Observation of tearing mode deceleration and locking in MST due to eddy currents induced in the conducting shell

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Motivation & introduction

-- Mode locking still a problem in the tokamak, RFP... but cause(s) not always known

-- In the MST RFP, observe braking and locking with appearance of single, large m = 1 mode (quasi single helicity spectrum, or QSH)

-- Not due to the usual causes in MST (error field, sawtooth crash, high density)

-- Test model based on torque from eddy currents induced in RFP conducting shell

-- With addition of time dependence, model fits the data quite well

Outline

-- A bit about the MST

-- Experimental braking/locking data

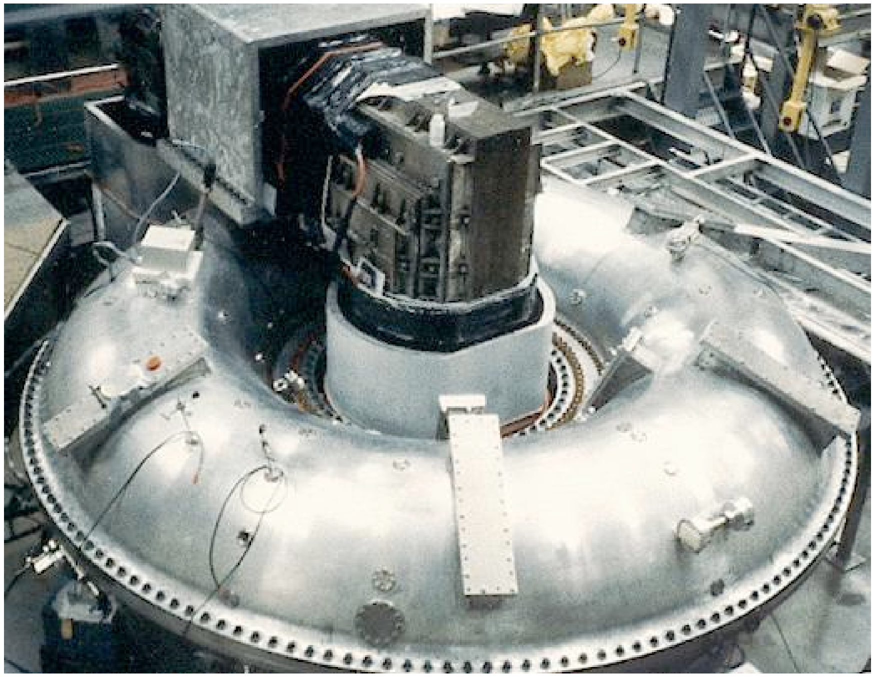
-- Discuss/test pre-established causes of braking

-- Discussion of eddy-current model

-- Application of model to MST data

-- Summary, conclusion

A bit about MST



-- R/a = 150 cm/52 cm

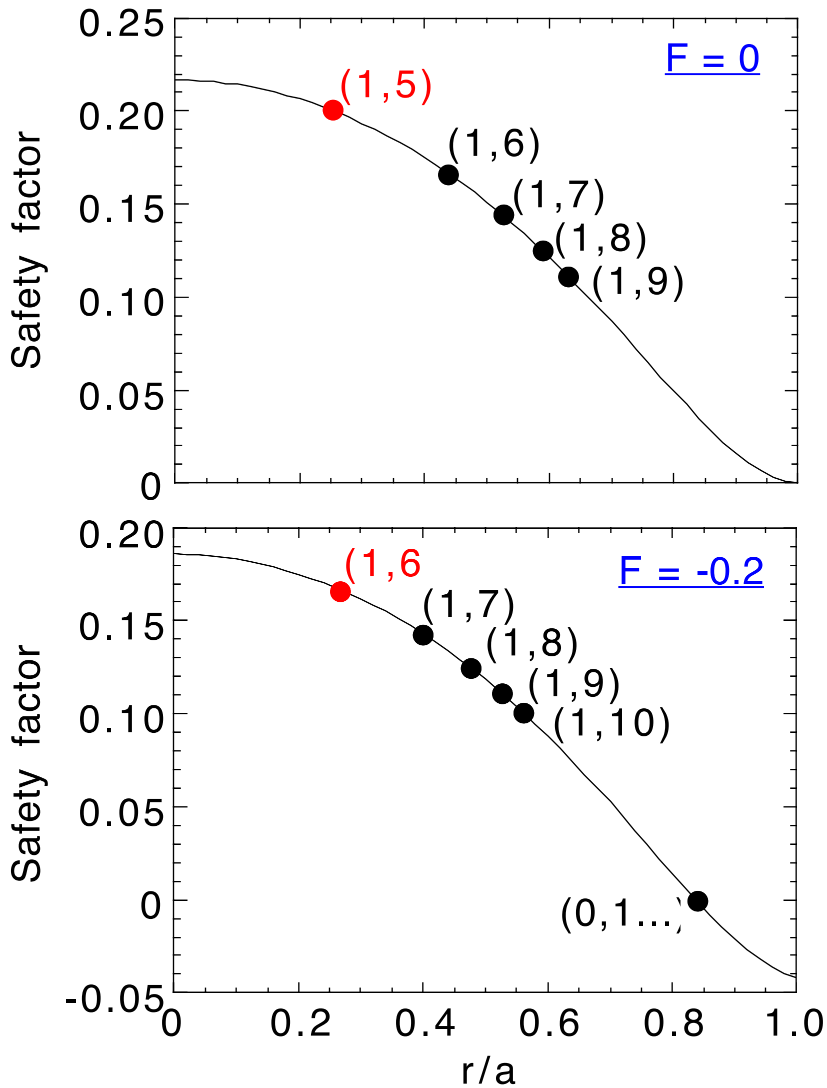
-- Single, close-fitting, 5-cm-thick aluminum shell (1 cm space between plasma and shell)

