Large transport induced operational limits in tokamak plasmas

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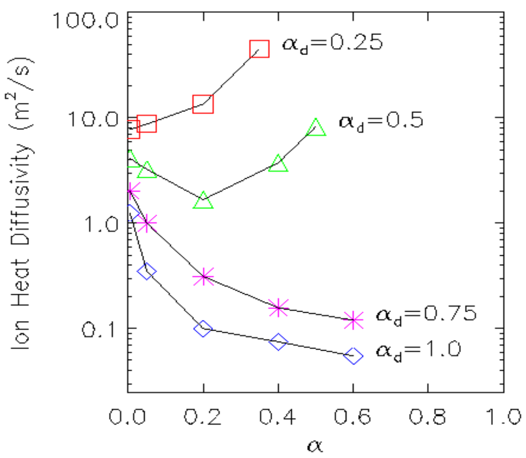
OUTLINE OF THE TALK

- MOTIVATION
- THEORETICAL/NUMERICAL MODEL
- COMPARISON WITH EXPERIMENTS
- CONCLUSIONS/FUTURE WORK

RECENT COMPARISON ON C-MOD WITH SIMULATIONS/THEORY

Rogers, Drake and Zeiler, PRL, 81, 4396, 1998
Guzdar, Kleva, Das and Kaw, PRL 2001
L-H transition criterion $\alpha_{MHD}\alpha_D^2$ =0.08-0.12

LaBombard et al NF 45,1568,(2005)



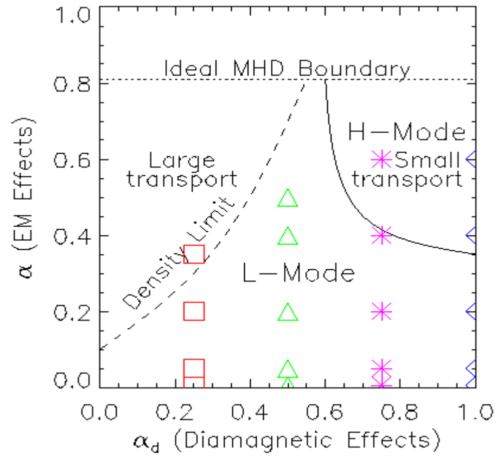
$$\alpha_D = \frac{\rho_s c_s t_0}{L_0 L_n (1+\tau)},$$

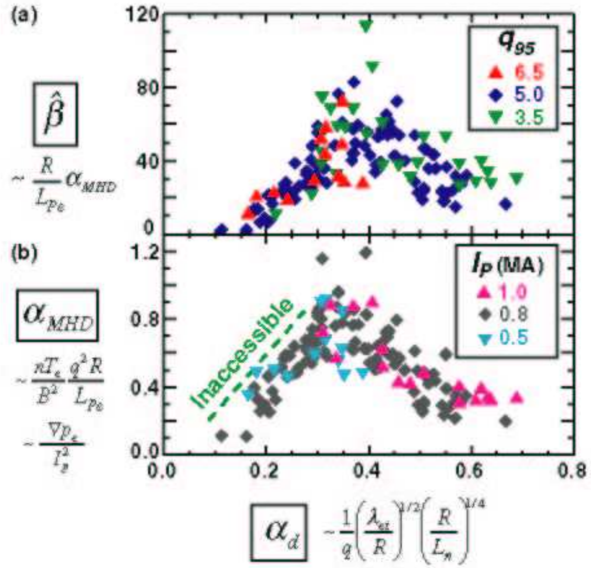
$$t_0 = \frac{(RL_n/2)^{1/2}}{c_s}$$

$$\alpha_{MHD} = \frac{q^2 R \beta}{L_p},$$

$$\hat{\beta} = \frac{q^2 R^2 \beta}{4L_p^2} = \alpha \frac{R}{4L_p}$$

$$L_0 = 2\pi q \left(\frac{\nu_{ei} R \rho_s}{2\Omega_e}\right)^{1/2} \left(\frac{2R}{L_n}\right)^{1/4}$$





