The role of instabilities in helicity-injection current drive in spherical tokamaks

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Helicity injection

- Helicity injection using DC electrodes is widely used and proposed for current drive in spherical tokamaks (NSTX, HIT-II, proto-SPHERA, HIST,…) and spheromaks

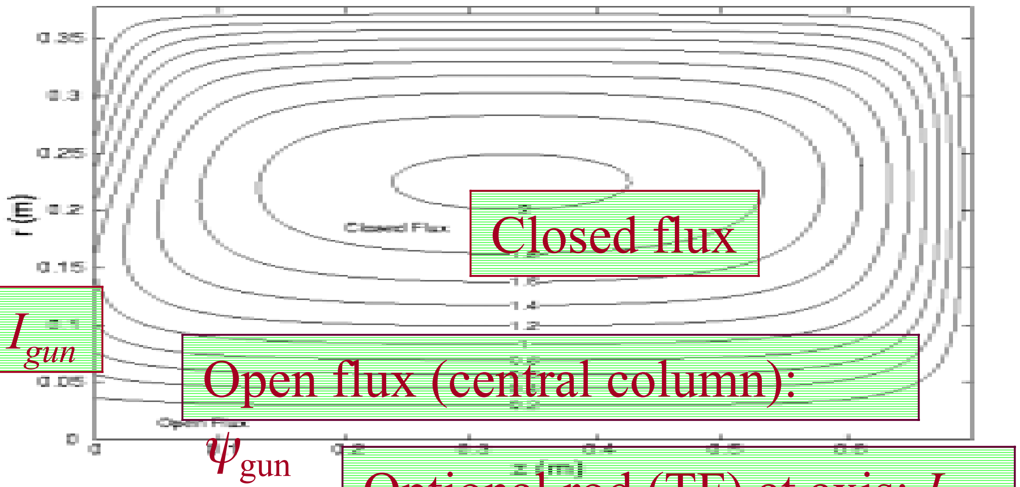
$$\frac{dK}{dt} = 2V_{gun}\psi_{gun} - \frac{K}{\tau_{diss}}$$

- Poloidal current directly driven on open flux (linking gun electrodes) - require mechanism to transfer this to toroidal current on the closed flux - a “relaxation process” *e.g. Taylor (1974)*

Fluctuations and the $n = 1$ mode

- Fluctuations with toroidal mode number $n = 1$ are common in helicity-injected spherical tokamaks and spheromaks
- Apparently play a major role in current drive (relaxation)
  - e.g. through a RMF like process involving rotating helical structures (*McCollam and Jarboe, 2002)*
- In SPHEX, $n = 1$ mode associated with:
  - Power flow from open flux central column to closed flux
  - MHD dynamo on central column $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$
  - Current drive: toroidal plasma current decays when mode is absent

(Browning et al, 1992; al-Kharky et al, 1993; Willet et al, 1999)



Closed flux

Electrodes: I_{gun}

Open flux (central column): ψ_{gun}

Optional rod (TF) at axis: I_{rod}

$$\nabla \times \mathbf{B} = \mu \mathbf{B}$$

$$\mu = \mu_0 j_{//} / B$$

High μ on open flux connected to electrodes

$$\mu = \mu_{gun} \equiv \mu_0 I_{gun} / \psi_{gun}$$

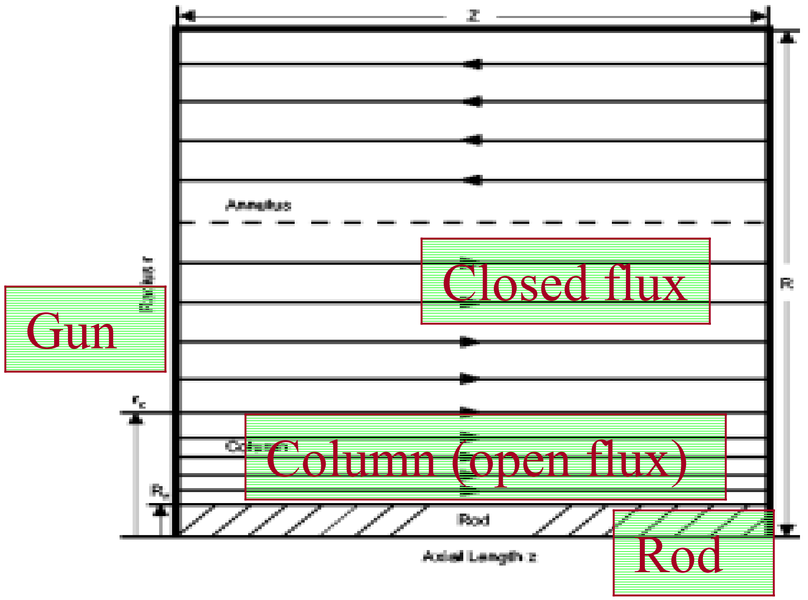
Lower μ on closed flux

- We propose $n = 1$ fluctuations arise from saturation of current-driven ideal “kink” instability of central column of open flux - rotating helical column drives current
  - (*Duck, Browning et al, 1997*)
- Current drive (relaxation) operates when the high current central column is linearly kink unstable
  - instability modified by surrounding closed flux plasma torus
- In spherical tokamaks at higher TF currents (I_{rod}), $n = 1$ fluctuations are dominant in outer layers of open flux (near wall) - we expect the character of instability to change with I_{rod}