-- Circular poloidal cross section

-- Amplitude and velocity of tearing modes measured with 32-position sensing coil array

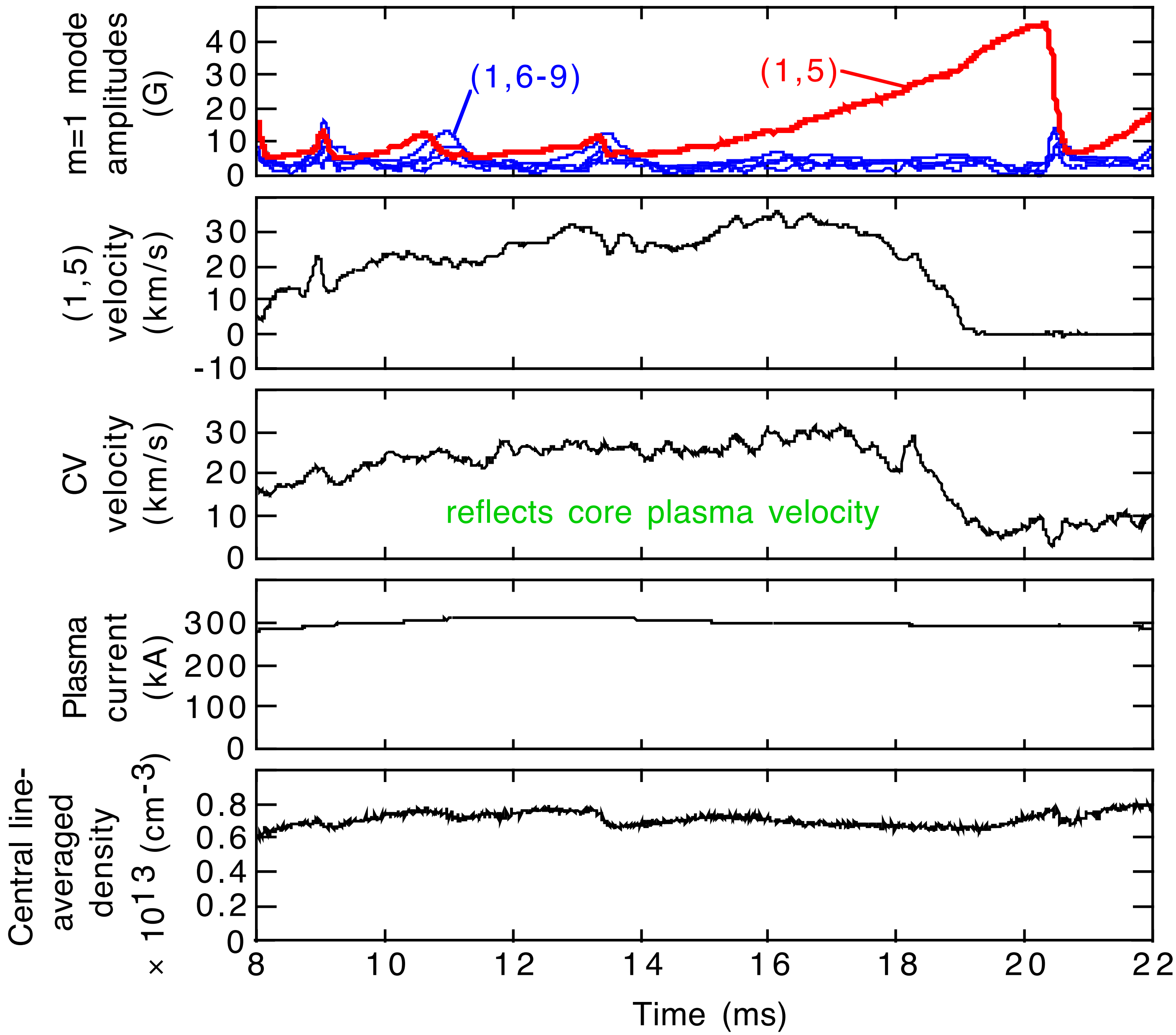
-- Plasma velocity measured with Doppler spectrometer

It is almost always the innermost resonant m = 1 mode that dominates the QSH spectrum in MST