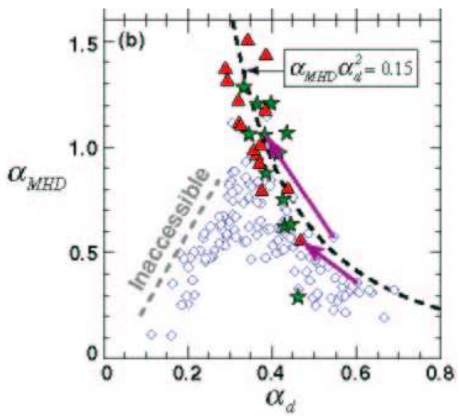
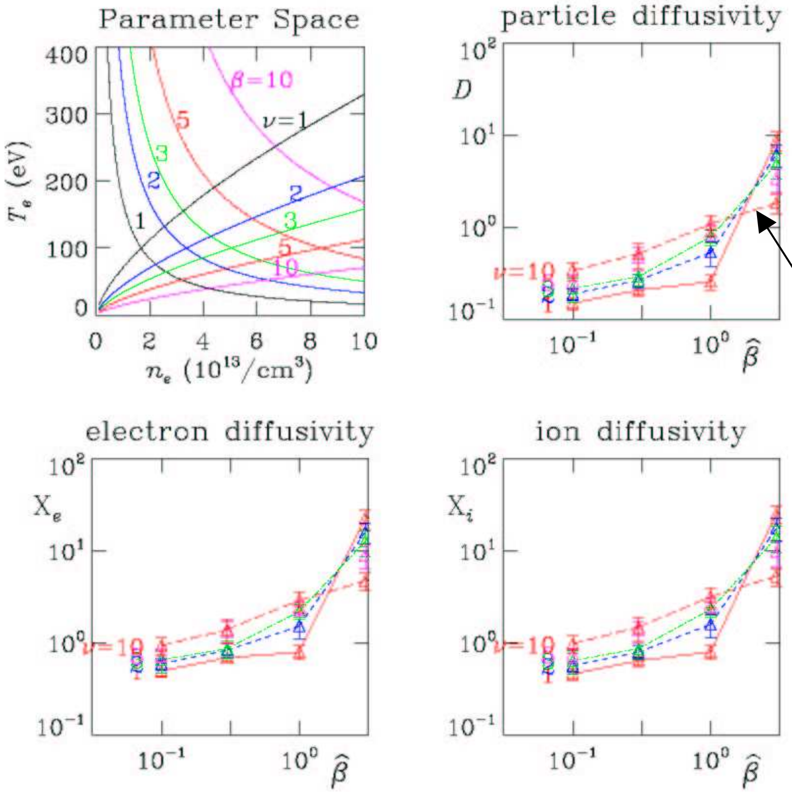


TABLE 1

LaBombard et al NF 45,1568,(2005)

	RDZ	Scott
	Definitions and Normalizations	
Time $\frac{\partial}{\partial t} \sim \frac{1}{t_0}$	Ideal Ballooning Time $t_0 = \left(\frac{RL_n}{2}\right)^{1/2} \frac{1}{C_s}$	Drift Scaling $t_0 = \frac{L_{Pe}}{C_s}$
Perpendicular $\nabla_\perp \sim \frac{1}{L}$	Linear Resistive Ballooning Scale $L = L_0 = 2\pi q \left(\frac{\rho_s \rho_e R}{\lambda_{ei}}\right)^{1/2} \left(\frac{2R}{L_n}\right)^{1/4}$	$L = \rho_s$
Parallel $\nabla_{//} \sim \frac{1}{L_{//}}$	$L_{//} = 2\pi qR$	$L_{//} = qR$
Background Gradients	$\frac{\nabla_\perp n_0}{n_0} \sim \frac{1}{L_n}$; $\frac{\nabla_\perp T_{e0}}{T_{e0}} \sim \frac{1}{L_{Te}}$; $\frac{\nabla_\perp T_{i0}}{T_{i0}} \sim \frac{1}{L_{Ti}}$; $\frac{\nabla_\perp p_{e0}}{p_{e0}} \sim \frac{1}{L_{Pe}}$	
	Key Control Parameters	
Poloidal Beta Gradient	MHD Ballooning Parameter $\alpha_{MHD} = \frac{q^2 R}{L_{Pe}} \beta$; $\beta = \frac{4\mu_0 p_{e0}}{B^2}$	$\hat{\beta} = \frac{q^2 R}{L_{Pe}} \beta \left(\frac{R}{4L_{Pe}}\right)$
Collisionality	Drift Frequency/Ballooning Time $\alpha_d = \frac{T_{e0} t_0}{eBL_n L_0}$ $\alpha_d = \left(\frac{\lambda_{ei}}{q^2 R}\right)^{1/2} \left(\frac{2R}{L_n}\right)^{1/4} \frac{1}{8\pi} \left(\frac{M_i}{m_e}\right)^{1/4}$	Normalized Collision Frequency $C_0 = \frac{m_e}{M_i} \left(\frac{qR}{L_{Pe}}\right)^2 \frac{\nu_{ei} L_{Pe}}{C_s}$ $C_0 = \left(\frac{q^2 R}{\lambda_{ei}}\right) \left(\frac{R}{L_{Pe}}\right) \left(\frac{m_e}{M_i}\right)^{1/2}$
	Relationships Between Control Parameters	
	$\alpha_{MHD} = \hat{\beta} \frac{4L_{Pe}}{R}$; $\alpha_d = \frac{C_0^{-1/2}}{4\pi} \left(\frac{R}{2L_n}\right)^{1/4} \left(\frac{R}{2L_{Pe}}\right)^{1/2}$	

