Effects of Magnetic Islands on Plasma Confinement and Self-driven Current Generation

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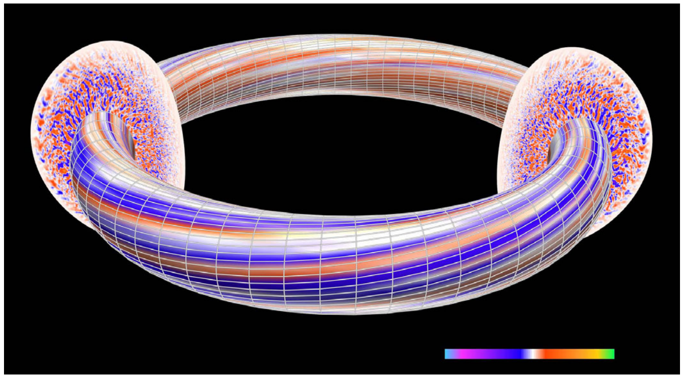

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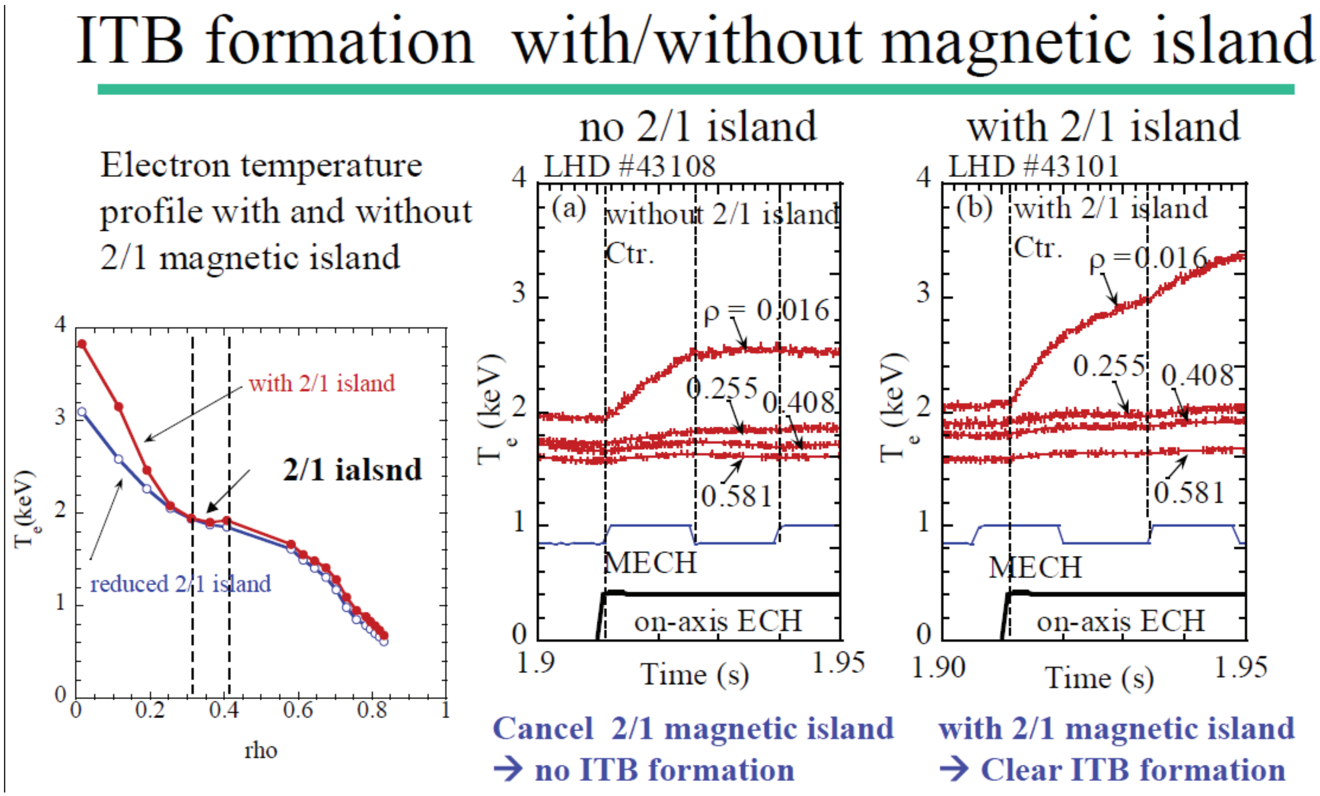
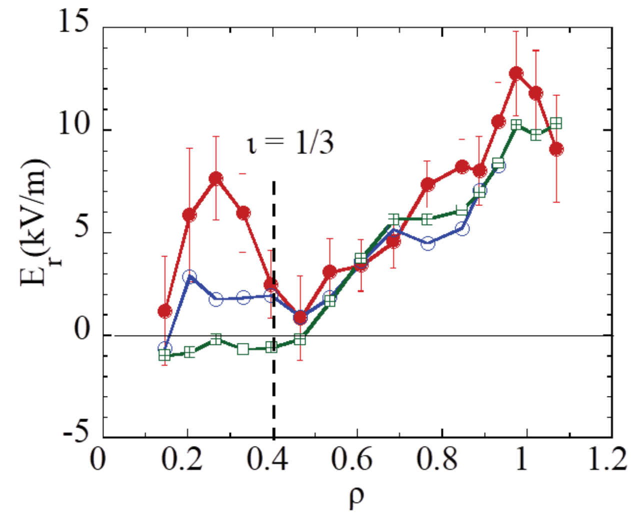
Magnetic islands have varied and complex impacts on plasma confinement in fusion experiments

- A large, uncontrolled island may cause confinement degradation
- Expts. also show some improved confinement may be link to islands
- ITB formation is usually near a low-order rational surface (home of island)
  - favorable weak or reversed magnetic shear
- ITB offers compelling features for steady state tokamak operation
  - improved energy confinement
  - high bootstrap current

Expts. suggest magnetic island may trigger ITB formation



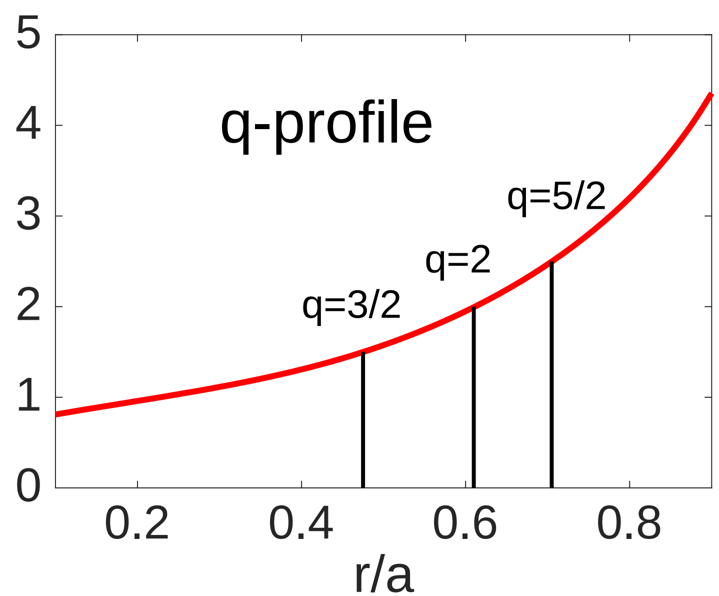


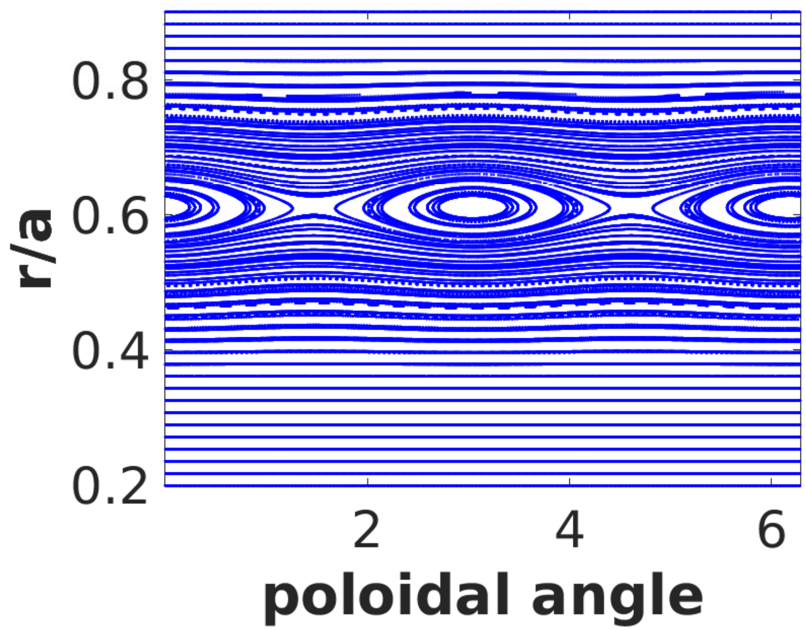
(Ida et. al., PoP'04)