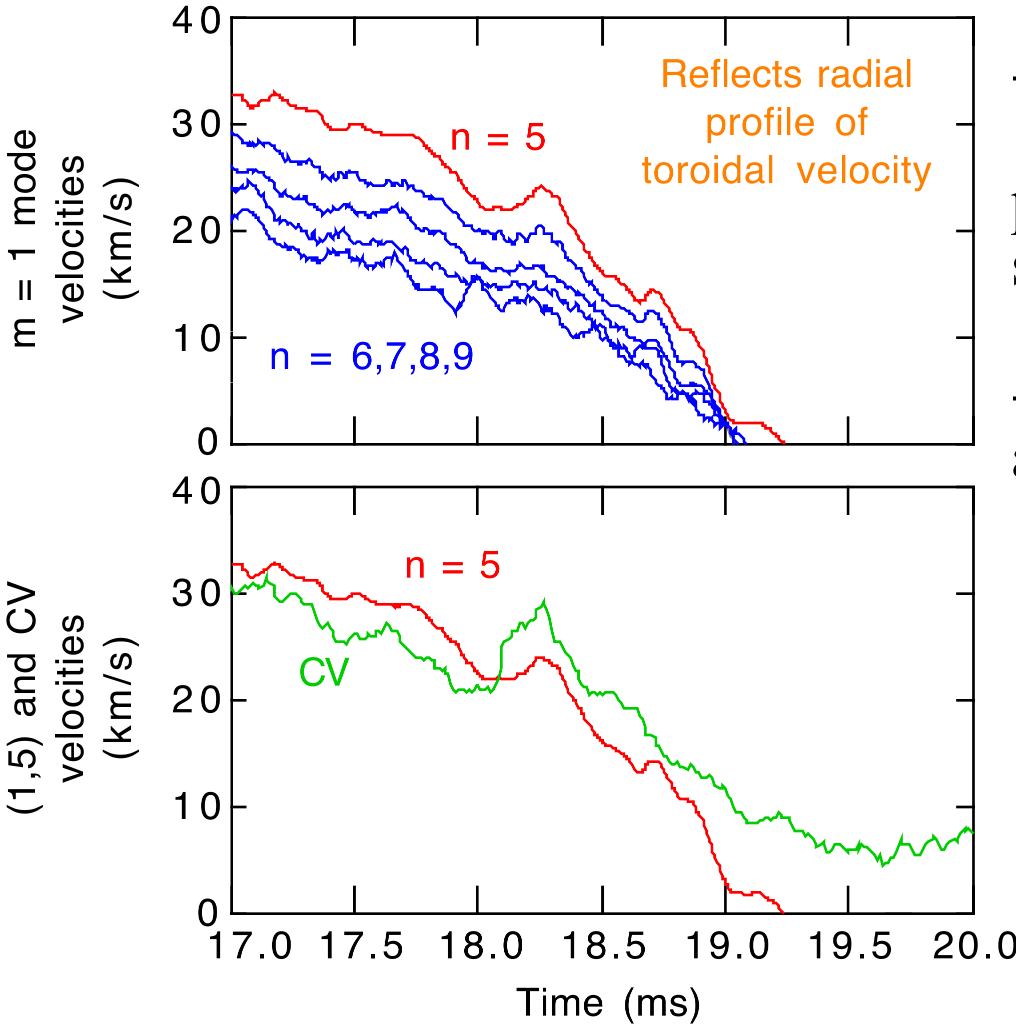


-- F = toroidal magnetic field reversal parameter ≡ $B_\phi(a)/\langle B_\phi \rangle$

Appearance of QSH mode corresponds to braking of QSH mode and bulk plasma



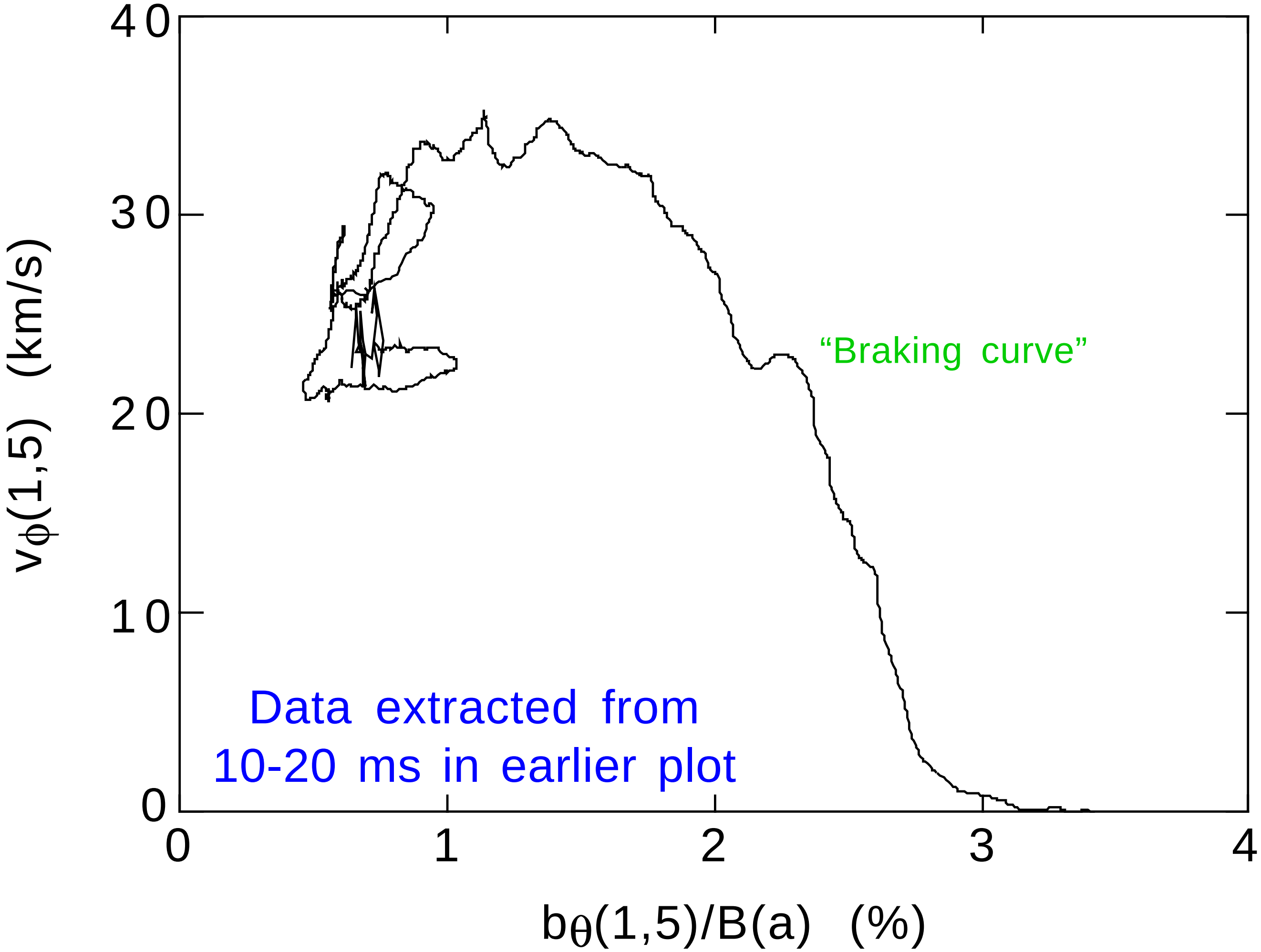
The m = 1, n > n_{QSH} modes also decelerate



-- Deceleration of dominant m = 1 modes consistent with bulk plasma deceleration (overlap in space)

-- Plasma and modes decelerate at about same rate

QSH mode velocity a relatively simple function of QSH mode amplitude when mode amplitude becomes large



Is the braking due to any pre-established causes?