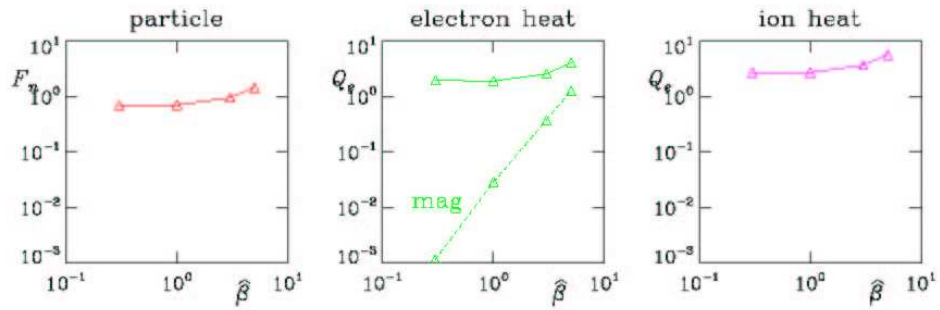
Scott NJP, 4, 52.1-52.30, (2002)
Braginskii Equations



$L_p = 4.25$ cm, R=169 cm, $L_n = 2L_T$

$\alpha_{MHD} = 0.1\hat{\beta} \qquad \alpha_D = 0.4\nu^{-1/2}$

Scott IAEA-11-S7, (2005)
Gyrokinetic Edge Code



$$\frac{R}{L_T} = 30, \ L_n = 2L_T, \ L_p = \frac{2}{3}L_T$$

$$\alpha_{MHD} = 0.09\hat{\beta} \qquad \alpha_D = 0.46$$

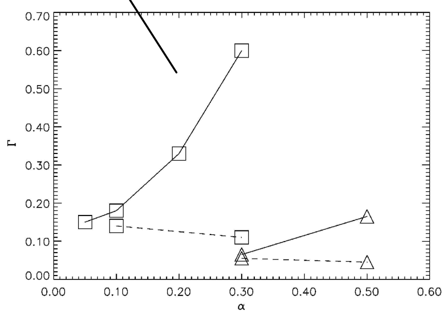
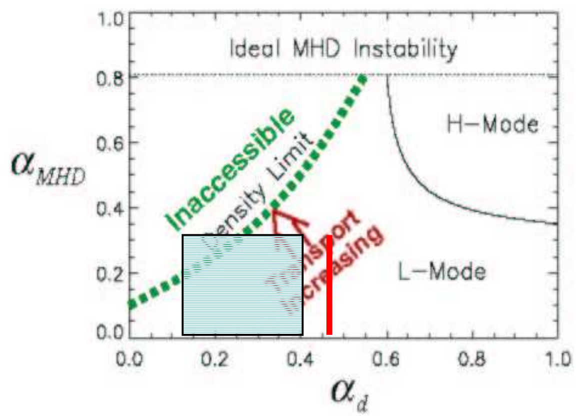


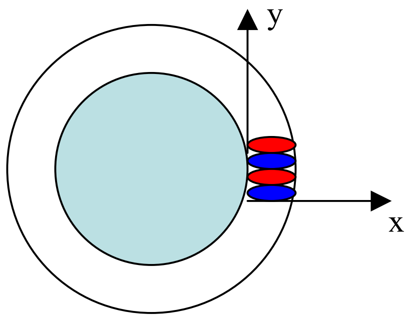
FIG. 3. Normalized particle flux Γ vs α.