- E_r shear layer observed at inner edge of magnetic island
  - increasing with island size
  - mainly at inner edge (little at outer edge)
  - finite radial extension (not so narrow)
- ITB foot point moves with island & reforms (Kenmochi et.al., Sci Rep.'20)

This simulation study employs a global gyrokinetic model with self-consistent turbulence + neoclassical physics

- To gain physics insight regarding role of island played in ITB formation
- To understand plasma self-driven current generation in island geometry

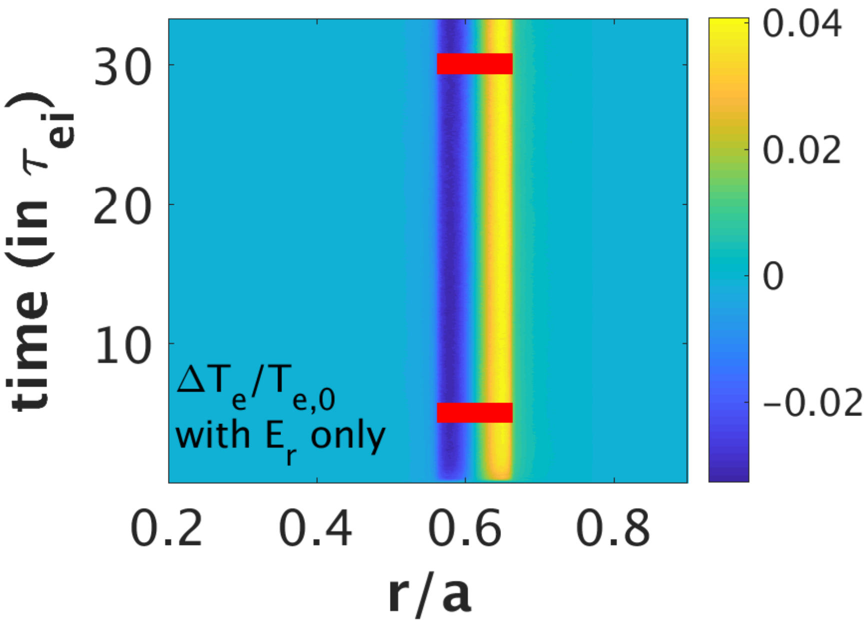


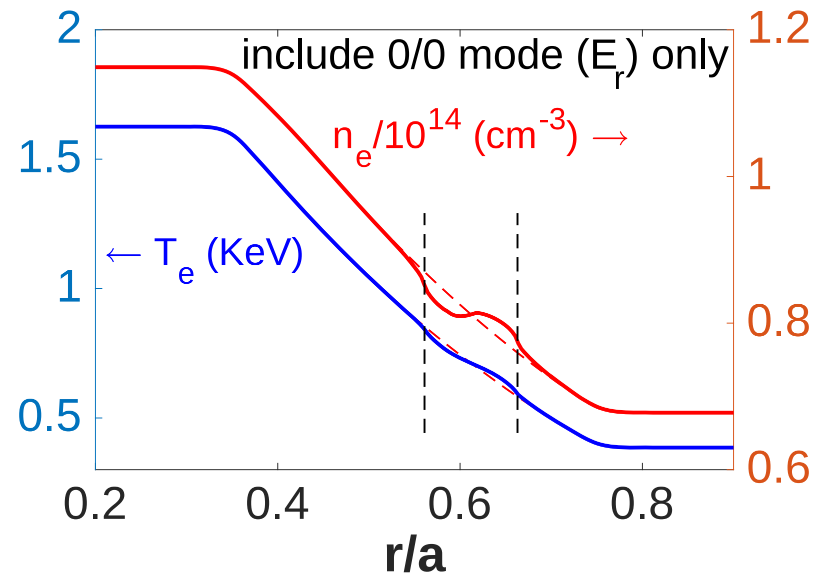


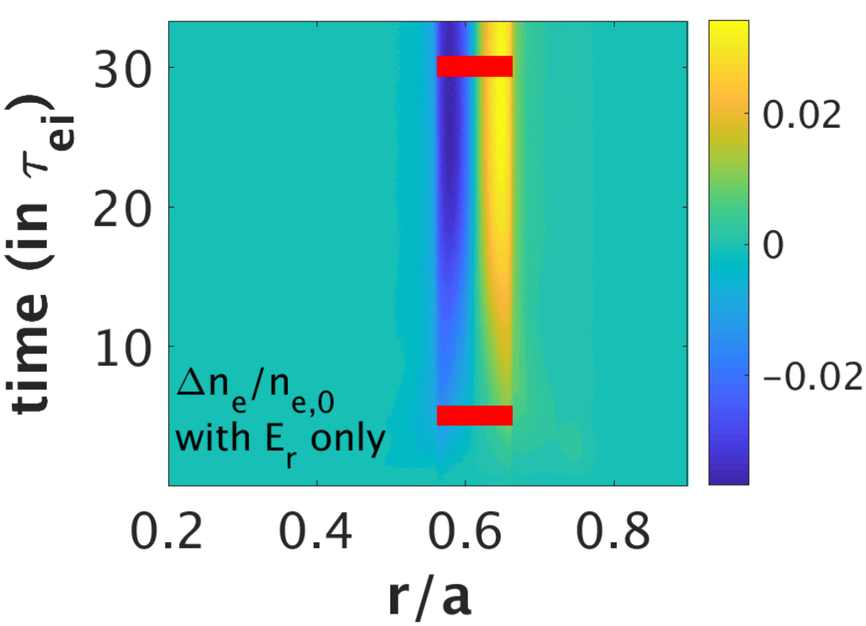
- C-MOD Ohmic L-mode discharge
- ITG-dominated turbulence in core plasma
- prescribed static 2/1 magnetic island at $q = 2$ $(r/a = 0.61)$

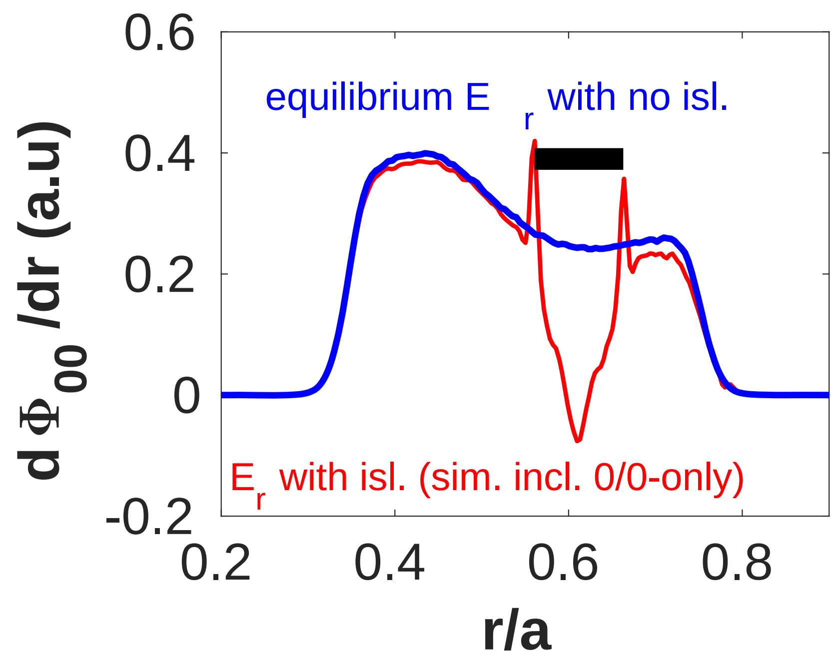
$$\delta \mathbf{B} = \nabla \times \alpha B_0; \quad \alpha = \alpha_{mn} sin(n\phi - m\theta); \quad \delta\psi_p = 4\sqrt{\alpha_{mn}/s}$$

Magnetic island modifies neoclassical equilibrium and profiles via fast parallel streaming along island surface