-- $\langle n_e \rangle$ well below usual slow-rotation/locking threshold

-- Sawtooth crashes routinely cause m = 1 mode braking and locking

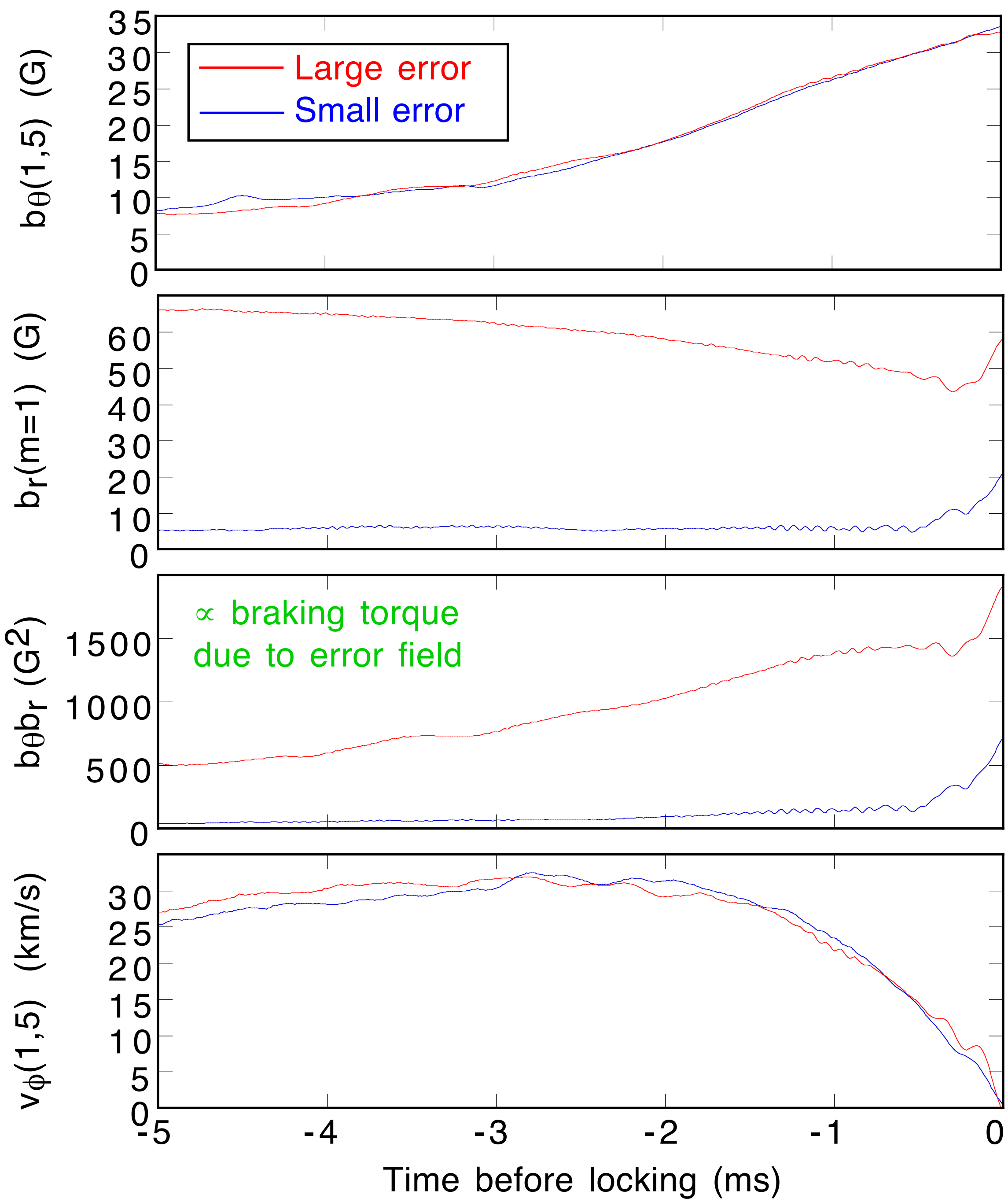
-- But plasmas with crash during QSH braking are excluded

-- What about an error field? --> vertical insulated cut in conducting shell: can be source of significant error field

-- Has been shown that sufficiently large m = 1 error can cause braking and locking in MST