Ideal kink instability of model 1D equilibrium

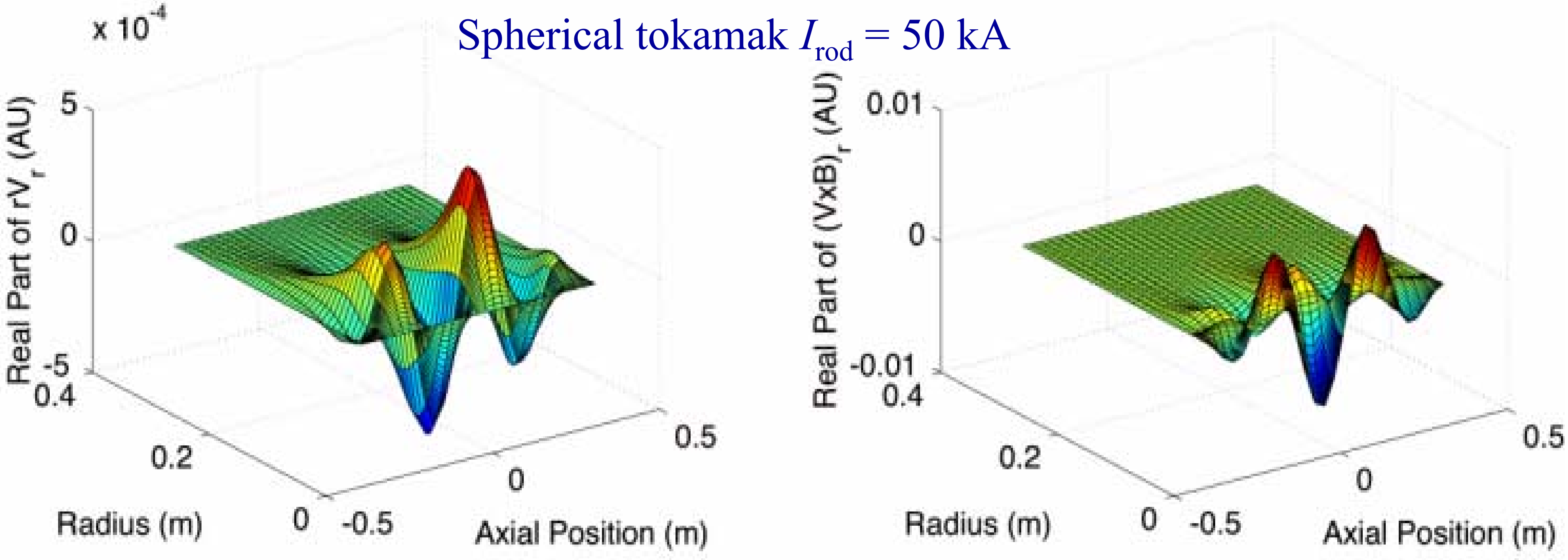
- Conducting walls - line-tied at $z = 0, L$
- Increasing column current (μ_c) destabilises $n = 1$ mode
- Increasing closed flux current (μ_a) → annulus expands and column compressed → kink instability stabilised

$\mu = \mu_c$ (open flux column),
$\mu = \mu_a$ (closed flux annulus)



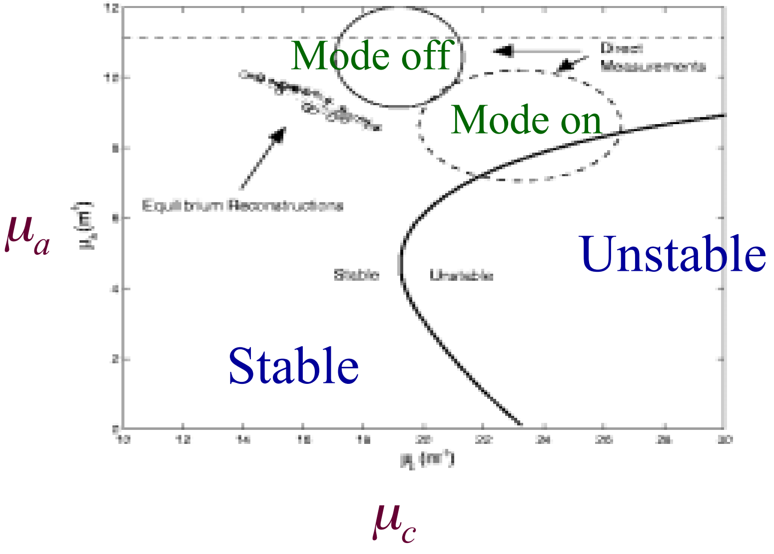
Mode structure

Spherical tokamak I_{rod} = 50 kA



- Eigenfunction of unstable mode is concentrated in open flux region (column)
- Wavelength in z determined by fieldline pitch