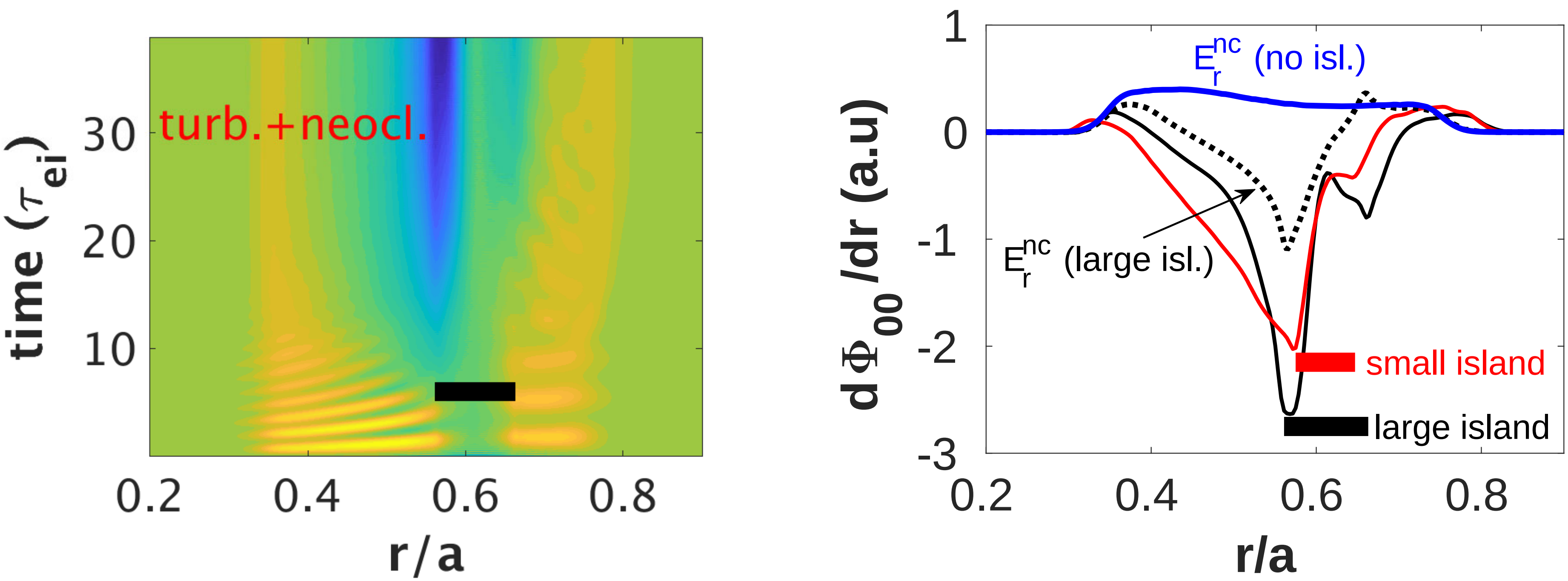








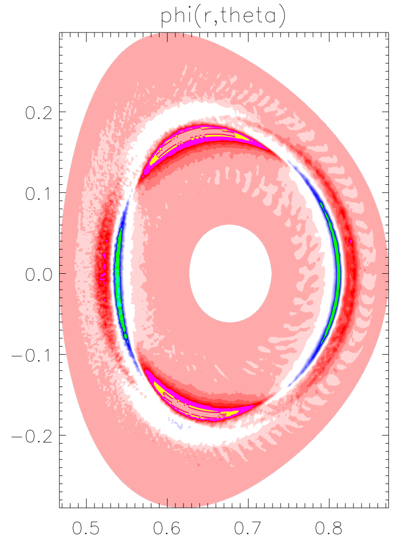
Island by altering magnetic topology has more significant effect on E × B flow structure

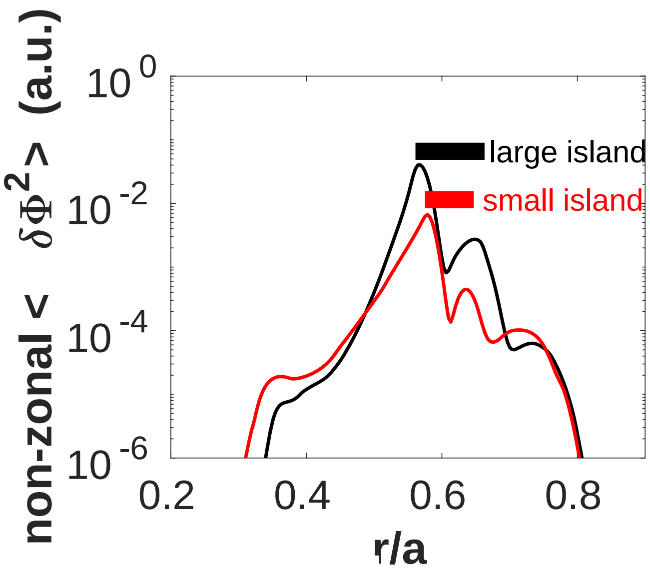


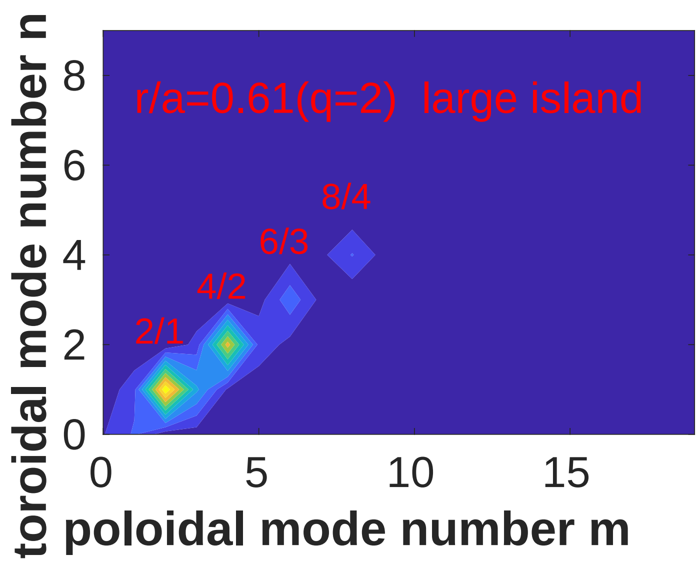
- Island breaks axisymmetry → alters ambipolarity condition → E_r
  weak negative E_r → strong positive E_r
- A stationary E_r-"well" formed near island; peaked at inner edge of island
- The wider the island, the deeper the E_r-well (the stronger $\mathbf{E} \times \mathbf{B}$ shear)
- Shows consistent features with expt. observations (Ida et.al.,PoP'04)
  – mainly at island inner boundary; – finite radial extension (not so narrow)

PPPL

In addition to strong ZF shear layer, 2/1 potential structures also forms at the same radial locations

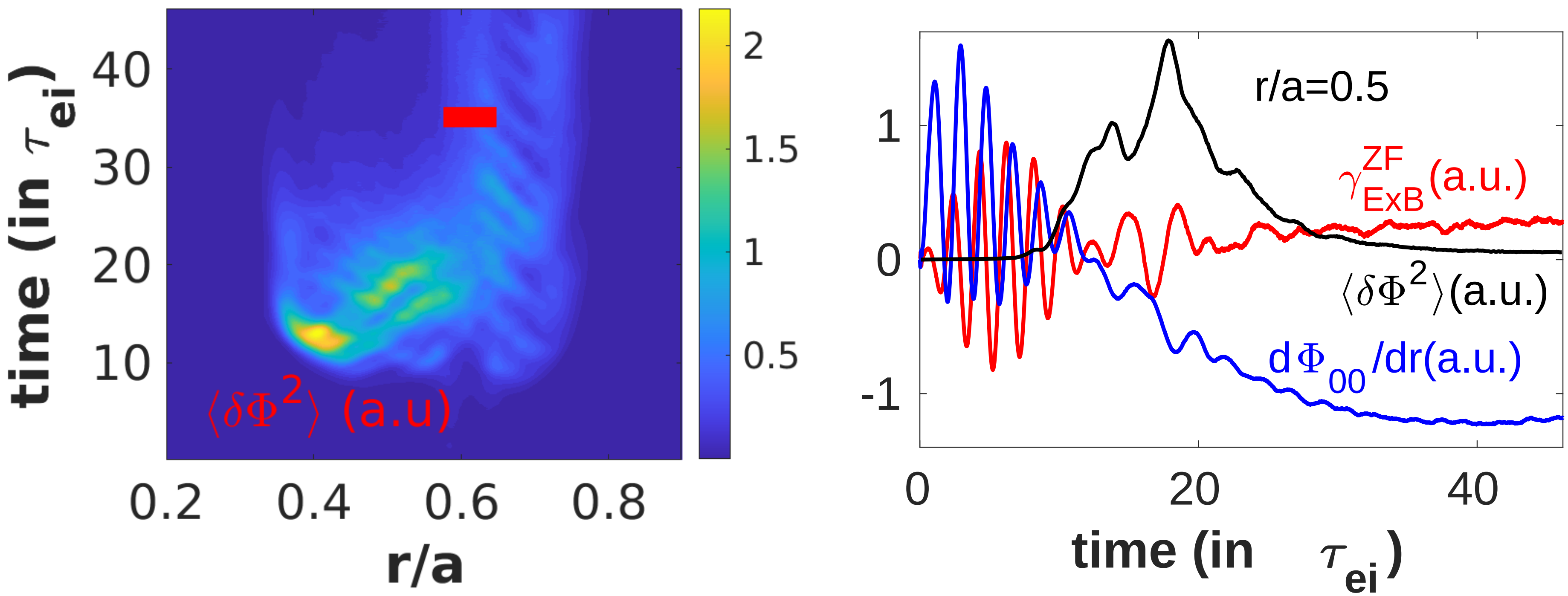






- Non-resonant & amplitude of 2/1 potentials much higher than turbulence
- Low-n harmonics generated at island center via mode beating

