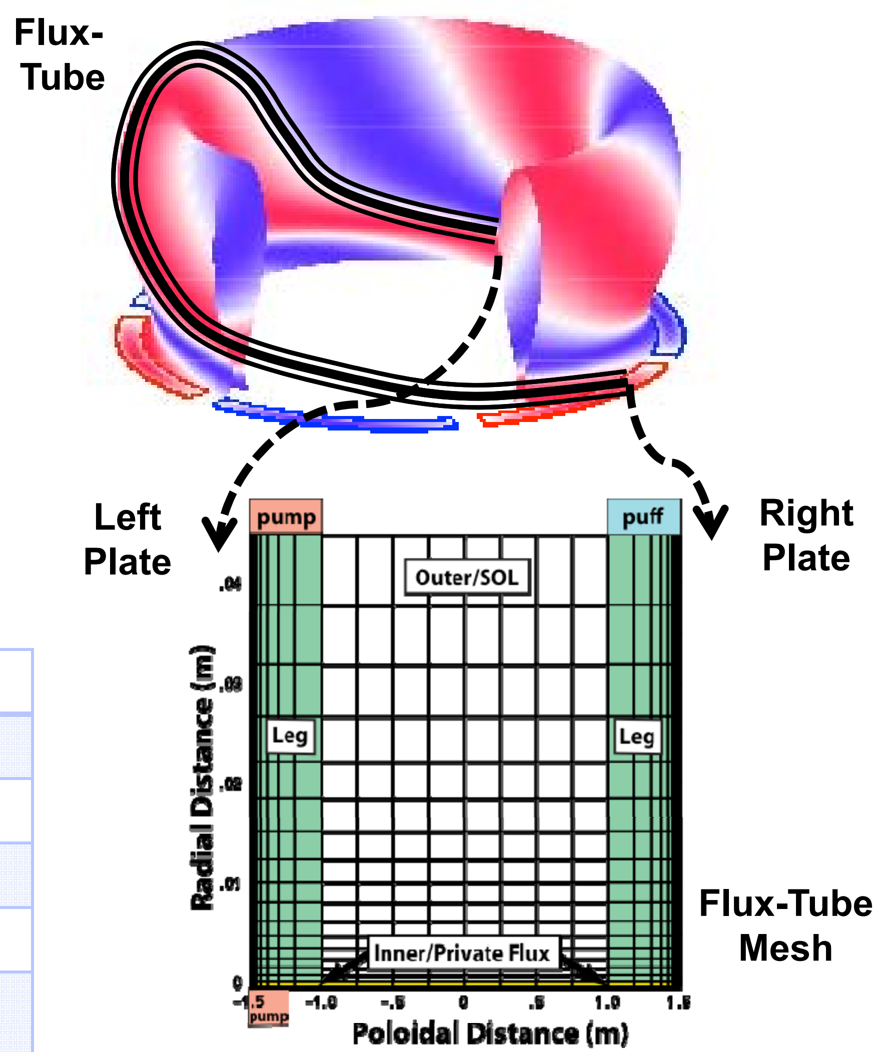
  $D = 0.3\ m^2/s$, $\chi = 0.5\ m^2/s$, $\mu = 1\ m^2/s$

- **Particle flux BC** (ions+neutrals)

  $\Gamma_{wall} = (1\text{-}R_i)n_i c_s + (1\text{-}A_n)n_n(T_n/2\pi m_n)^{1/2}$

  - R_i = ion recycling coefficient
  - A_n = neutral albedo coefficient

Method	Parameter	$K_{\|\|}$ (kA/m)	$I_{\|\|}/I_{sat}$
Biasing	Φ=+95V	21	82%
Wall pumping	R_i=85%	6.2	56%
Pumping PFR	A_n=85%	4.9	39%
Pumping SOL	A_n=85%	3.4	24%
Puffing SOL	I_n=70A/m x 10m =700 A	1.6	6%



[1] I. Joseph & T. D. Rognlien, J. Nucl. Mater. (2011)