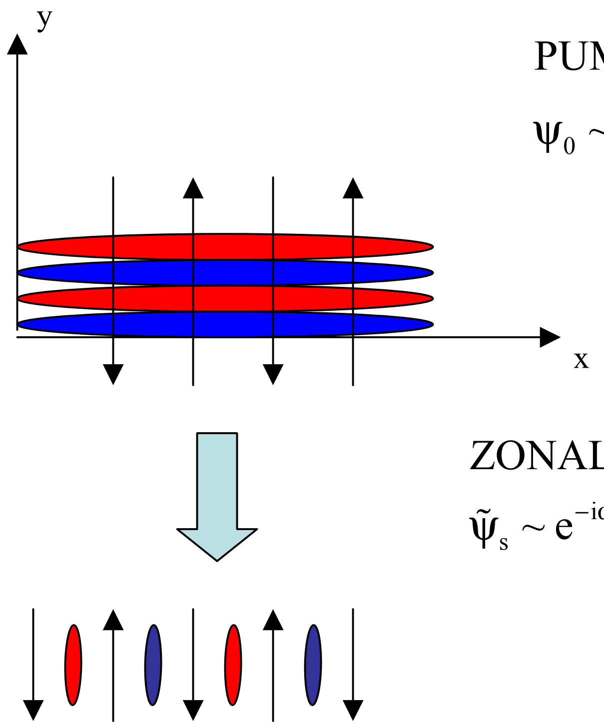


BASIC IDEA FOR PRESENT MODEL-1

- BASIC INSTABILITIES IN THE EDGE REGION OF TOKAMAKS ARE FINITE β DRIFT WAVES AND DRIFT RESISTIVE BALLOONING MODES

- "MODULATIONAL" INSTABILITY GENERATES ZONAL FLOWS WHICH SATURATE FINITE β DRIFT WAVE/RESISTIVE BALLOONING TURBULENCE





PUMP WAVE

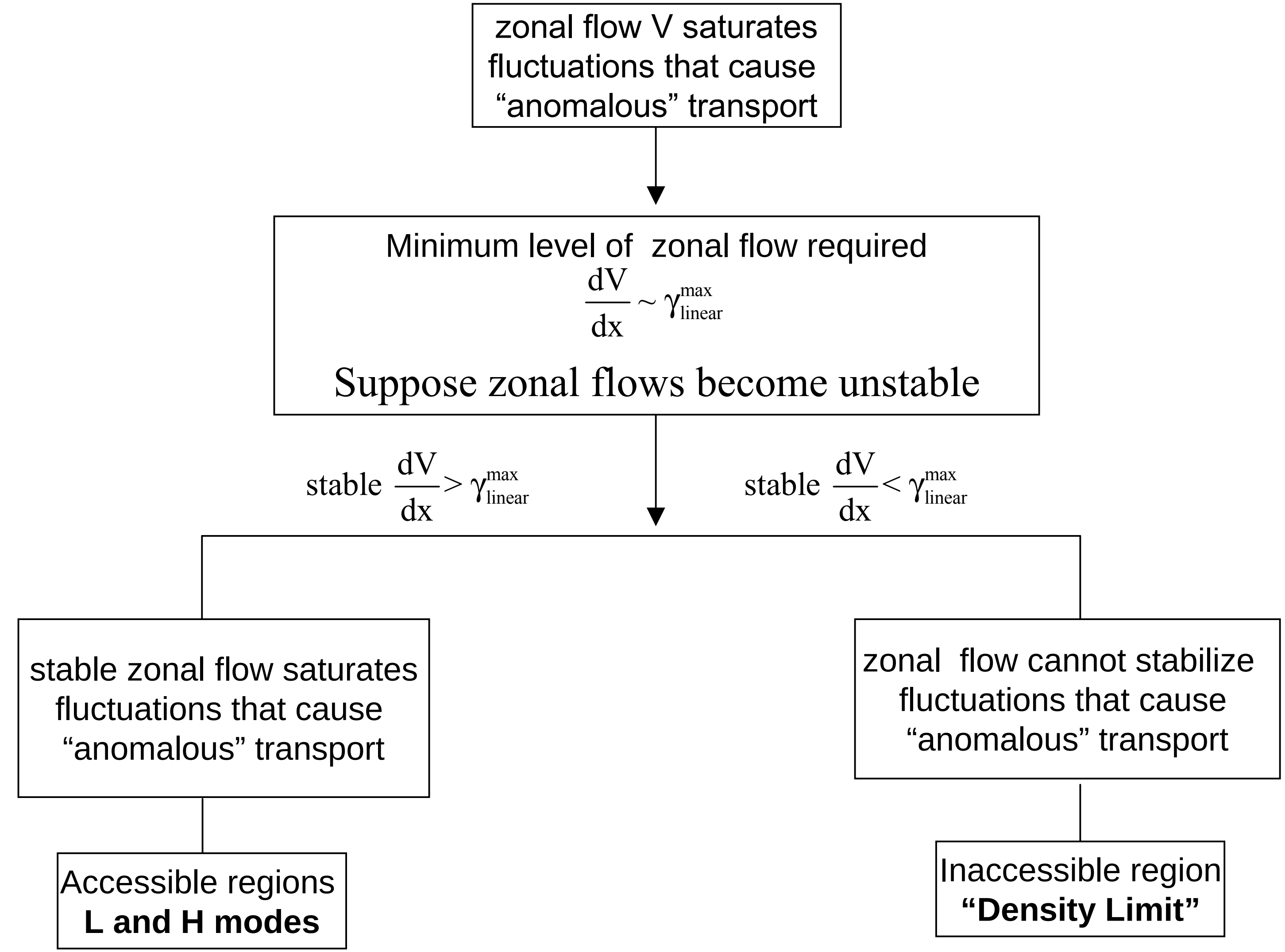
$\psi_0 \sim e^{-i\omega_0 t + ik_y y + ik_\parallel z}$