Strong E × B shear layer formed next to island can effectively reduce/suppress turbulence in inner core region

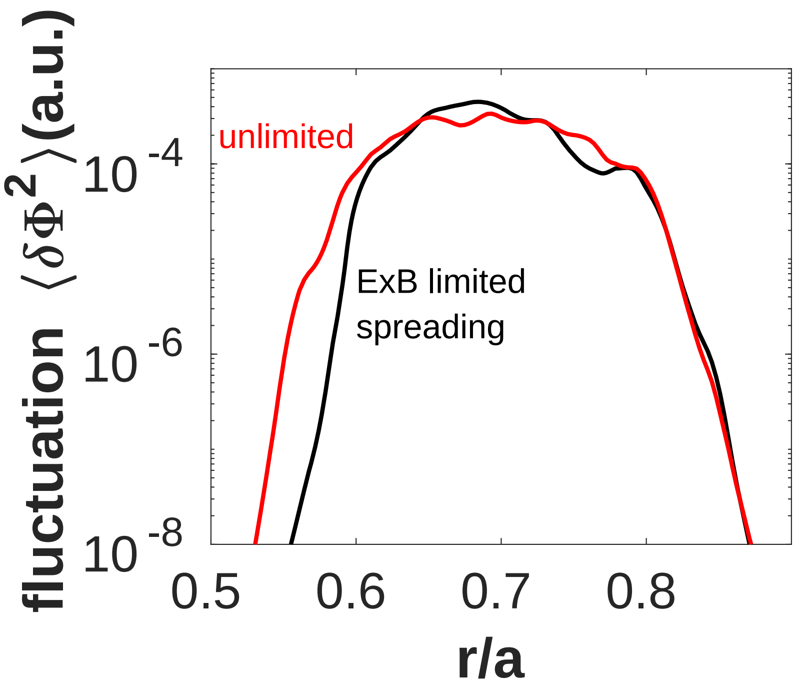


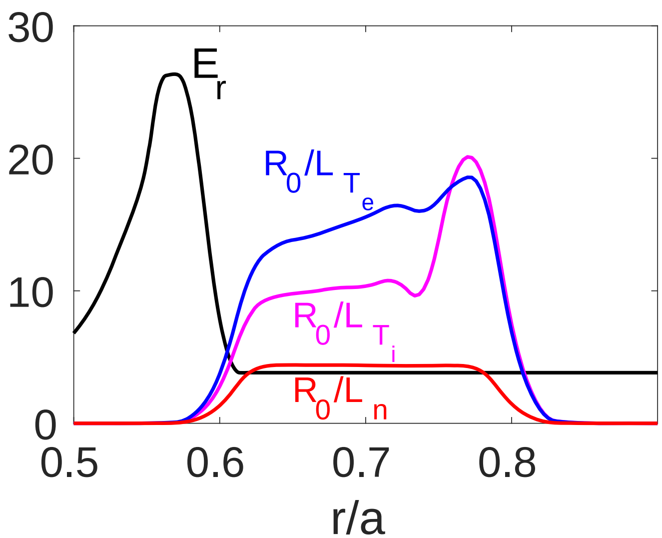
- Strong Reynolds stress gradient across and peaked at inner boundary of island is observed and likely responsible for continued growth of $\mathbf{E}\times\mathbf{B}$ flow beyond neoclassical level

$$\frac{\partial\langle V_{E\times B}\rangle}{\partial t} = -\left\langle \frac{\partial}{\partial r}\langle\tilde{v}_r\tilde{v}_\theta\rangle\right\rangle$$

- Fluctuations are reduced/suppressed from island inner edge extending to core following growth of zonal flow amplitude (energy) and its shear

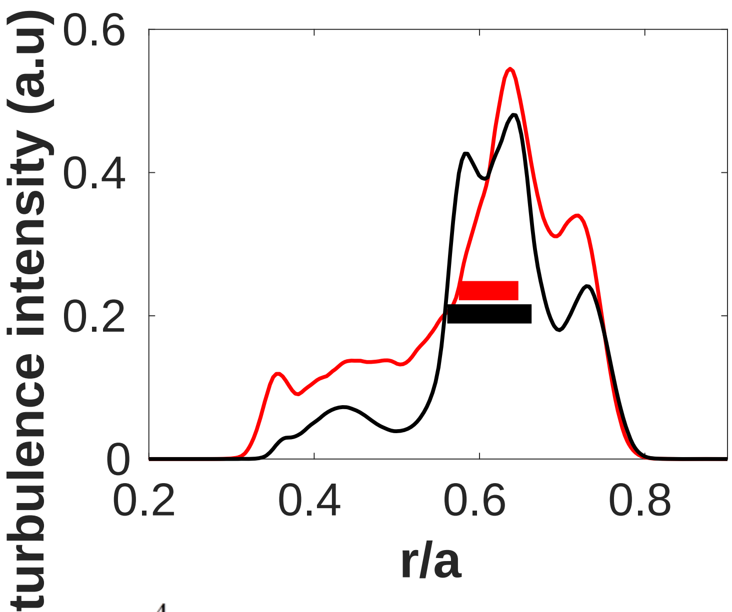
Island-induced E × B shear layer is capable of preventing turbulence spreading

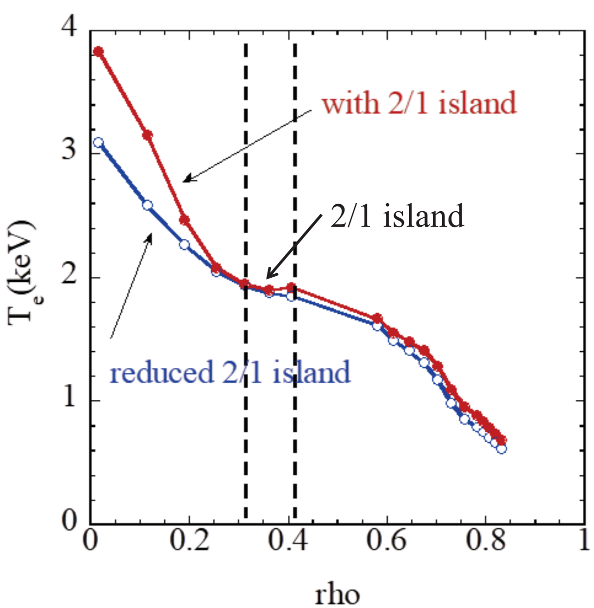




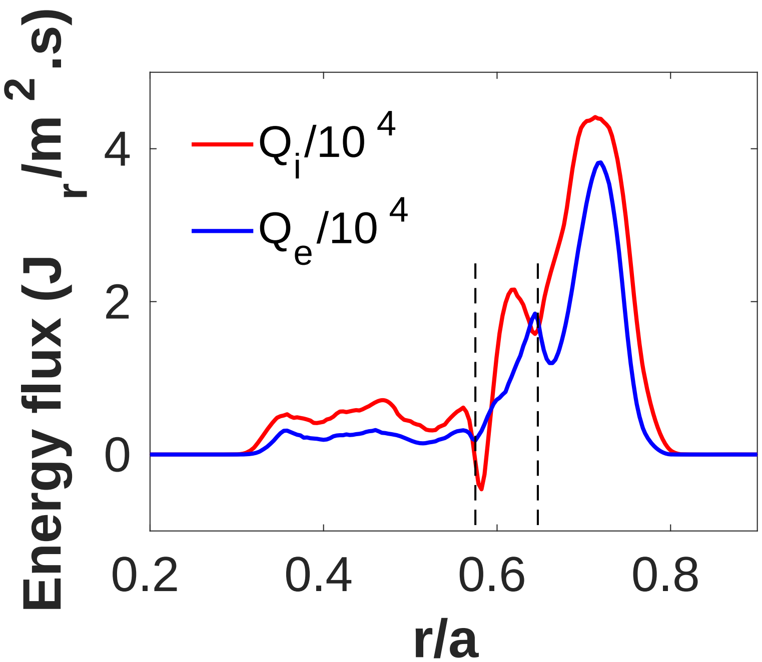
- Turbulence spreading causes nonlocal transport & affects global confinement
- A strong **E** × **B** shear layer can reduce/block turbulence spreading
  – transfer to high-k_r → dissipation
  – reduce toroidal mode-coupling
  (Wang et. al., PoP'07; Grenfell et. al., NF'19)
- Island-induced **E** × **B** shear decouples plasmas inside shear layer from outside

Radially localized strong $E \times B$ shear layer formed next to island can facilitate transport barrier formation