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CONCLUSION

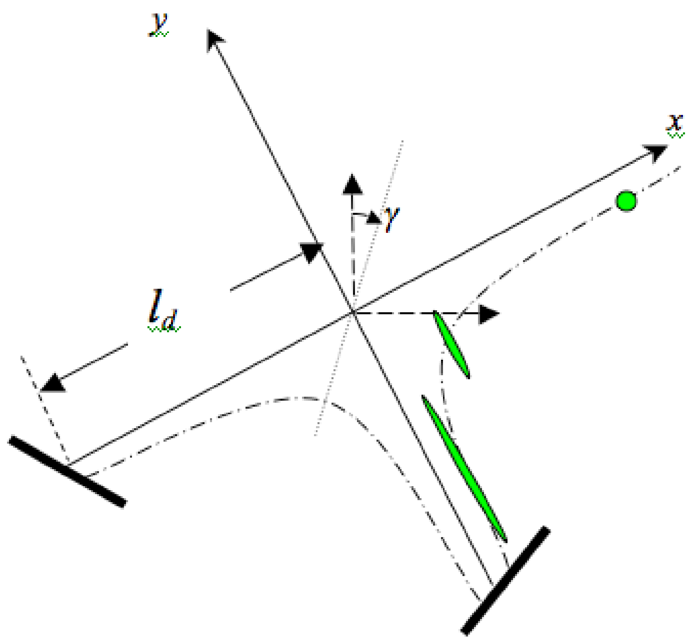
- **ST heat fluxes may be mitigated by using non-axisymmetric divertor perturbations to control edge plasma transport & stability**
  - Electric potential generates convection that spreads steady-state fluxes
  - Parallel current generates RMPs for ELM pacing and/or ELM control

- **First experiments have shown promise**
  – Full divertor biasing MAST was able to widen the strike-point
  – NSTX electrodes are able to locally affect plasma
    – So far, effects in NSTX are small (1cm), but may be optimized (more to come)
  – Active biasing techniques need to be better understood
    – Direct measurement of SOL current, convection, & fields is desirable

- **Next-generation experiments are needed: NSTX-Upgrade**
  - Prove that active biasing can be used to reduce peak fluxes
  - Prove that SOL current be used to impact ELMs
  - Use passive drive techniques for the first time (requires specific divertor design)

Non-axisymmetric electrostatic perturbations can also be used to stabilize or destabilize divertor instabilities

- **Kelvin-Helmholtz modes can be destabilized by the sheared flows in the convection cell pattern**
- **Target plate tilt controls the stability of some of the most virulent instabilities near the target plate[1]**
  - Tilt can be used to drive convection by generating divertor asymmetries

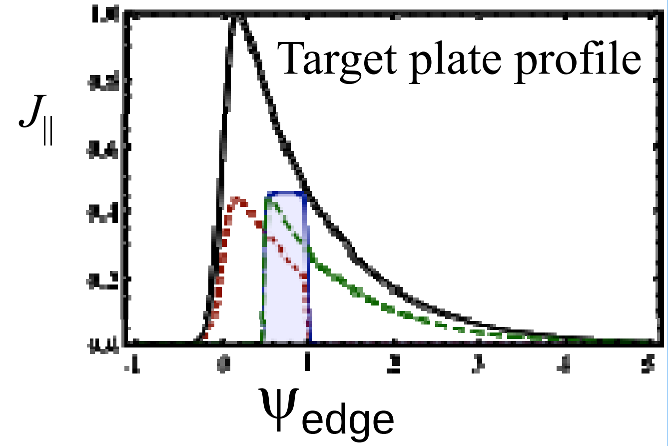


- **The modes[2] are driven by Te' and destabilized by sheath resistance**
  - dominate locally generated turbulence due to large growth rates

[1]D.D. Ryutov and R.H. Cohen, Contrib. Plasma Phys. **48** 48 (2008)
[2]H.L. Berk, et al., Nucl. Fusion **33** 263 (1993)

SOL current drive efficiency can be optimized by controlling the target plate $J_{\|}$ profile