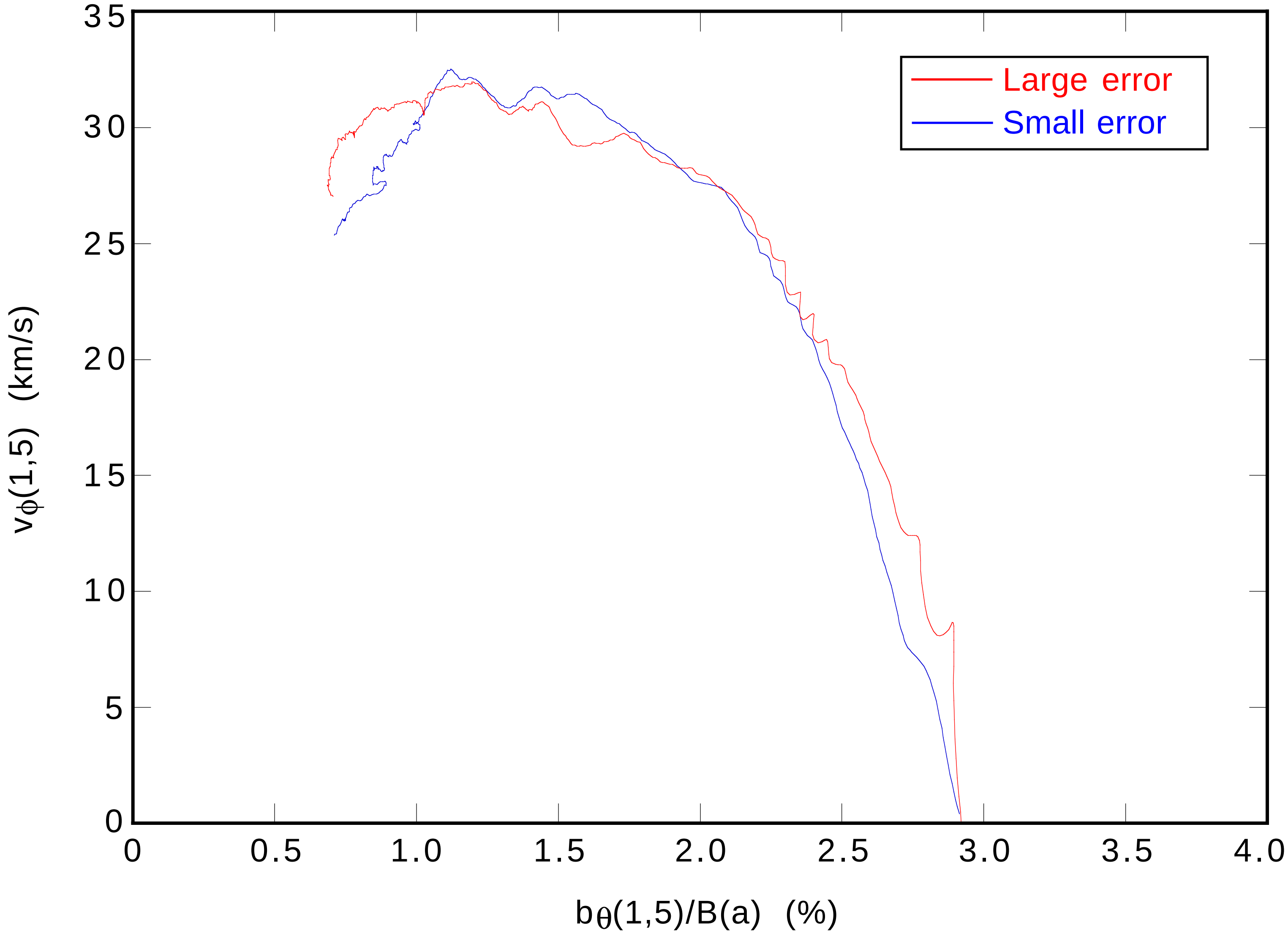
-- Error minimized for this work, but error torque $b_{mode}b_{error}$, and b_{mode} large with QSH

QSH mode amplitude and velocity vary little with large and small m = 1 error fields



-- Shot-ensembled data from F = 0 plasmas with similar current, electron density...

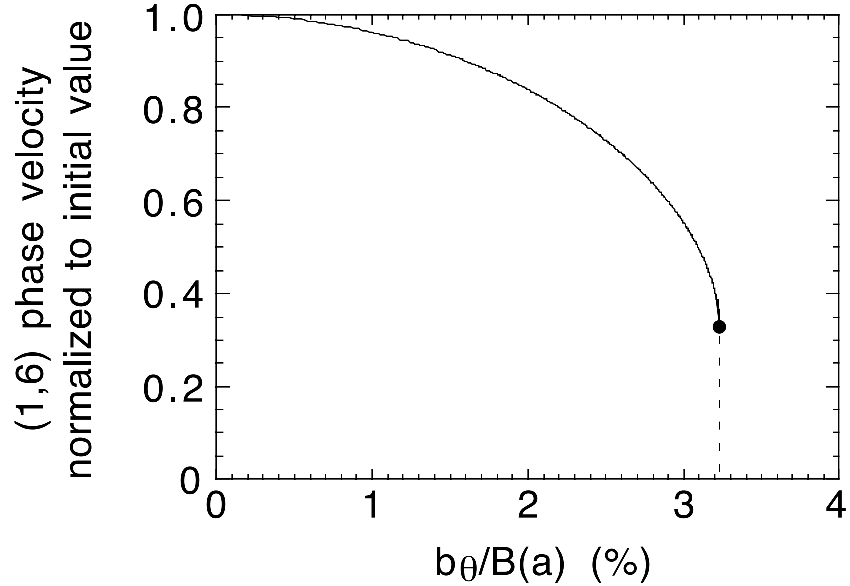
Braking curve not significantly affected by error field variations



-- Locking *was* induced by an error field 50% larger than already shown

Plot in Fitzpatrick *et al*. 1999 paper for RFP suggested eddy currents as source of the QSH braking

-- Predicted time-independent braking curve MST:



-- Roughly similar to expt. braking curves already shown

-- Mechanism formerly thought unlikely to be important in MST due to the large mode amplitude required (QSH is relatively recent phenomenon)

Braking by eddy currents: some previous work

-- Model first proposed to account for locking with single large tearing mode in tokamak and RFP [Nave and Wesson, 1987 & 1990; Hender, Gimblett, and Robinson, 1988 & 1989]

-- Consistency with tokamak [Snipes *et al*., 1988] and RFP [Brunsell *et al*., 1993] expt. data reported

-- Accounted for "forbidden bands" of rotation in a tokamak [Gates and Hender, 1996]

-- Model augmented with inclusion of detailed viscous response for tokamak [Fitzpatrick, 1993] and RFP [Fitzpatrick *et al*., 1999]

-- Mode amplitude locking threshold in RFP's consistent with model [Fitzpatrick *et al*., 1999; Yagi *et al*., 1999 & 2001; Malmberg *et al*., 2000]

-- Model without viscosity did not account for recent tokamak braking data [Hutchinson, 2001]

Basic physics of the model, with viscosity

-- Model details differ for tokamak and RFP, but physics generic:

(1) rotating tearing mode, $\mathbf{b}_{mode}(m,n)$ induces eddy currents in conducting shell

(2) eddy currents cause current sheet, $\mathbf{j}_{sheet}(m,n)$ in vicinity of mode resonant surface

(3) local $\mathbf{j}_{sheet} \times \mathbf{b}_{mode}$ braking torque results

(4) local plasma, mode deceleration countered by viscous restoring torque due to external plasma

(5) with significant viscosity, $\mathbf{j} \times \mathbf{b}$ torque must brake entire plasma to brake and lock mode (m,n)

(6) global viscous momentum diffusion sets time scale for local deceleration

Model describes well the braking dynamics of MST QSH plasmas

-- But only with addition of time dependence

-- Model applied to standard-confinement plasmas (not "PPCD")

-- Plasma core largely stochastic

-- Applied to plasmas with different fuel isotopes, magnetic equilibria, initial mode rotation velocities...

Time-*independent* modeling for MST

-- Changes in b_{mode} occur much more slowly than changes to v_{mode}

-- Some assumptions:

(1) single unstable m = 1 mode
(2) cylindrical geometry, large R/a, zero β
(3) no local plasma-island slippage

-- Calculate $\mathbf{j} \times \mathbf{b}$ torque and balance with viscous restoring torque for each b_{mode}

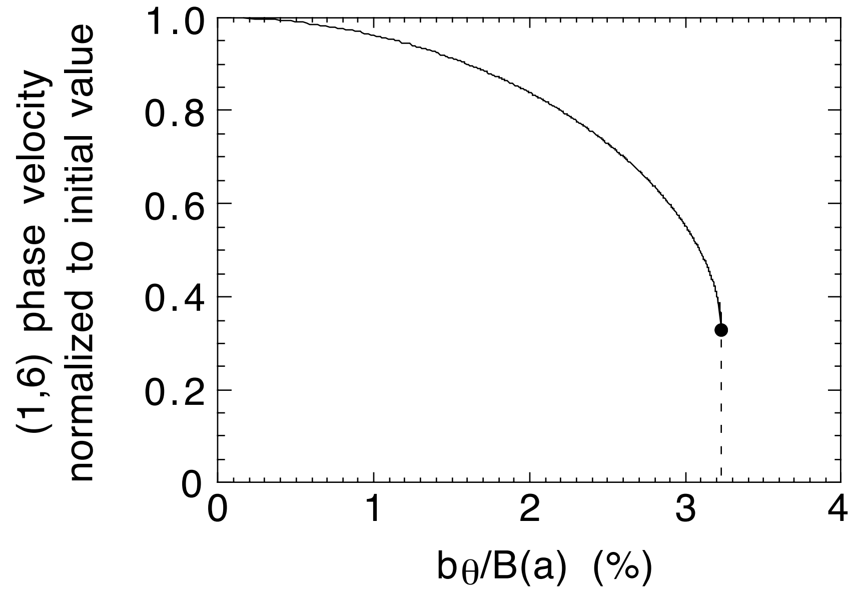
-- Leads ultimately to "braking equation":

$v_{mode} = f(b_{mode},\tau_M,E_{sb},E_{bs},r_s,n,m,m_{ion},n_{e0},v_{mode,0})$

$\tau_M \equiv$ global momentum confinement time $\approx \tau_E$
$E_{sb}\&E_{bs} \equiv$ tearing mode stability parameters
$v_{mode,0} \equiv$ initial ("natural") mode velocity

-- All variables but v_{mode} measured/calculated

Time-independent modeled braking curve for MST



-- Each point on curve is torque-balanced equilibrium

-- At 1/3 of initial velocity, transition to very-slow (effectively no) rotation predicted

Present time-dependent modeling for MST

-- Mode amplitude allowed to change (grow) on same time scale as mode deceleration