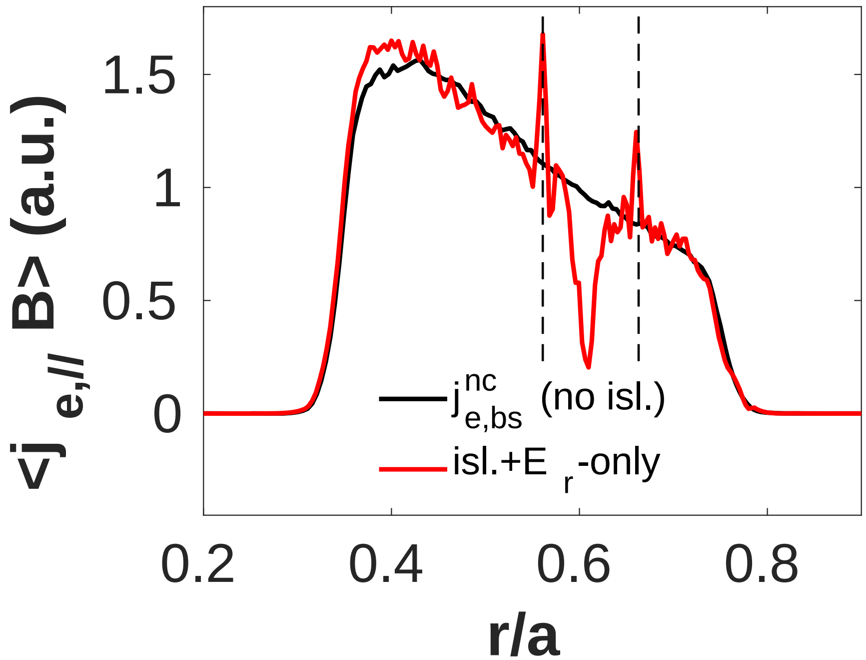


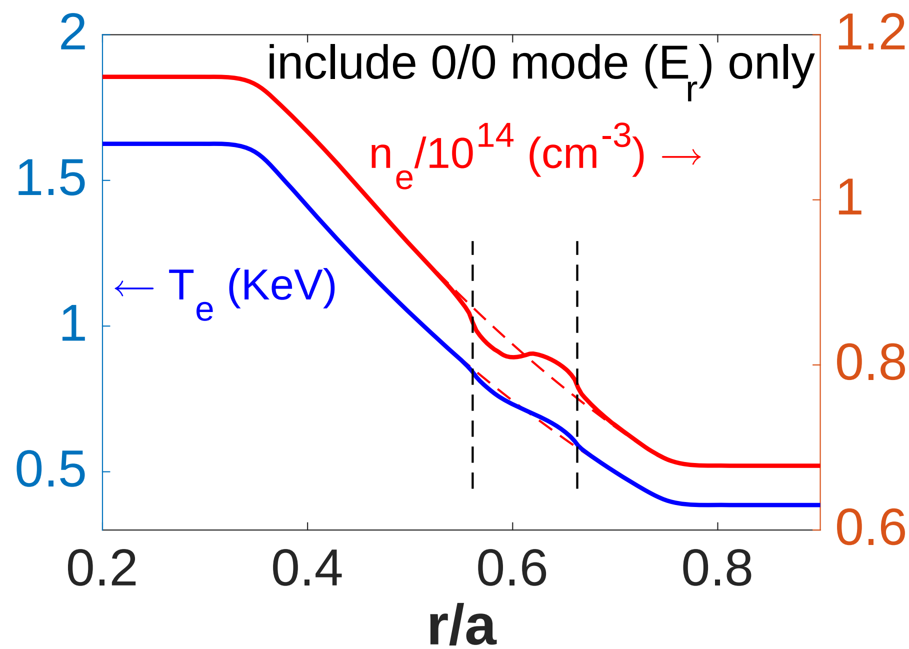
(Ida et. al., PoP'04)



- There may exist a critical island width for triggering ITB
- Control and optimize island width and location $\Rightarrow$ usable ITB

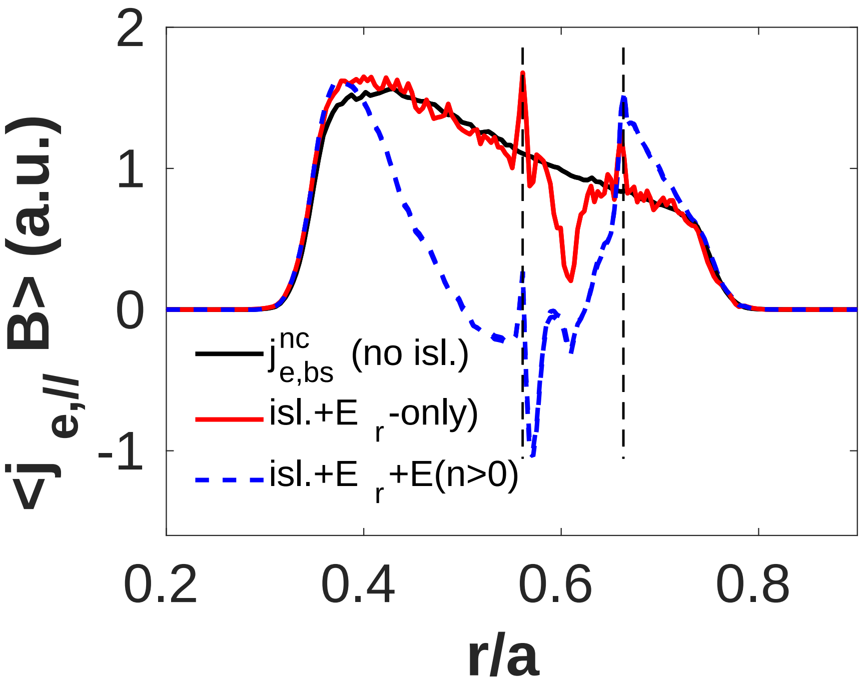
How magnetic island modifies bootstrap current – a conventional picture

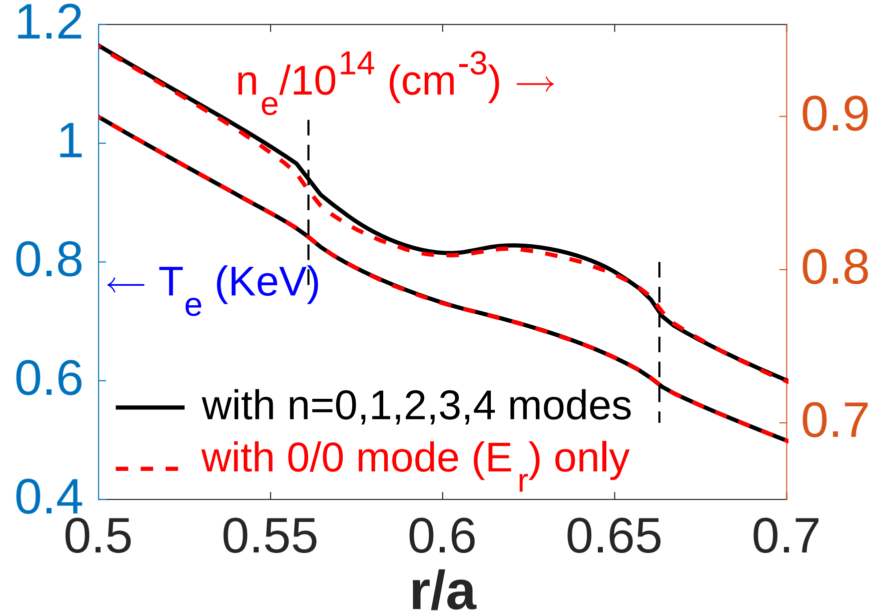




- j_{bs} is modified according to island-induced profile modification
- Local in island region
- Electron current is reduced in island region but remains finite

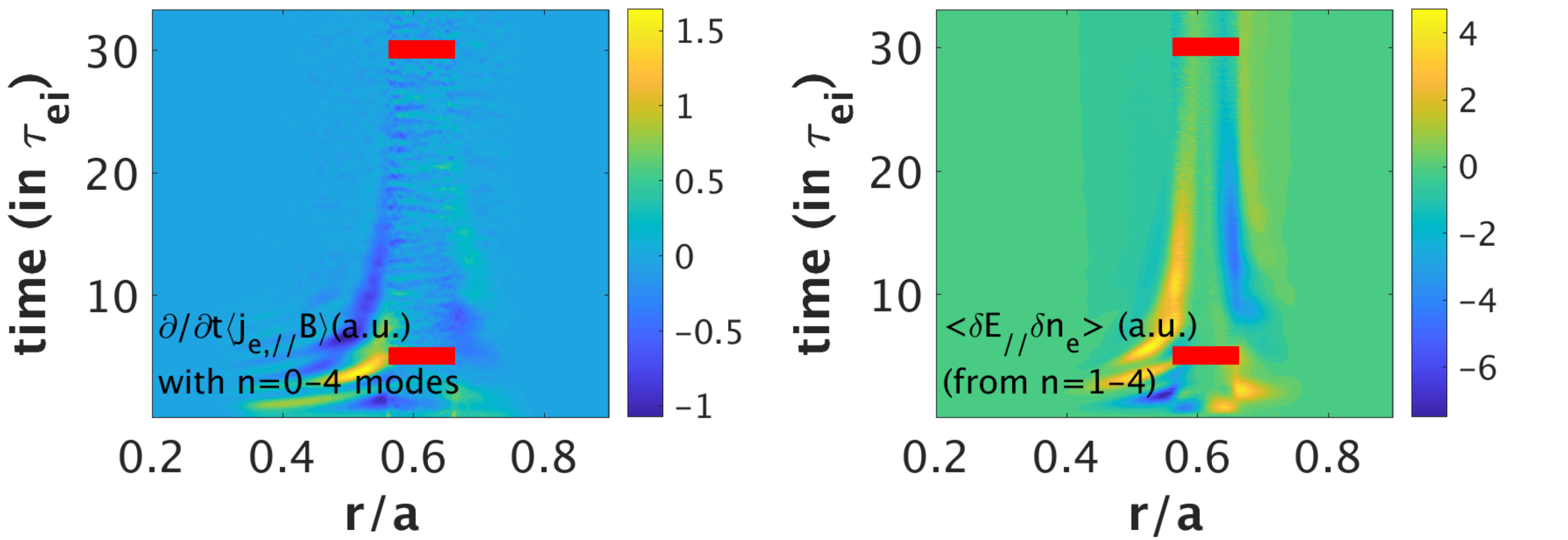
Large change in plasma self-driven current found to relate to island-induced static low-n (2/1-dominated) modes