- **Location & width of the $J_{\|}$ profile changes the efficiency**



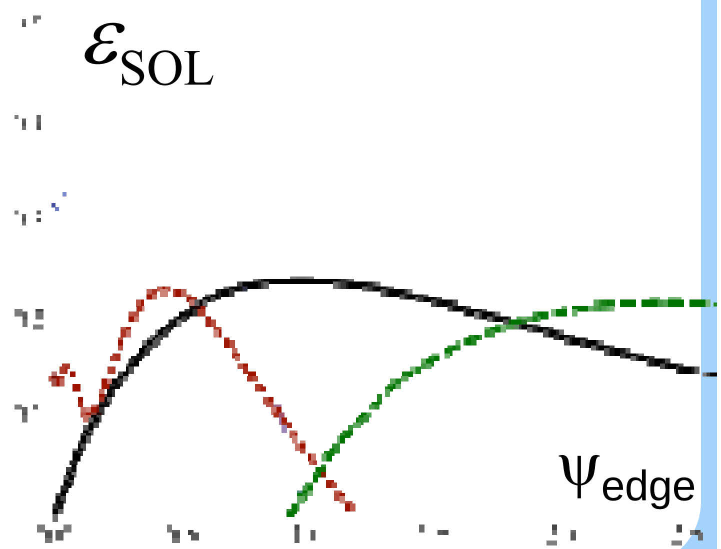
- **Efficiency of SOL current drive at midplane**
  - definition independent of flux expansion

$$\varepsilon_{SOL} = \frac{\left|\int J_{SOL}\, d\psi\right|}{\left|\int J_{target}\, d\psi\right|} = \frac{\left|RB_p K_{\|}\right|_{SOL}}{\left|RB_p K_{\|}\right|_{target}}$$

- **Effective width set by phase coherence**

$$\psi_b - \psi_a\Big|_{\Delta\varphi_{SOL}=\pi} = \sqrt{\psi_a \psi_b}\, 2\sinh\left(\theta_* / 2nq_*\right)$$

  - **Optimal "Coherence width"** shrinks as strike point is approached

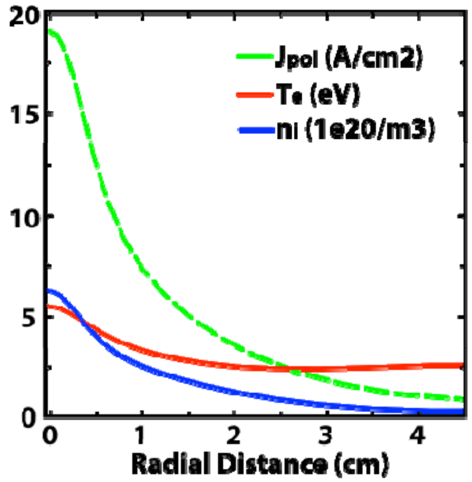


- **δB is largest at low toroidal mode numbers**
  - Probably limits useful range to $n \sim 1\text{-}3$

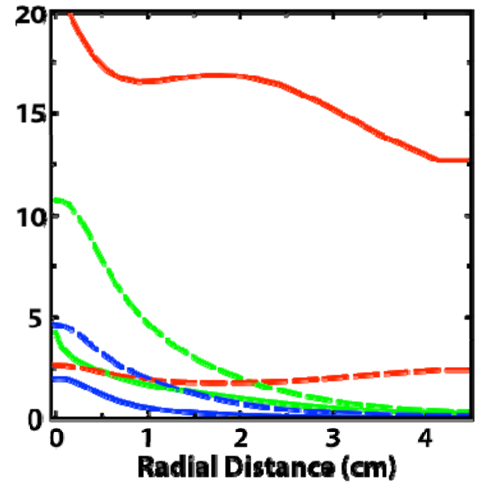
Fusion Energy Program

Enhanced pumping generates asymmetric target plate conditions that drive SOL current