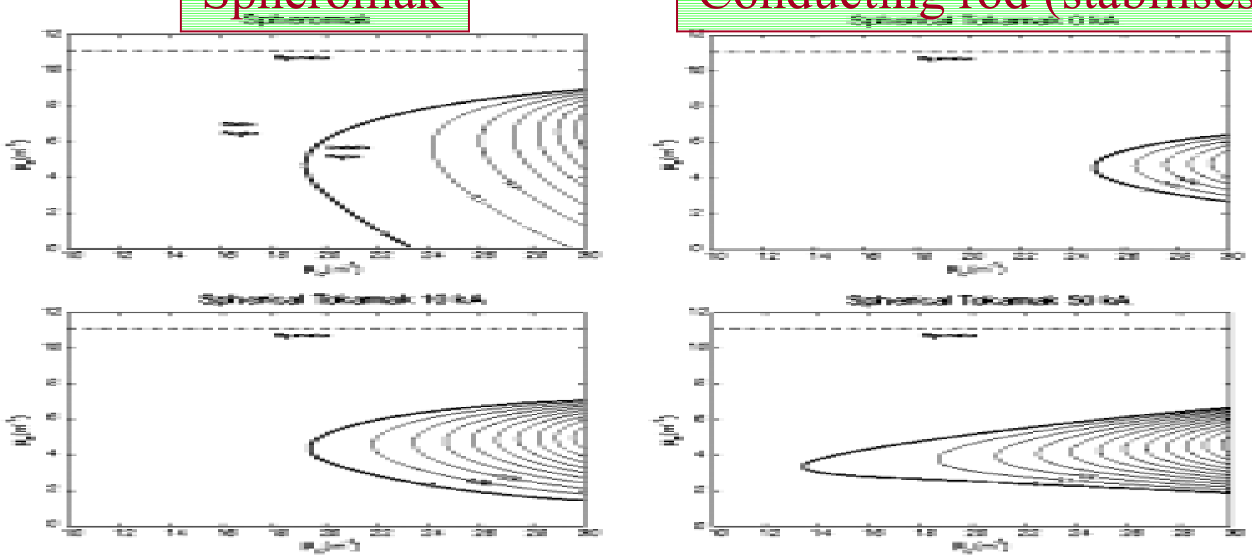
Comparison with experiment



- Expect operation near upper stability threshold - current drive “switches off” at sufficiently large plasma current (μ_a)
- In Ti gettered operation in SPHEX, n = 1 mode was intermittent - current drive “switched off” when mode absent
- Inferred stability threshold according to fitted μ profile at onset of mode

Stability threshold for varying TF current

1D model



Spheromak

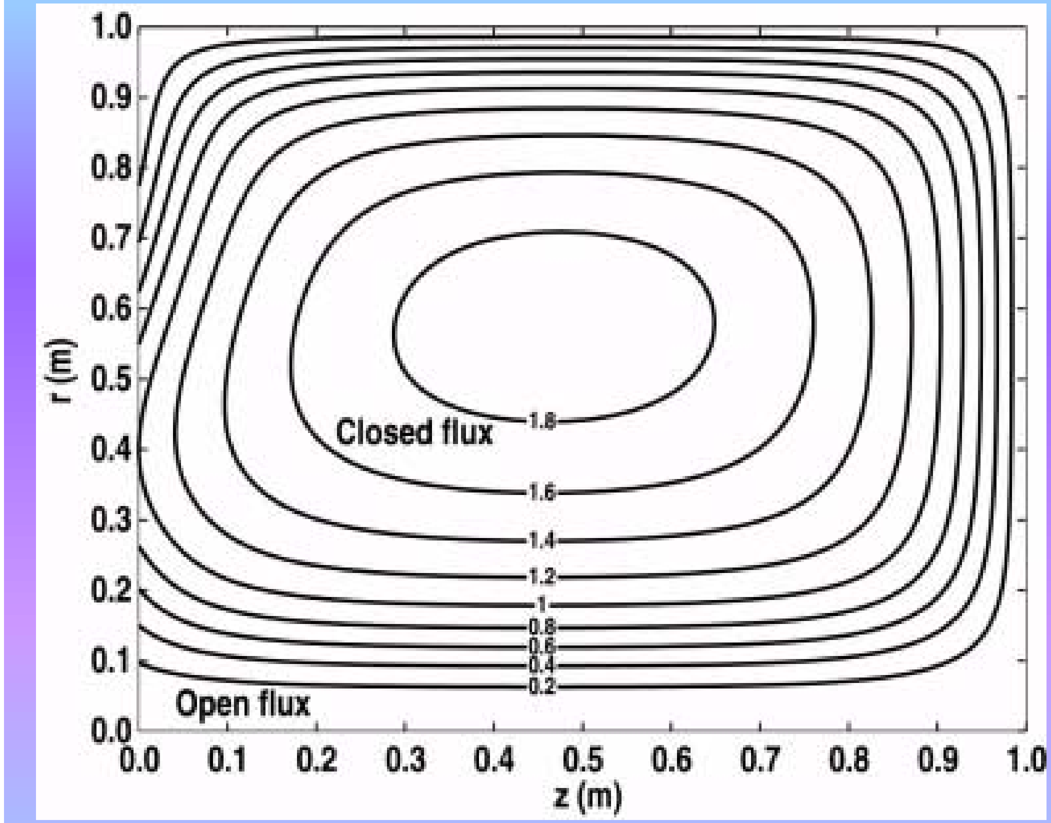
Conducting rod (stabilises)