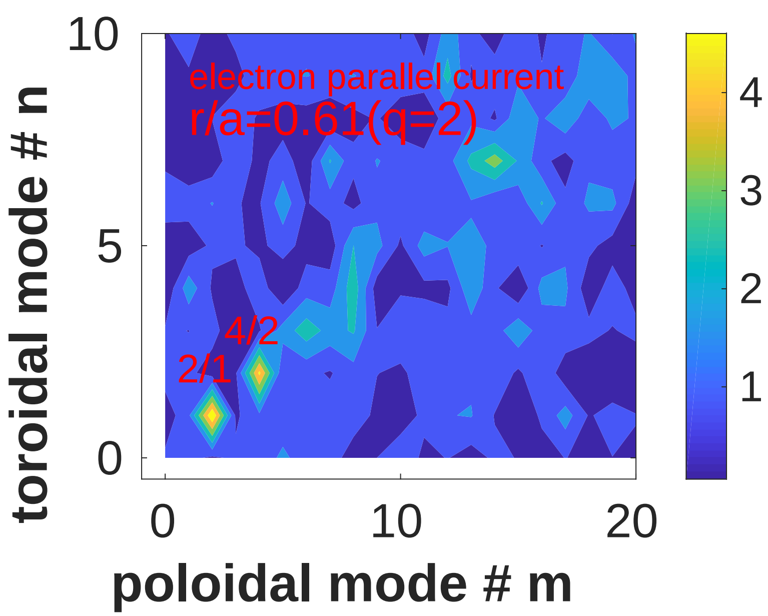




- Large change not only in island region, but also globally
- Static low-n modes (part of 3D ambipolar potential) affect electron flow but do not impact temperature and density

Electron parallel acceleration by static, non-resonant 2/1 mode (with intrinsic $k_\parallel \neq 0$) likely very effective





$$\frac{\partial\langle j_{\parallel,e}\rangle}{\partial t} + \nabla\cdot\langle \delta v_{E\times B}\delta j_{\parallel,e}\rangle$$

$$= -\frac{e^2}{m_e}\langle \hat{b}\cdot\nabla\delta\phi\delta n_e\rangle$$

- Helical current is generated and dominates in island region

Summary

Magnetic islands may trigger ITB formation inside a rational magnetic surface

- Island induces a strong localized E_r-well across island inner boundary (not due to island-induced pressure profile change)
  – its shearing rate increases with island width
  – strong turbulence-driven Reynolds stress gradient contributes to continued growth of $\mathbf{E} \times \mathbf{B}$ flow beyond NC level
- Island also drives large non-resonant 2/1 modes at island edges
- Island-induced $\mathbf{E} \times \mathbf{B}$ shear layer can facilitate ITB formation
  – locally suppress turbulence of inner core region
  – prevent turbulence spreading from outside into the core

Island-induced static, non-resonant low-n modes may largely change plasma self-driven current via parallel acceleration of electrons

– both locally and globally; more than change in j_{bs} by island-modified profiles

– helical current is dominant in island region

BACKUP SLIDES

Sum of zonal (m/n=0/0) and 2/1 components produces a potential well aligned with perturbed flux surfaces

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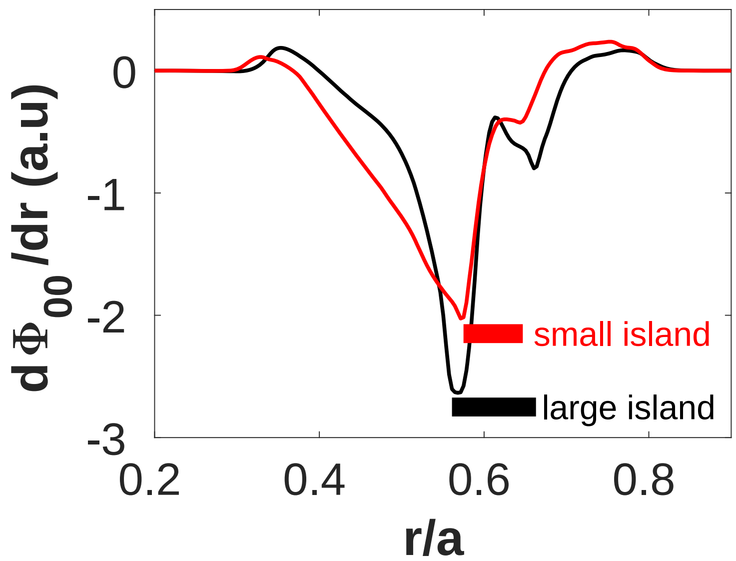