Symmetric Solution



Enhanced Pumping in Private Flux Region

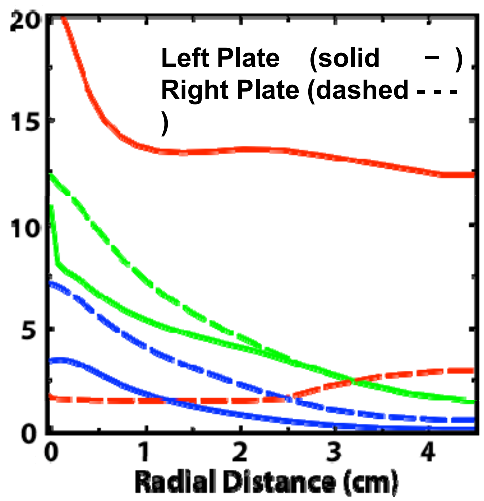


Left Plate Albedo 85%

$I_{||} = 4.9$ kA/m

$I_{||}/I_{sat} = 39\%$

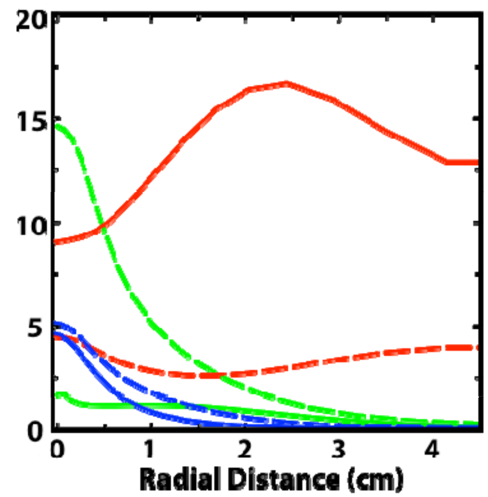
Left Plate Biased to +95 V



$I_{||} = 21$ kA/m

$I_{||}/I_{sat} = 82\%$

Enhanced Pumping in Outer SOL



Left Plate Albedo 85%

$I_{||} = 3.4$ kA/m

$I_{||}/I_{sat} = 24\%$

Fusion Energy Program

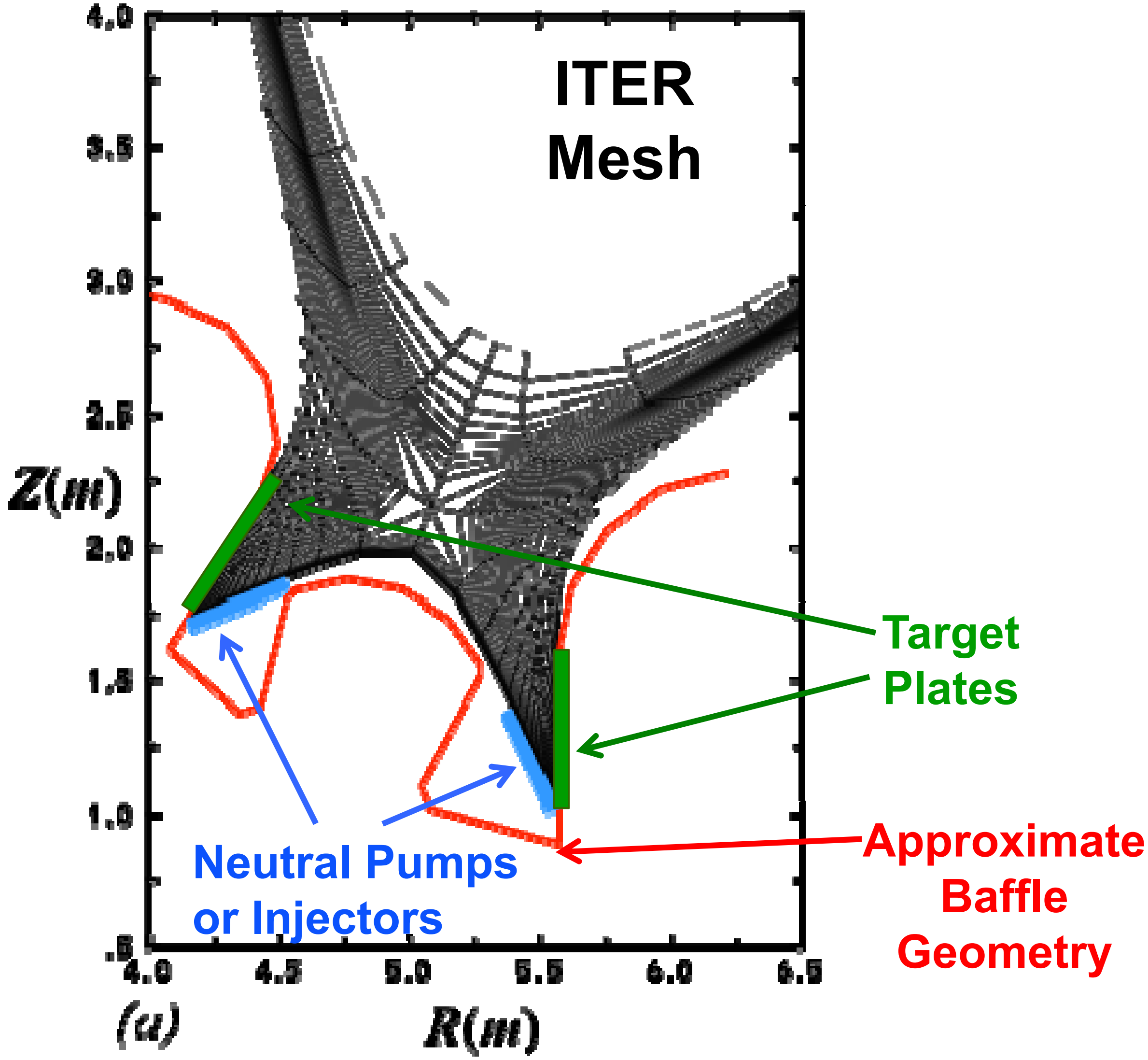
Efficiency of various methods for the flux tube model