ZONAL FLOW/FIELD

$\tilde{\psi}_s \sim e^{-i\omega t + ik_x x}$

INACCESSIBLE REGION DUE TO VERY LARGE EDGE TRANSPORT
-GREENWALD PPCF 44, R27-R53 2002
WHAT PHYSICAL PROCESS LEADS TO VERY LARGE TRANSPORT ?

SCENARIO FOR LARGE EDGE TRANSPORT



STABILITY OF ZONAL (SHEAR) FLOWS

B. N. Rogers and W. Dorland PoP **12**, 062511 2005

Marginal stability (for linear velocity and magnetic shear)

$$\underbrace{k_y V_E'}_{\substack{Kelvin-Helmholtz\\ drive}} = \underbrace{\frac{k_y \hat{s}_{eff}}{\sqrt{\alpha_{MHD}}}}_{fieldline\ bending}$$

With ion diamagnetic effects

$$V_E' = \left[\frac{(\hat{s} - f\alpha_{MHD})^2}{\alpha_{MHD}} + \frac{\alpha_D^2}{4x_L^2} \right]^{1/2}$$

$$x_L \sim 1,\ localization - width$$

LINEARIZED EQUATIONS FOR UNSTABLE MODES IN THE EDGE REGION OF TOKAMAKS

Rogers, Drake and Zeiler, PRL, **81**, 4396, 1998,
Hastie Ramos and Porcelli PoP, **10**, 4405, 2001

$$\frac{d}{d\theta}\left[f_1(\theta)\Psi\right]+i\alpha_{MHD}\left[\Omega f_1(\theta)\Phi+f_2(\theta)N\right]=0$$

$$\frac{d}{d\theta}\left[\Phi-(\tau+1)\hat{m}\alpha_D N\right]-\frac{\hat{m}^2 f_1(\theta)}{4\pi^2}\Psi+i\left(\Omega-\hat{m}\alpha_D\right)\Psi=0$$

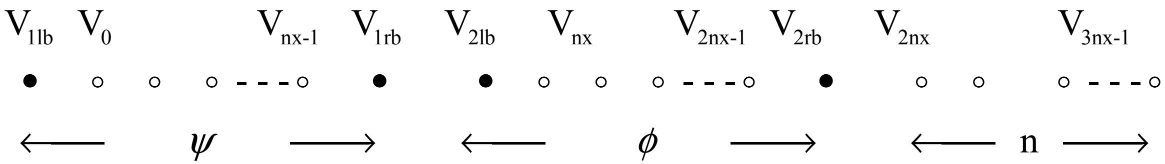
$$\left[1-2\varepsilon_n f_2(\theta)\right]\Phi-\tau\hat{m}\alpha_D N-\Omega\left[N+\frac{\hat{m}\hat{\rho}_s^2}{\alpha_D}f_1(\theta)\Phi\right]=0$$

$$f_1(\theta)=1+\left[s\theta-\alpha_{MHD}Sin(\theta)\right]^2$$

$$f_2(\theta)=Cos(\theta)+\left[s\theta-\alpha_{MHD}Sin(\theta)\right]Sin(\theta)$$

NUMERICAL METHOD

- Finite difference the equations
- Create vector V=(Ψ,Φ,n)