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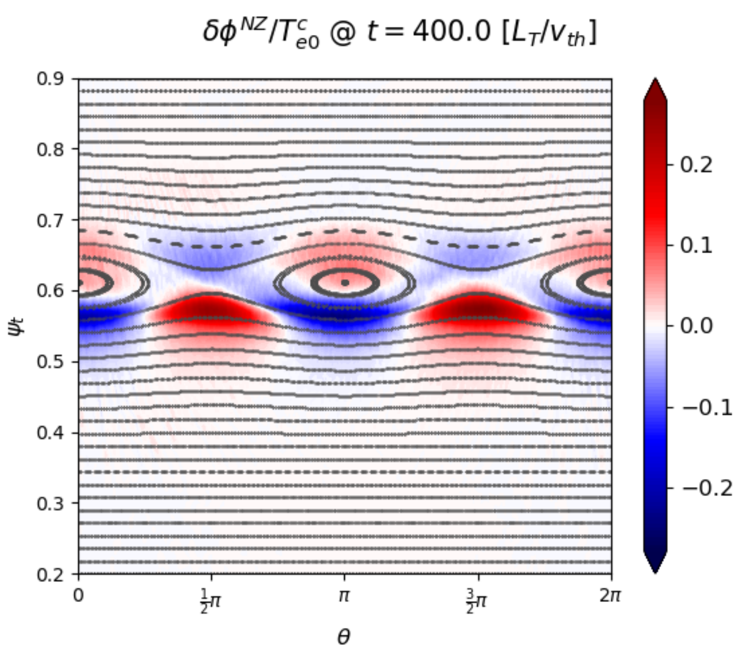
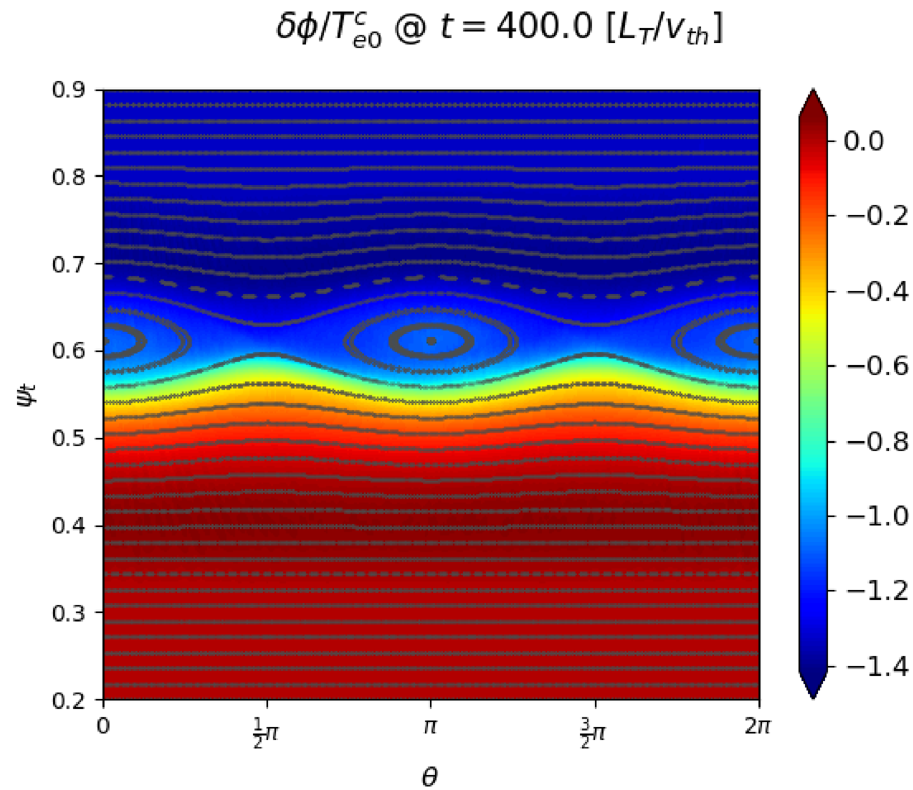
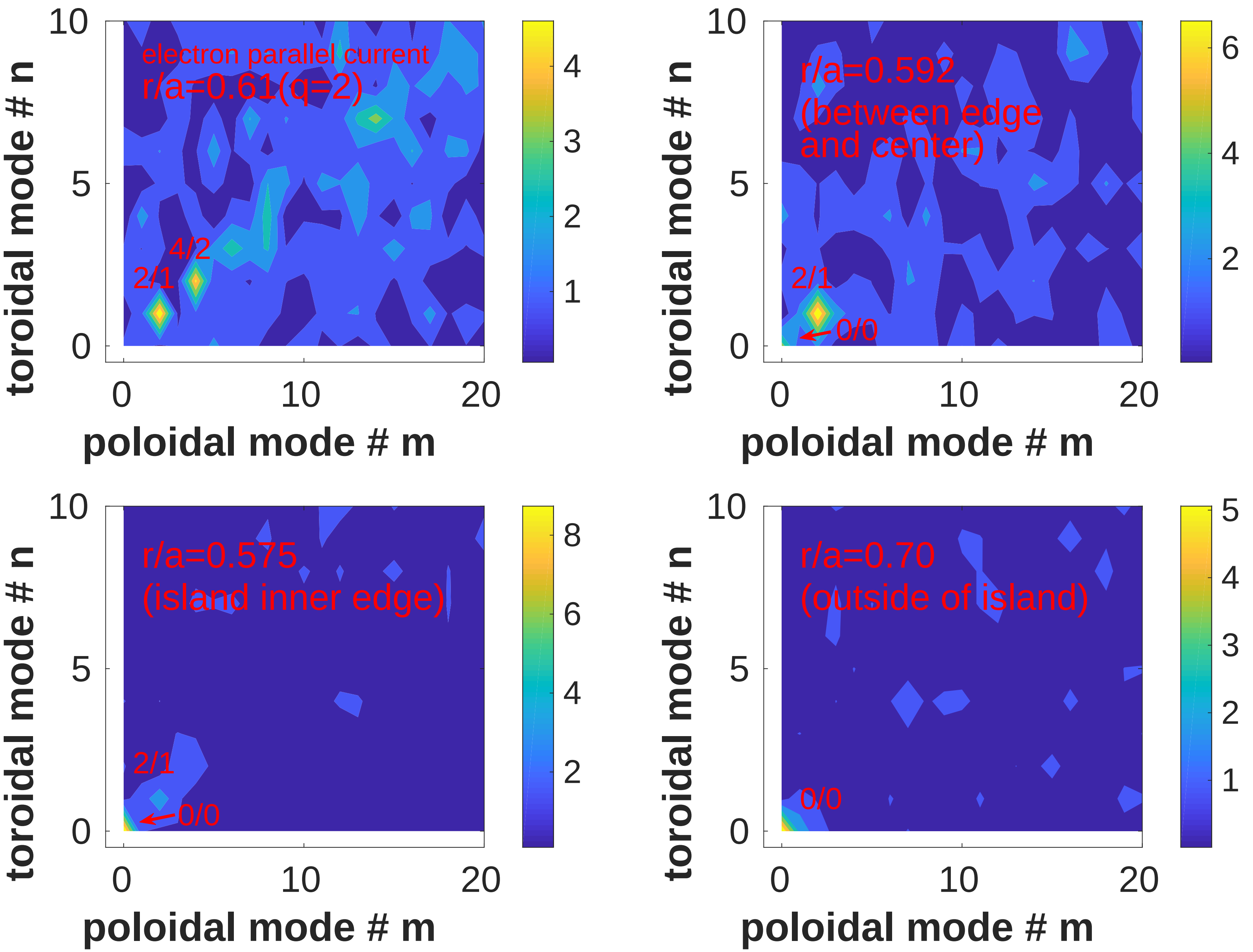


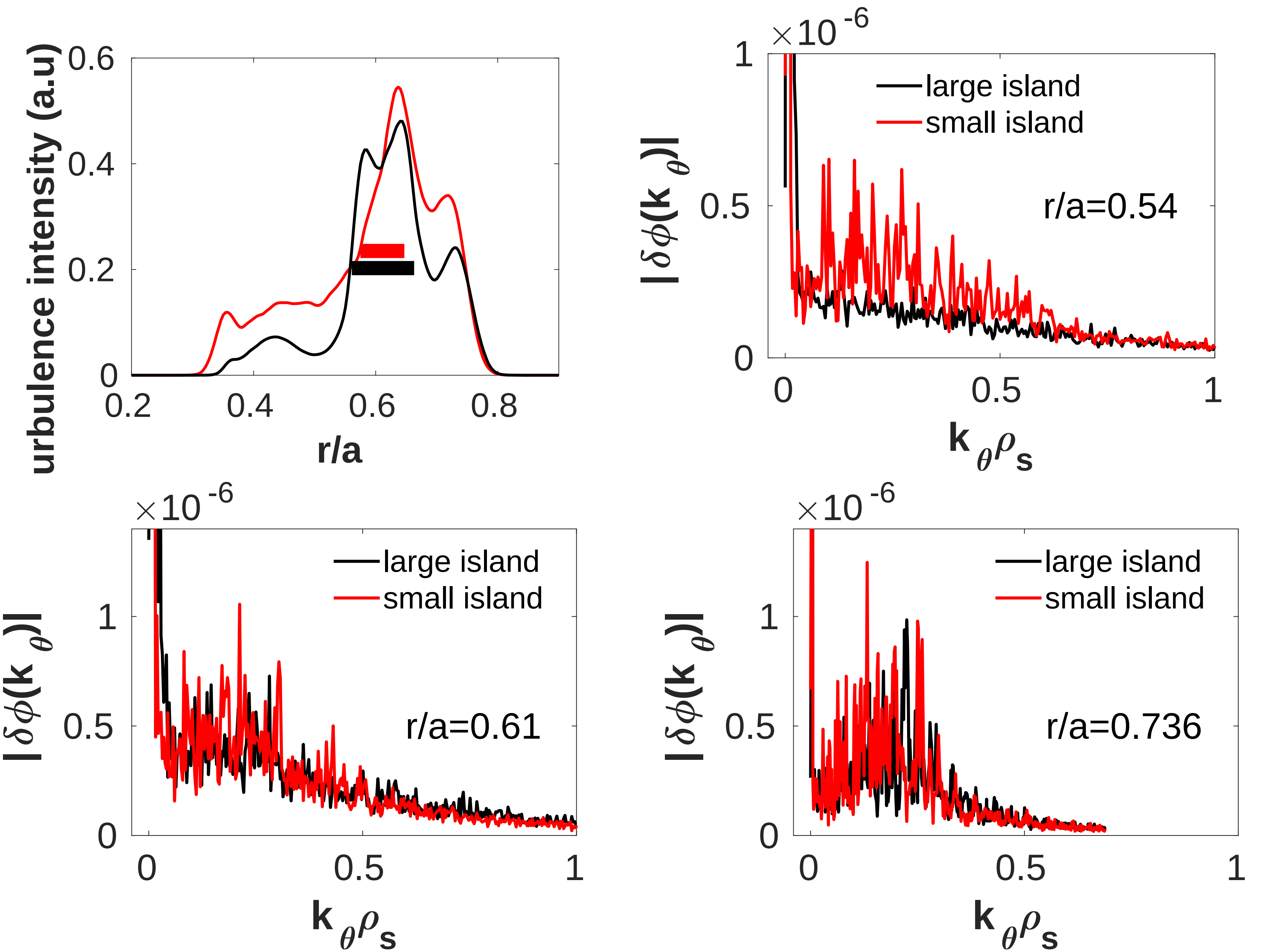


- Helical zonal flows akin to magnetic island formed in island geometry
  – poloidal $\mathbf{E}\times\mathbf{B}$ shear flow on perturbed magnetic surfaces

A helical electron current is generated and dominates in island region – how this impacts island evolution?