Method	Parameter	$\left\langle \frac{n_{e,\text{leftt}}}{n_{e,\text{right}}} \right\rangle$ (%)	$\left\langle \frac{T_{e,\text{right}}}{T_{e,\text{left}}} \right\rangle$ (%)	$\langle \Phi_{\text{thermo}} \rangle$ (V)	$I_{\parallel}$ (kA/m)	$I_{\text{sat,right}}$ (kA/m)	$\frac{I_{\parallel}}{I_{\text{sat,right}}}$ (%)	ε_{SOL} (%)
Electric Bias	$\Delta\Phi_{\text{wall}}$=95V	46	9	23	17.3	21	82	2
Recycling	$R_n = 85\%$	14	4	50	6.2	11	56	5
Pump inner	$A_n = 85\%$	37	10	28	4.9	13	39	6
Pump outer	$A_n = 85\%$	68	23	20	3.4	15	24	9
Puff outer	I_n=70A/m	69	29	10	1.6	26	6	20
Pump & puff outer	$A_n = 85\%$ I_n=40A/m	67	13	19	3.9	18	21	8

- **Recycling & pumping from private flux zone are most effective**
- **All techniques are within range for ELM control at 100% SOL efficiency**
  - The minimum SOL efficiency ε_{SOL} required to achieve $\delta B/B > 10^{-4}$ for B =2 T is shown in the final column

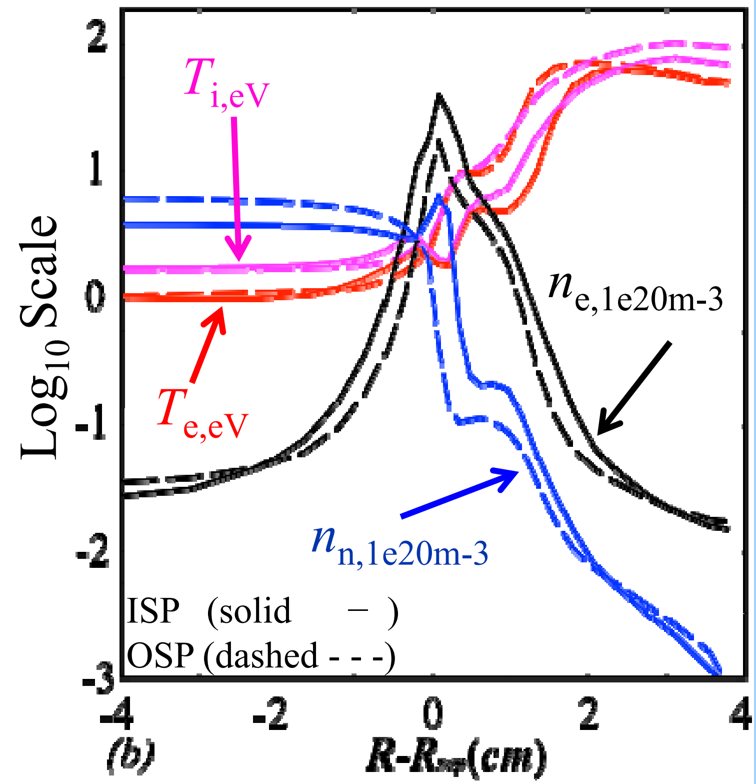
ITER Reference Case: 50% D-T, fixed impurity fraction 3% C