-- Same basic physics as time-independent model

-- Assumption of single unstable m = 1 mode valid for QSH plasmas

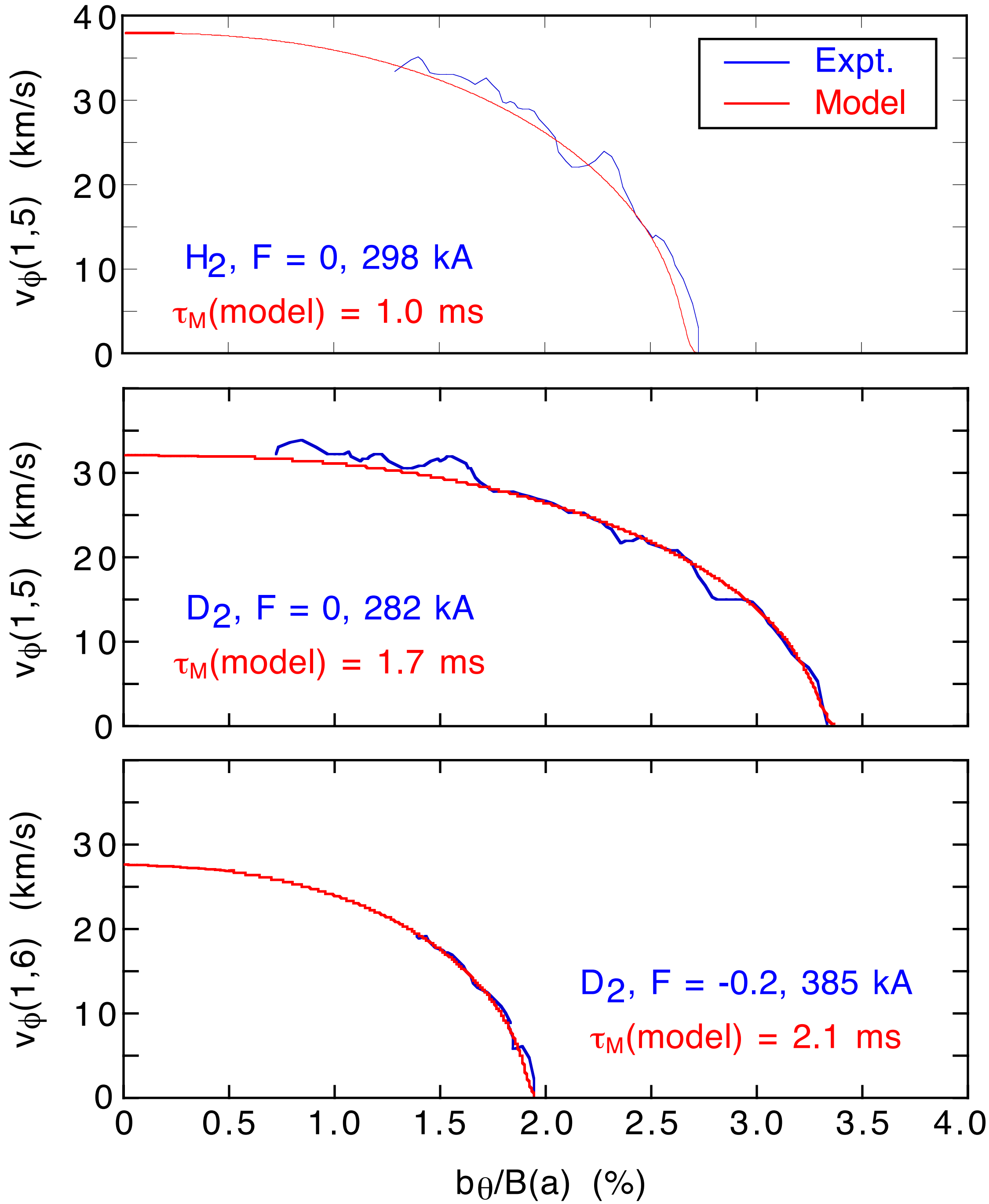
-- **B**(r), $\langle n_e \rangle$... fixed during braking

-- $v_{mode}(t) = f(b_{mode}, \square_M, E_{sb}, E_{bs}, r_s, n, m, m_{ion}, n_{e0}, v_{mode,0})$

-- $\square_M$ now deduced from fit to expt. data

-- $v_{mode}(t)$ predicted by model

Model fits well the expt. mode braking curves

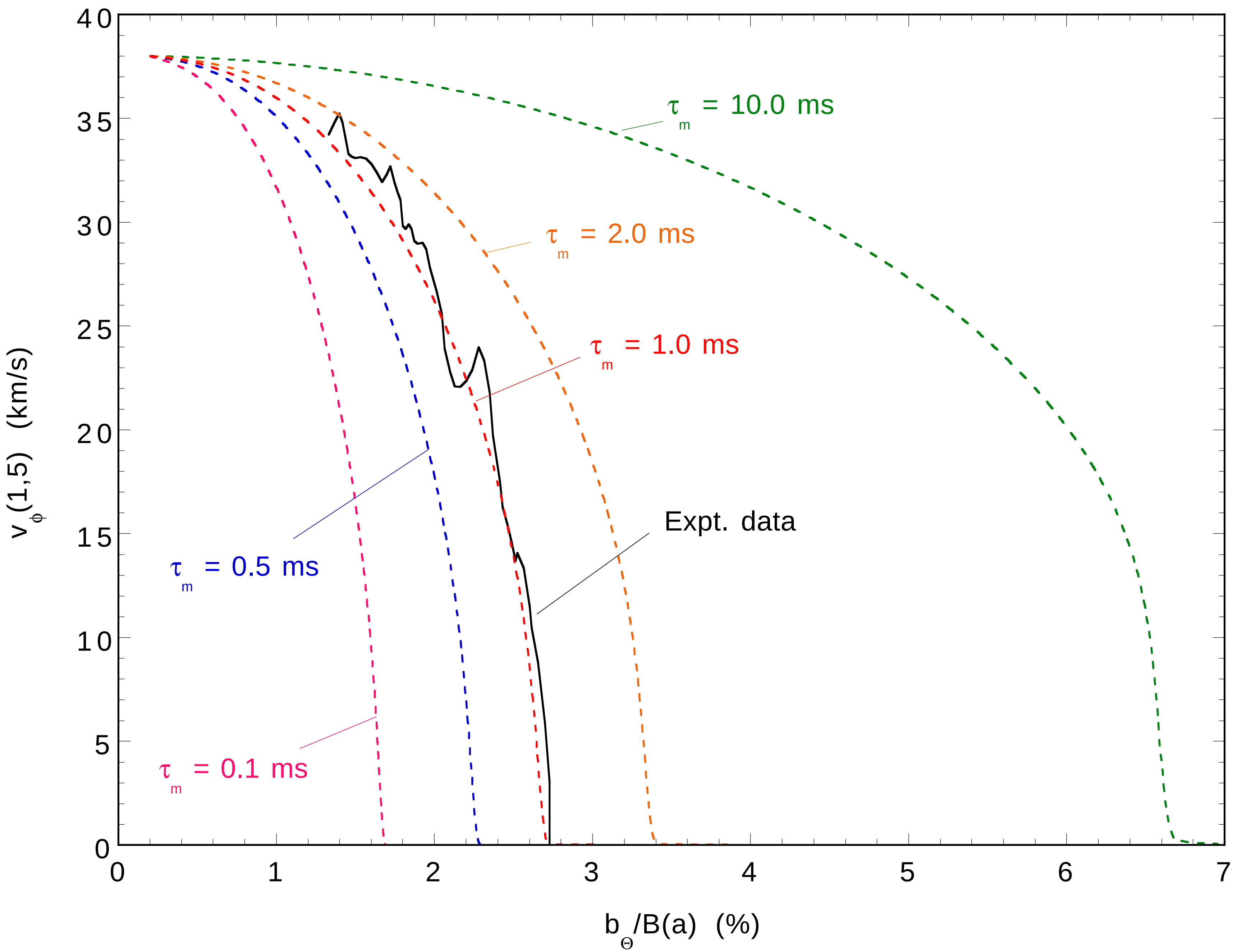


-- Only adjustable parameter in model is τ_M

-- Adjusted such that expt. & model curves coincide at locking

-- Model curves *not* fit to the expt. curves; shape depends on all the other expt. input data