Wider island results in stronger fluctuation suppression in inner region by forming a deeper E_r well



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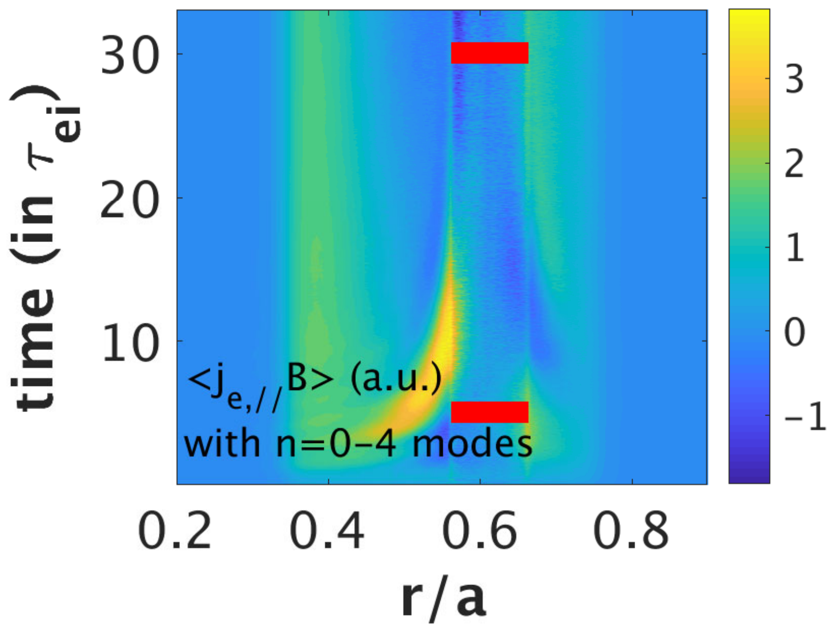

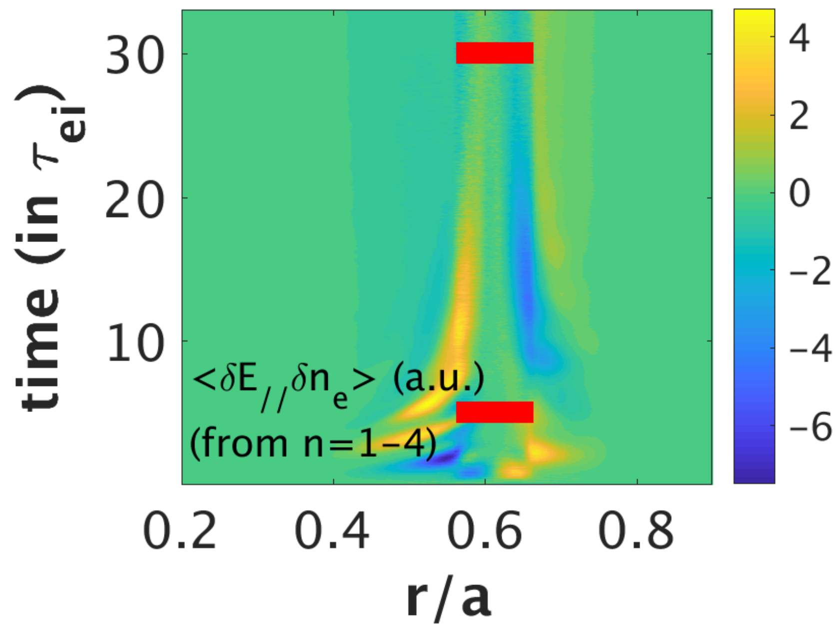

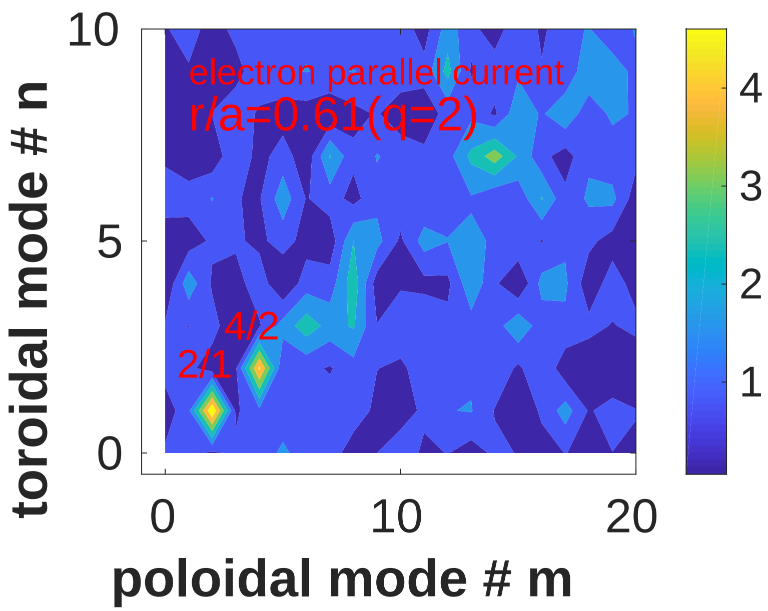

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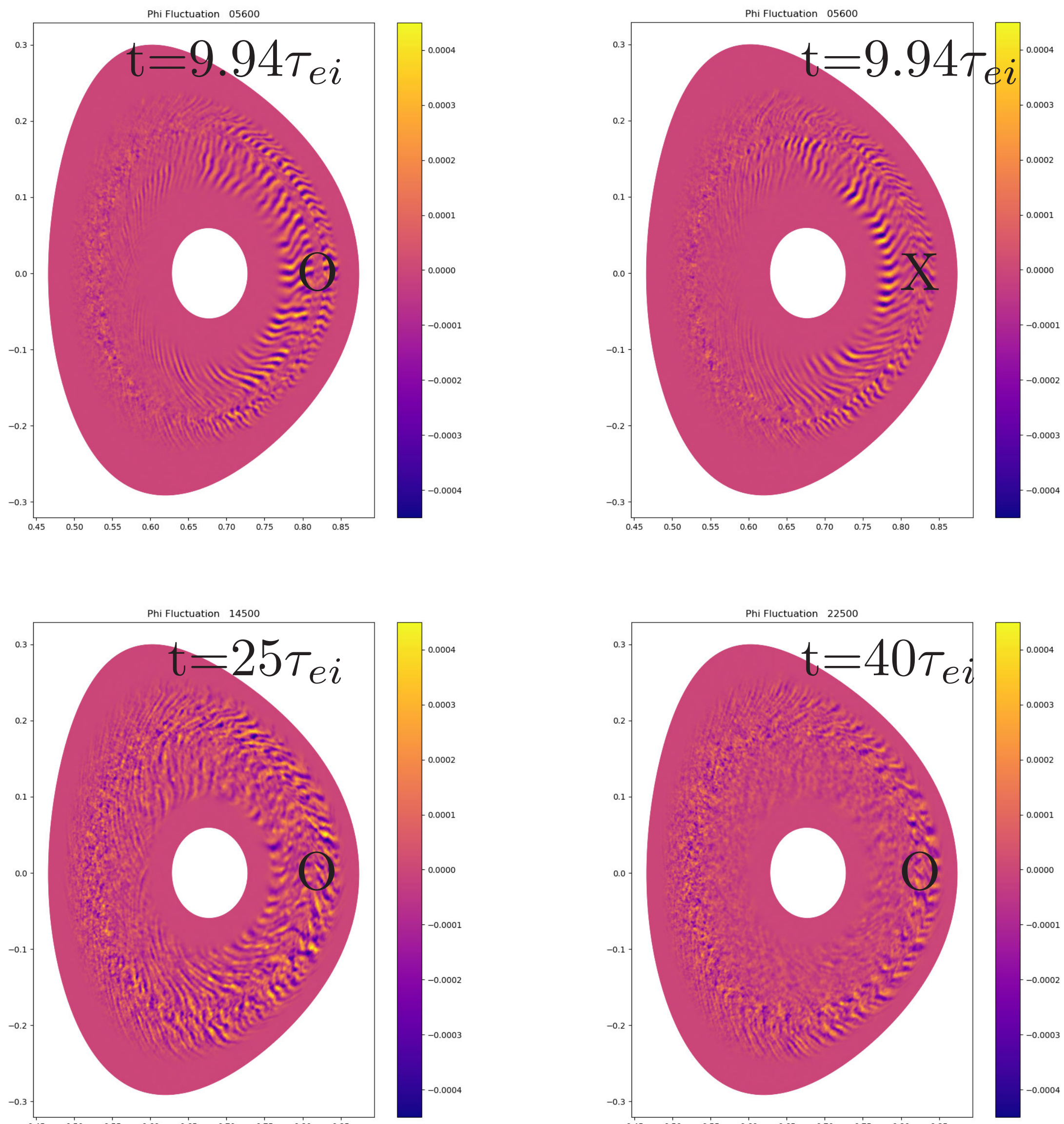
$$= -\frac{e^2}{m_e} \langle \hat{b} \cdot \nabla \delta\phi \delta n_e \rangle$$

- Helical current is generated and dominates in island region

How turbulence develops in island geometry? – subtle difference between O- and X-point



- Turbulence starts at X-point on low-field-side mid-plane;
- Get into O-point via turbulence spreading

(images by E. Feibush)