- **Geometry**
  - $B_t = 5.3$ T, $R = 6$ m
  - R_{mid}-R_{sep} = (-6,4) cm
  - $L_{leg} = 1$ m
  - $L_{con} \sim 20$ m
- **Plasma Parameters**
  - $n_{e,core} = 6\text{x}10^{19}$ m^{-3}
  - $P_{e,core} = 50$ MW
  - $P_{i,core} = 50$ MW
  - $R_i = 1$ (no recycling)
  - $A_n = 0.98$ (pumping)
- **Transport Model**
  - $D_{ne} = D_{ni} = 0.3$ m^2/s
  - $\chi_{Te} = \chi_{Ti}$ 1.0 m^2/s
  - $D_{visc} = D_{utor} = 1.0$ m^2/s



Tilted plates lead to partially-detached divertor plasma

- **Strong variation radially across plates**
  - T_e, T_i ~1-2 eV near pump, >50 eV on outer edge
  - n_n~$10^{21}m^{-3}$ near pump, but <$10^{18}m^{-3}$ on outer edge
  - □ λ_n ~ 1mm near pump, but >5 cm on outer edge
  - f_{rad} = 56 %, P_{Ohmic} = 1 MW



- **Current driven by asymmetries is sizeable**
  - ISP: $I_{\|,sat}$ = 4.9 MA, OSP: $I_{\|,sat}$ =3.1 MA
  - Total current $I_{\|}$ = 5.4% $I_{\|,sat}$

	$I_{\|}$ (kA)	R (m)	$K_{\|}$ (kA/m)	δB (G)	B_t (T)	$\delta B/B_t$ (10^{-4})
ISP	290	4.2	11.1	7.0	7.65	9.1
OSP	190	5.6	5.6	3.48	5.71	6.1

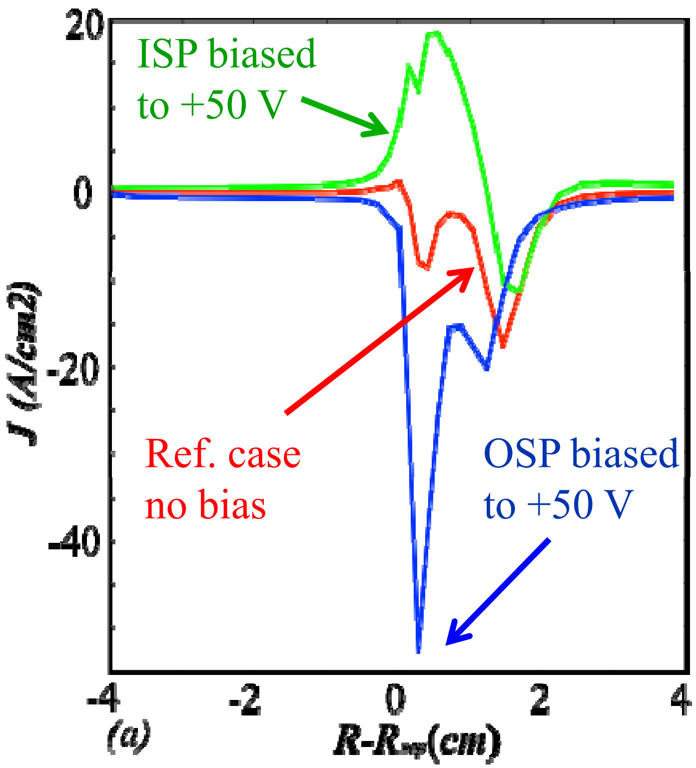
Exceeds ELM control threshold!