I_{rod} = 10 kA

I_{rod} = 50 kA

Stability threshold at lower plasma currents as I_{rod} increases

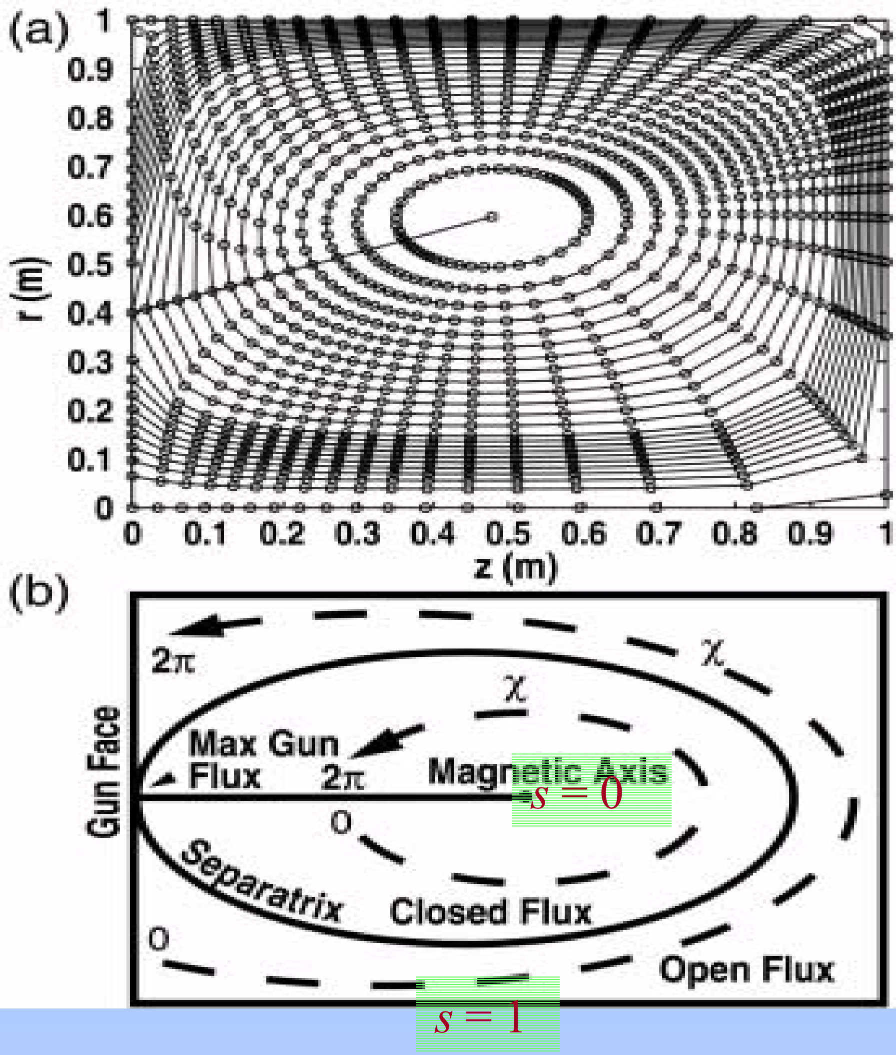
2D equilibrium: SCOTS stability code



$$\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2} + FF' = 0, \quad F = \int \mu d\psi$$

- Cylindrical flux conserver, optional TF central rod
- 4th order accurate f.d. equilibrium code
- Calculate growth rates and eigenmodes of linearised ideal MHD equations with finite element discretisation
- Conducting walls, line-tying at gun ($z = 0$)

Coordinate system for stability analysis



- Non-orthogonal coordinates ψ (flux), χ (angle-like on closed flux) and ϕ
- Coordinate system fully continuous and smooth, including across separatrix
- Derive metric tensor in (s, χ, ϕ) coordinates where $s = (1 - \psi/\psi_{max})^{1/2}$

Angle-like coordinate χ

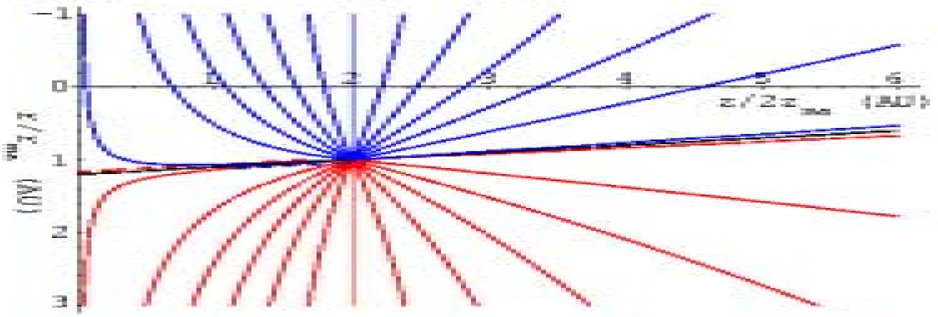
The common forms of poloidal coordinate, based on integrals along lines of constant flux, become infinite at the separatrix. We need a poloidal coordinate which can be calculated across the separatrix, with continuous first and second derivatives and retains the straight line limit at the gun face along $\chi=0,2\pi$, is defined by the function