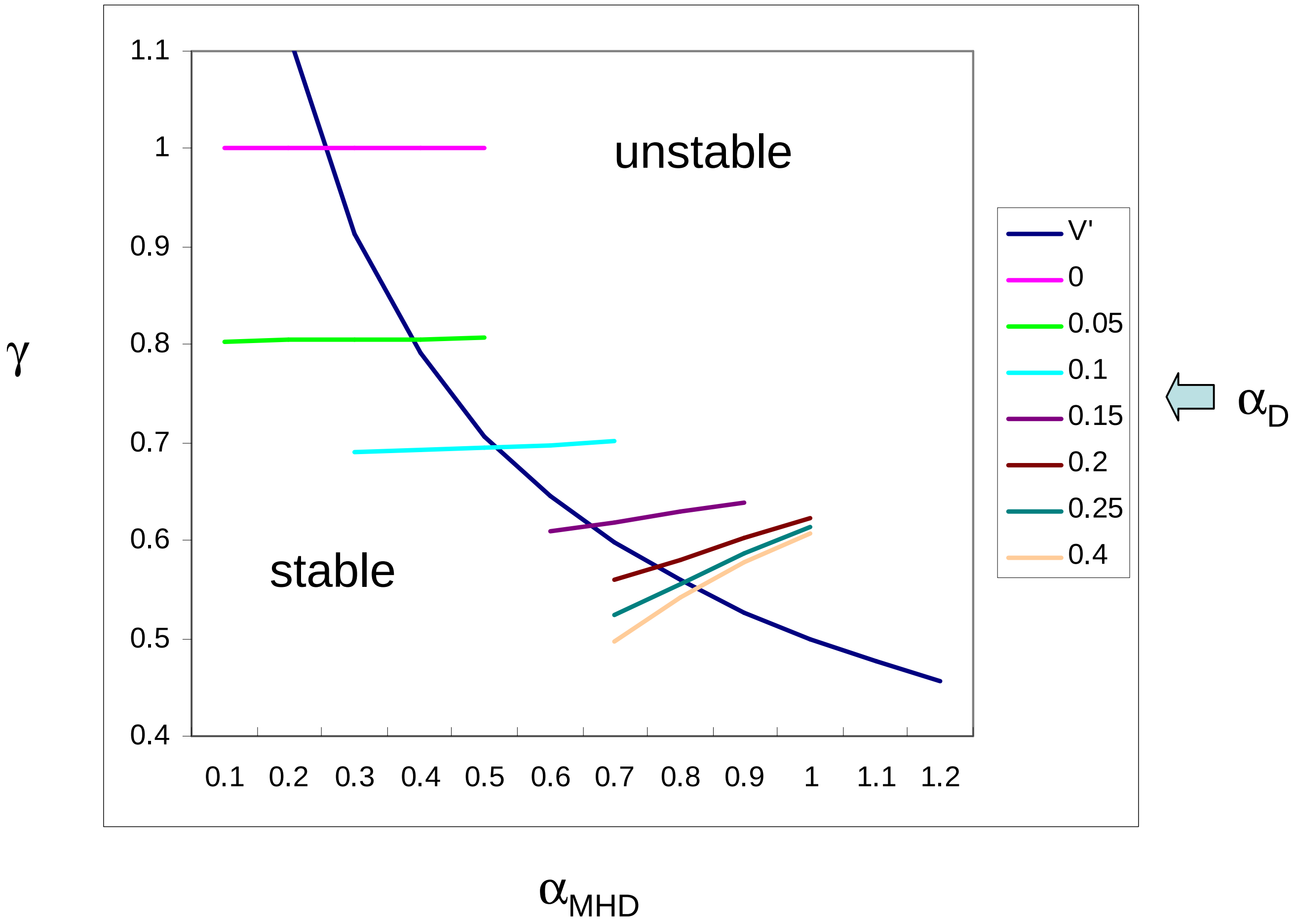


- Reduce three coupled equations to eigenvalue equation
- A and B are matrices

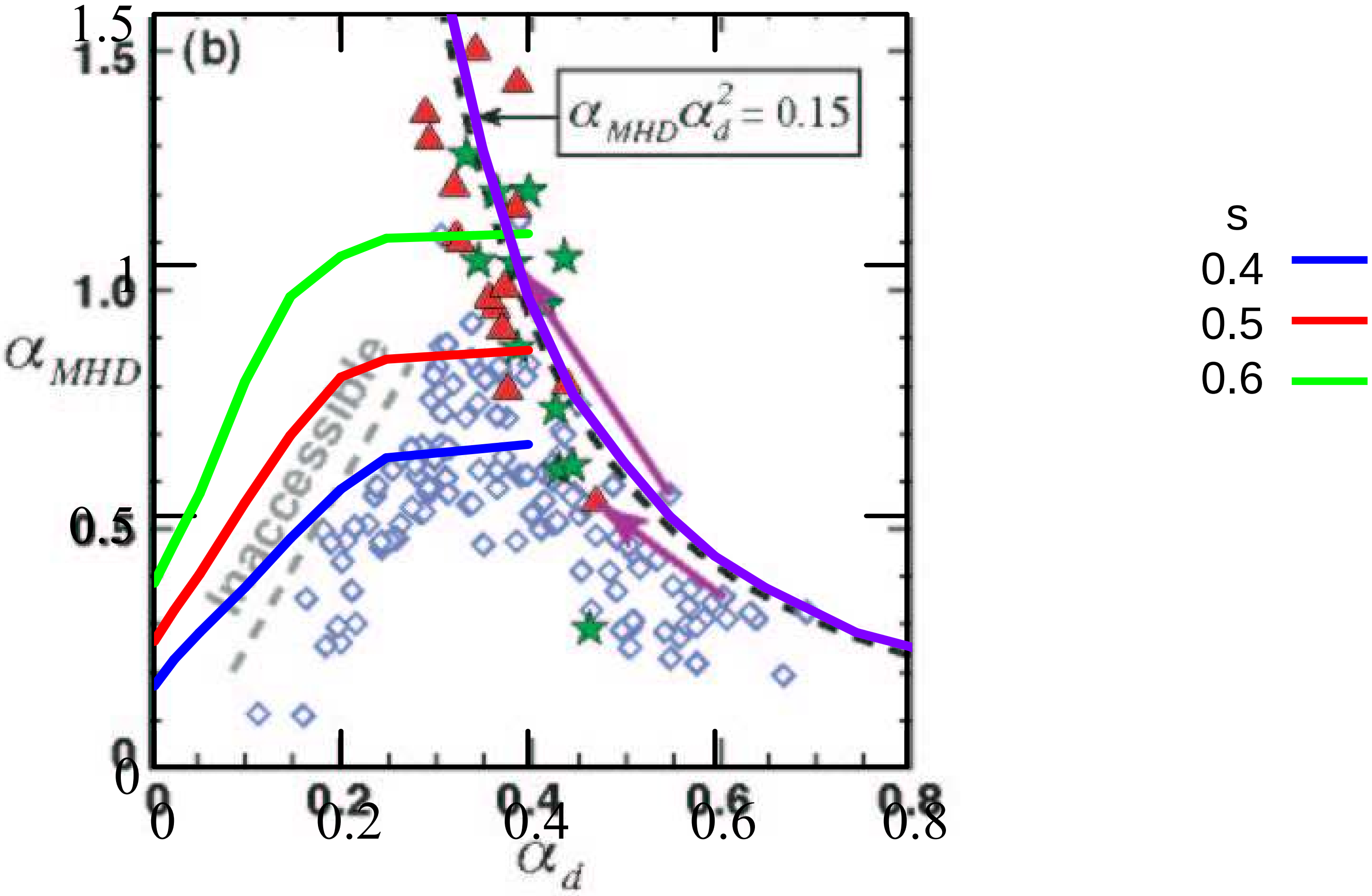
$$\underset{\sim}{A}\vec{V}=\Omega\underset{\sim}{B}\vec{V}$$

Leads to determination of unstable eigenmodes from “all” branches, finite β dissipative drift waves and drift resistive ballooning modes