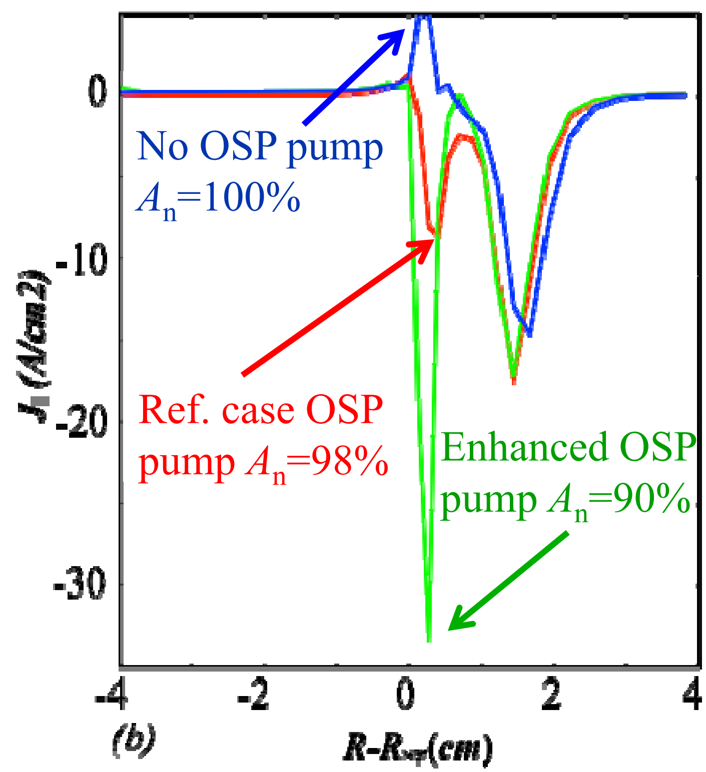
- **However, divertor plasma is rigid to changes in natural poloidal asymmetry generated by neutral pumping or injection**

Two asymmetry-driven peaks in current profile: one near strike point and one near outer side of plate

- **Reference Case:** no bias, both ISP & OSP pumps have A_n=0.98

  Hotter OSP drives current toward ISP (negative sign below)





- **Electrical biasing to +/- 50 V**

  $(I_{\parallel}-I_{ref})/I_{sat}$ ~ 10%, $\delta B/B$~2x10^{-3}

- **Changes in OSP pumping**

  $(I_{\parallel}-I_{ref})/I_{sat}$ ~ 2%, $\delta B/B$~2x10^{-4}

- **Neutral injection at Γ_n = 0.1-1 kA can enhance effect of pumping by ~10-20%**

Fusion Energy Program

Power and Current Scaling

- **Assume density scales with Greenwald limit** $n \sim n_G = I_P / \pi a^2$
- **Assume Jsat scale length follows** $\lambda_{sat} \sim R / I_P$

Sheath-Limited

$$n_t \propto n_G \propto I_P / a^2$$
$$T_t \propto T_{up} \propto \left(P_{inj} / aRI_P\right)^{2/3}$$
$$J_{sat} = n_t C_s \propto \left(I_P^2 P_{inj} R / a\right)^{1/3} R^{-1}$$
$$K_{sat} = \lambda_{sat} J_{sat} \propto \left(P_{inj} R / aI_P\right)^{1/3}$$

High recycling

$$n_t \propto n_G{}^3 \propto I_P^3 (qR)^2 \left(qP_{inj} / a\right)^{-8/7}$$
$$T_t \propto n_G{}^{-2} \propto \left(I_P qR\right)^{-2} \left(qP_{inj} / a\right)^{10/7}$$
$$J_{sat} = n_t C_s \propto I_P^2 qR \left(qP_{inj} / a\right)^{-3/7}$$
$$K_{sat} = \lambda_{sat} J_{sat} \propto I_P qR^2 \left(qP_{inj} / a\right)^{-3/7}$$

	B (T)	I_P (MA)	R (m)	P_{inj} (MW)	J_{sat} factor	***δB/B factor***	K_{sat} factor	***δB/B factor***
NSTX	0.5	1	0.85	1	1	**1**	1	**1**
NSTX-Upgrade	1	2	0.85	10				
sheath					3.4x	**1.7x**	1.5x	**0.75x**
recycle					1.5x	**0.75x**	0.75x	**0.37x**
ARIES-ST	2	30	3.2	400 (α)				
sheath					4.5x	**1.1x**	0.59x	**0.12x**
recycle					93x	**23x**	12x	**3x**