$f=z1-z2(1+(1/\tan^2((\chi+\pi)/2)-1)(r'/(r'+2a\ z2/\tan^2((\chi+\pi)/2))))$

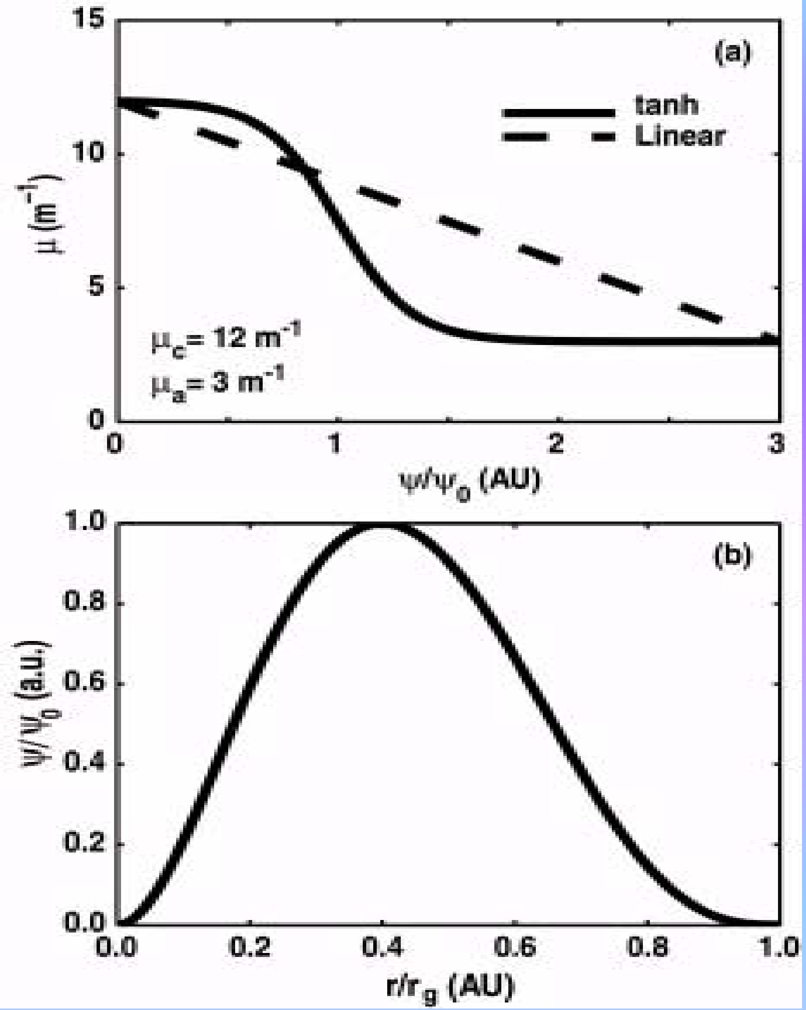
where:

$r1=r-r_{mg}$
$r2=r_{ma}-r_{mg}$
$z1=z-z_{mg}$
$z2=z_{ma}-z_{mg}$

$r'=r1-(r2/z2)(z1-z2)-r2$

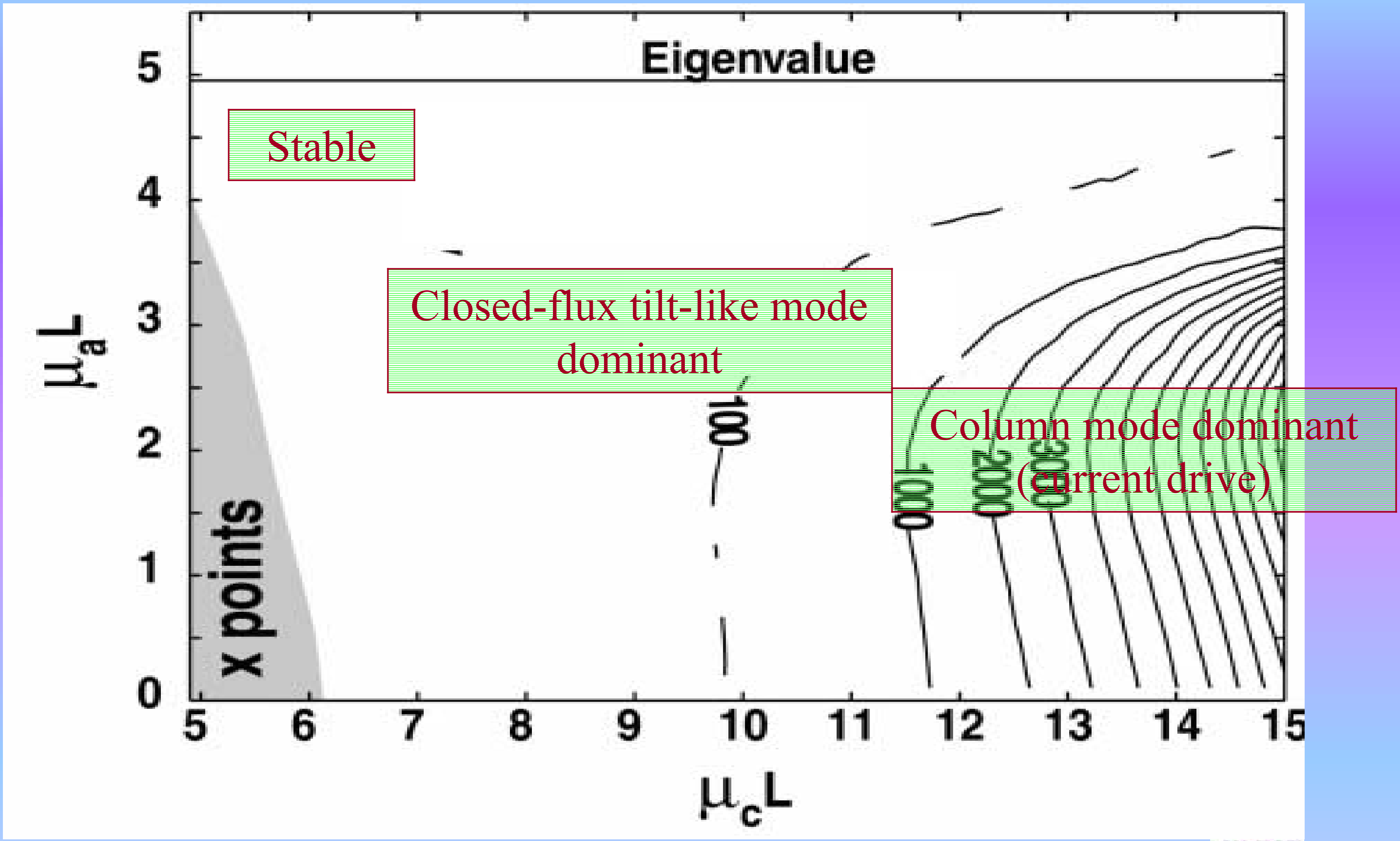


Current profiles



- High μ on open flux connected to electrodes, lower μ on closed flux - continuous transition across separatrix
- μ linear function of ψ or smoothed step-profile (*tanh*)
- Parametrise by average values of μ in open flux (μ_c) and open flux (μ_a)
- Impose flux distribution at gun (must be compatible with G-S at corners)

Growth rate contours

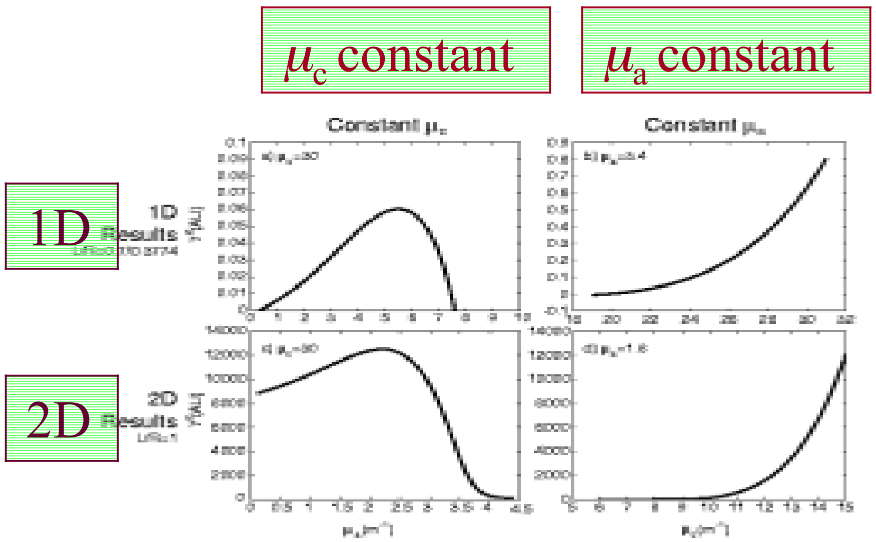


Stable

Closed-flux tilt-like mode dominant

Column mode dominant (current drive)

Comparison of 1D and 2D models

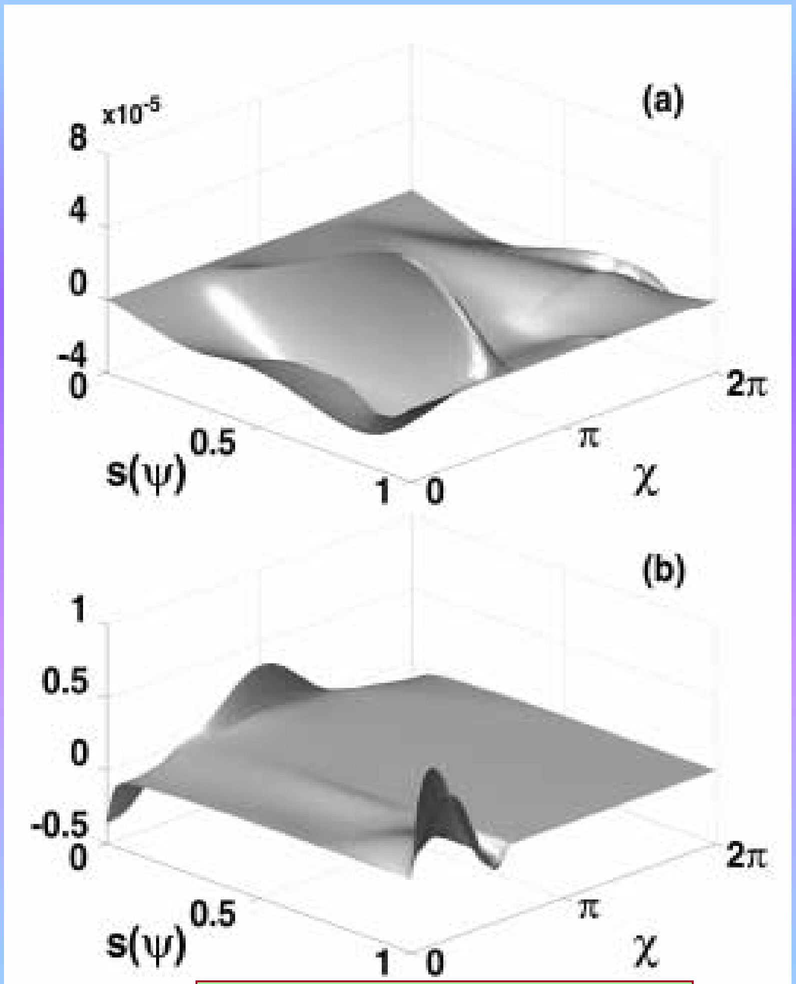


- Good agreement for spheromak
- 2D equilibria do not completely stabilise at higher annulus currents (μ_a) or lower column currents (μ_c) due to appearance of a weak tilt-like instability with eigenfunction peaking on closed flux
- May expect different results from 2D model for higher I_{rod}