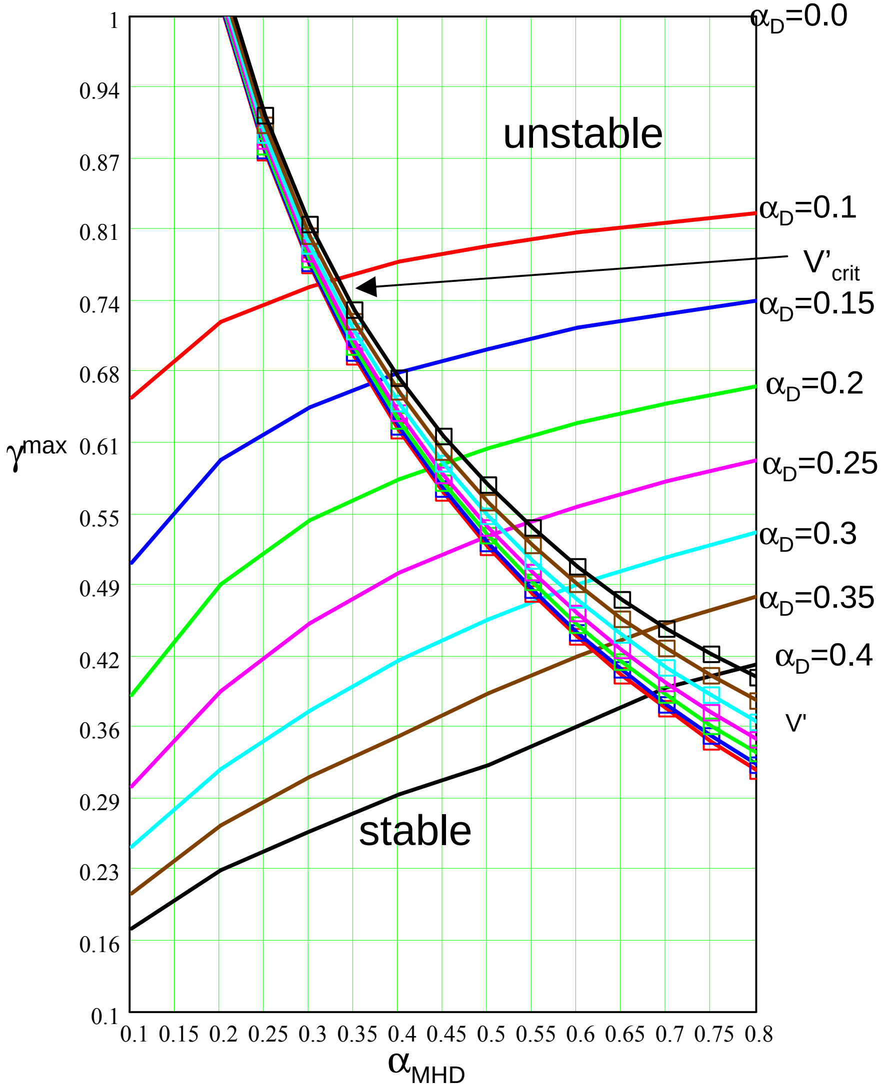
NUMERICAL RESULTS



NUMERICAL RESULTS

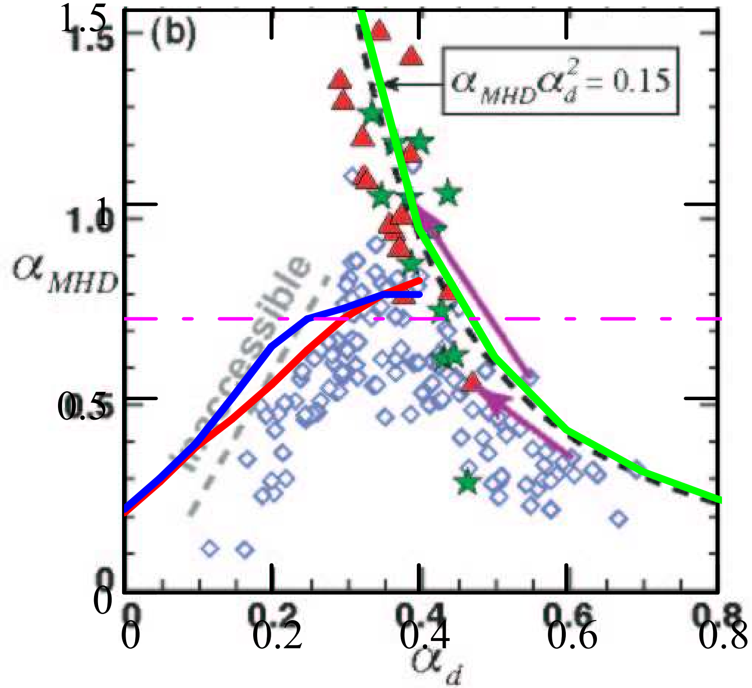


NUMERICAL RESULTS



s=0.5 f=0.0

s=0.5 f=0.5



NUMERICAL RESULTS

"DENSITY LIMIT" CONDITION
NOT GREENWALD LIMIT

From

$$\alpha_{MHD} = 3f(s)\alpha_D \qquad f(s)\sim 1$$

$$\sqrt{n}\,\frac{a^2}{I_p} = 2\,\frac{R^{7/12}L_n^{1/4}f(s)}{B^{1/3}Z_{eff}^{1/6}}$$

$$n(10^{20}/m^3),\ a(m),\ R(m),\ I_p(MA), B(T)$$

CONCLUSIONS

- Investigated stability of zonal flows
- Criterion for inaccessible boundary stable dV/dx < Max(γ_{linear})
- Gives qualitative boundary consistent with observations and Rogers' et al. simulations
- Present model suggests weak magnetic shear in edge for quantitative comparison with C-MOD data

FUTURE WORK

- Improve estimate of stability condition for zonal flow
- Incorporate shaping effects in model for threshold for KH instability of zonal flows and finite beta drift wave/DRBM modes

- Explore the "interaction" region between the stability boundary for KH and LH to identify type of ELMS. ELMS are interplay between ballooning type modes and zonal and/or shear flow
- Extend study to full two dimensional eigenvalue stability of modes with shear to determine stability boundary more accurately
- Explore the connection of the "operational limit" boundary in (α_{MHD}, α_D) space to the Greenwald limit