Open-flux-localised mode eigenfunction

f_1

f_2



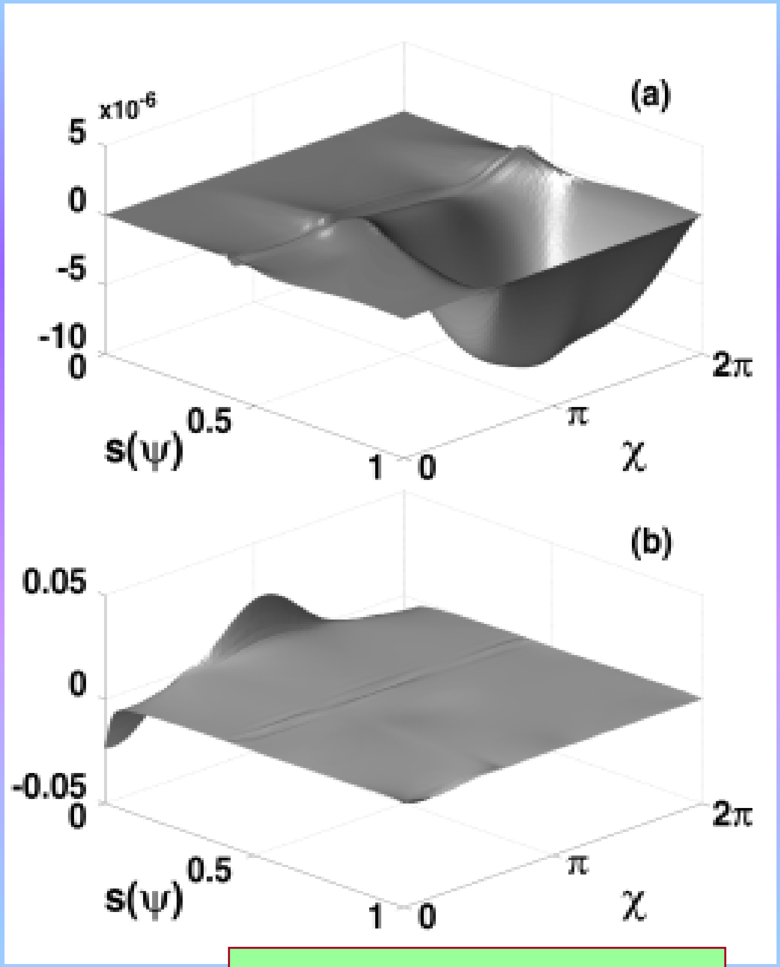
$\mu_c L = 12,\ \mu_a L = 1.2$

- Similar to 1D results
- f_1 component localised around high current region - outer layers of flux (larger s), near midplane ($\chi \approx 0.6$)
- f_2 component localised around geometric axis ($r = 0$)
- Also smaller peaks reminiscent of closed-flux (tilt-like) mode

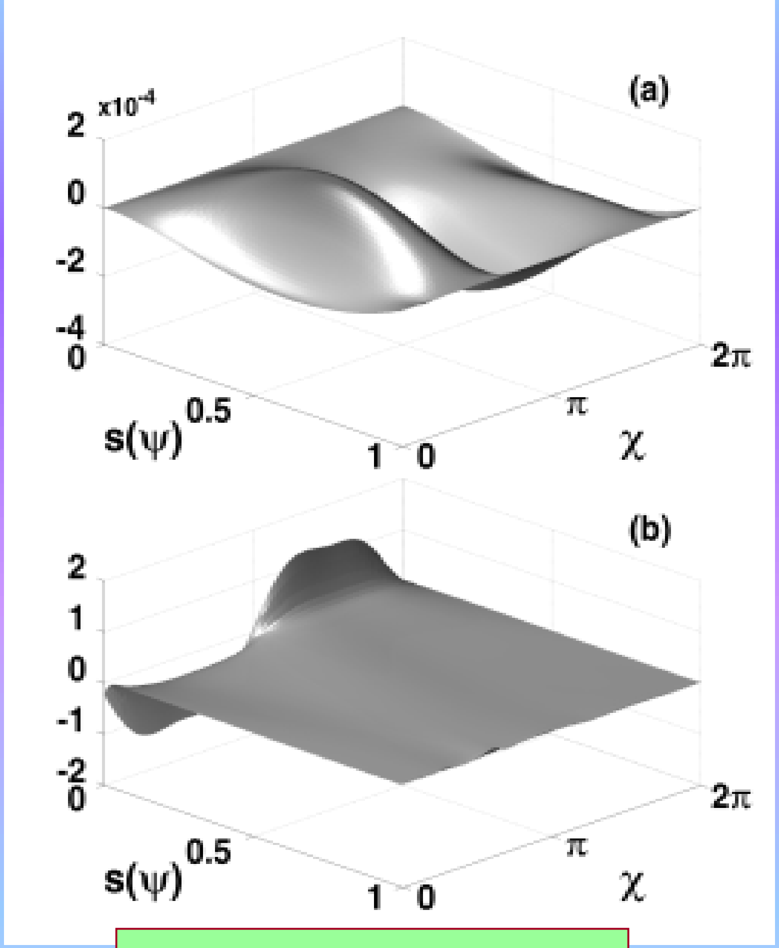
Closed-flux dominant eigenfunction

f_1

f_2



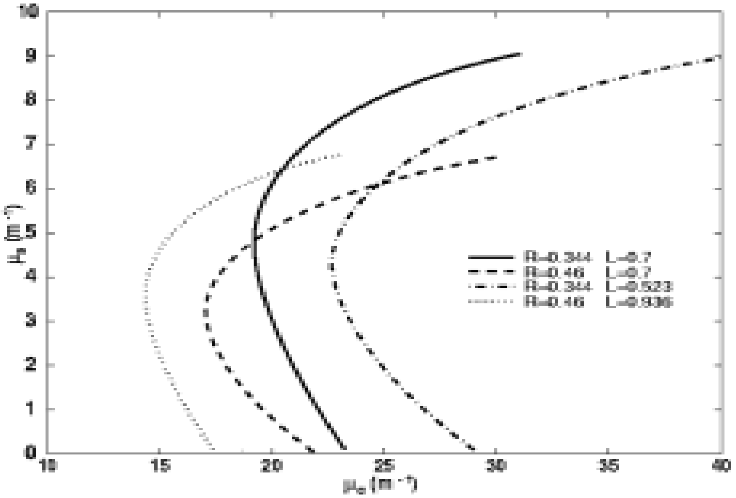
$\mu_c L = 6$, $\mu_a L = 1.2$



Tilt mode, $L/R = 1.85$

Toroidal current limit

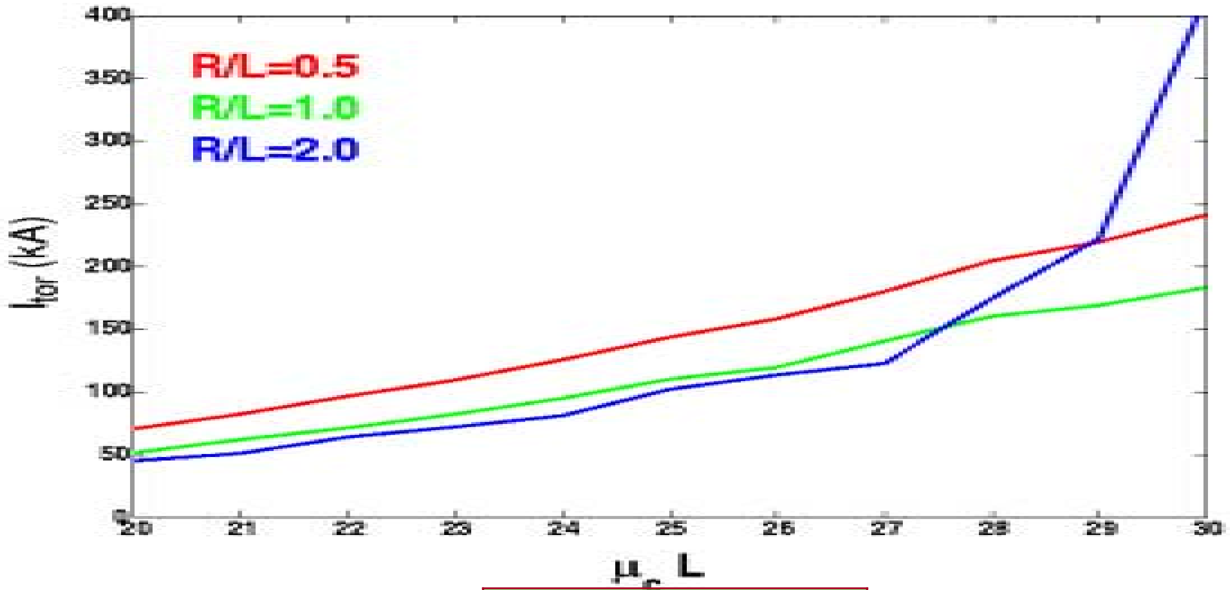
Stability threshold in μ_a μ_c space - various *R, L*



- Current drive requires operation near upper boundary of stable region

□maximum μ_a (hence maximum I_{tor}) for each μ_c

- We may thus predict variation of plasma toroidal current with electrode current (I_{gun}) and TF current (I_{rod}) for various geometries (*L, R)*



↑

$I_{\text{gun}} \approx 85$ kA

$$\mu_c L = \mu_0 I_{gun} L / \psi_{gun}$$

Ongoing and future work

- Modify coordinate system to allow X-points
- Full study of 2D spherical tokamak equilibria - find marginal stability threshold for various I_{rod} - expect instability becomes dominant on open flux near edge
- Real device geometries
- Nonlinear simulations with 3D MHD code (Nimrod) - saturation of mode amplitude (helical column), current drive effects
- Finite _ in instability code

Summary

- Helicity injection current drive in spherical tokamaks and spheromaks is closely associated with n = 1 fluctuations arising from kink-like instabilities of high current open flux regions
- A new ideal linear stability code (SCOTS) has been developed which properly models both open and closed flux regions
- The kink instability is stabilised at sufficiently high plasma currents (μ_a) - the current drive is thus self-limiting - maximum toroidal current for given helicity injection parameters