Model prediction of momentum confinement time is well constrained



Modeled τ_M's consistent with experimental data

	Case I	Case II	Case III
Number of shots	6	8	4
Working gas	H_2	D_2	D_2
$F = B_\phi(a)/\langle B_\phi \rangle$	0.0	0.0	-0.2
b/B @ locking (%)	3.3	3.2	1.9
τ_M (ms)	1.3 ± 0.3	1.9 ± 0.4	2.1 ± 0.1

-- Experimentally, $\tau_M \sim 1.5$ ms in standard H_2 MST plasmas (only one measurement thus far)

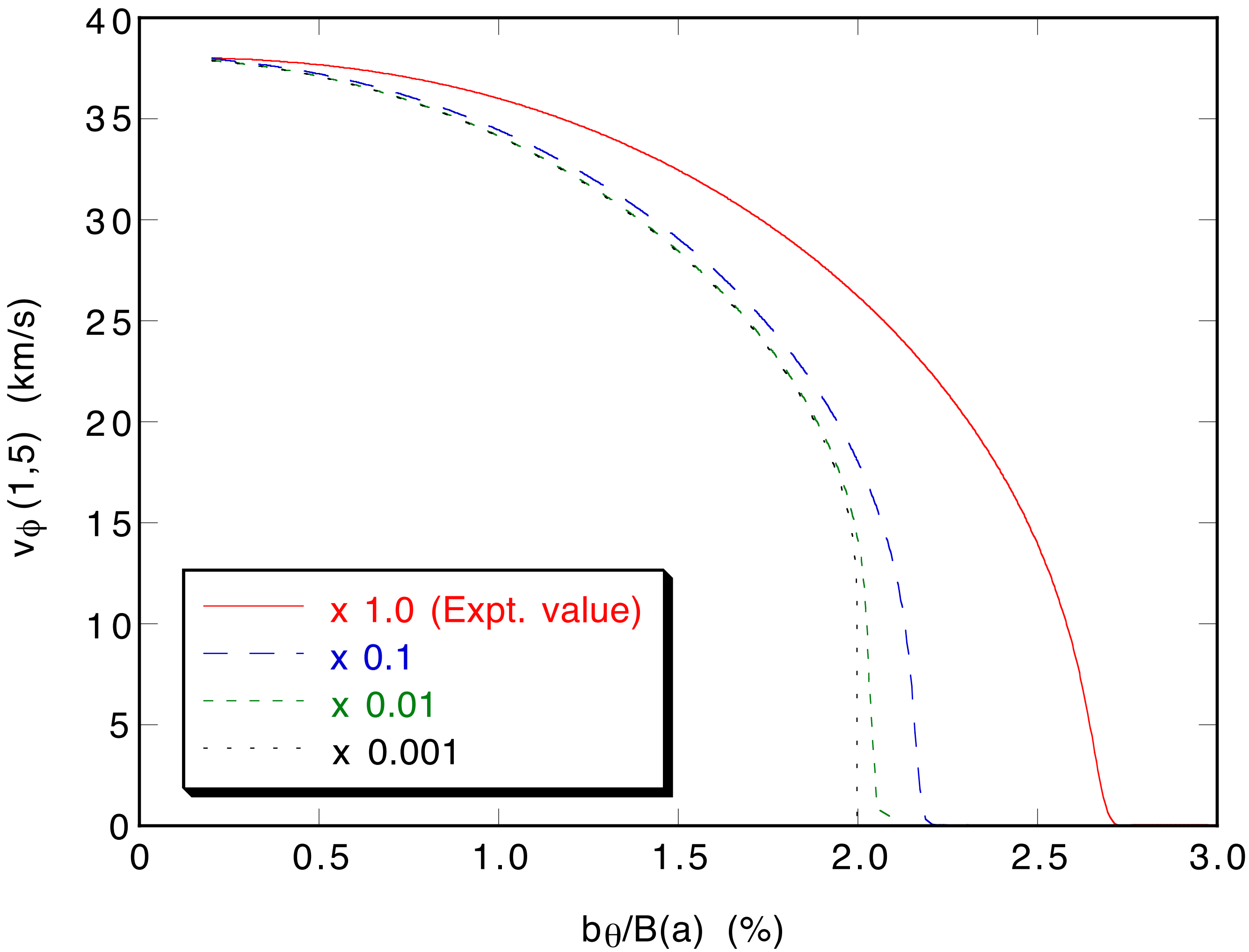
-- τ_E (MST standard plasmas) ranges from 1 - 2 ms over entire range of accessible parameters

-- τ_M expected to behave similarly, as in many tokamaks

-- Modeled $\tau_M(D_2) > \tau_M(H_2)$ also consistent with experimental expectation: larger central neutral density observed with H2, leading to larger CX momentum loss

For given τ_M, (model) braking curve depends on mode growth rate

-- With four different linear growth rates ($b_\theta \sim t$):



-- Slowest growth rate asymptotes to time-independent curve, with discontinuity

-- With experimental growth rate, no discontinuity

Summary & conclusion

-- Growth to large amplitude of m = 1 tearing mode in MST leads to braking and locking

-- Not accounted for by error-field torque

-- Apparently explained by eddy currents induced in MST's conducting shell:

(a) deceleration curve reproduced by the model (including viscosity)

(b) model predictions of momentum confinement time consistent with experimental measurements

-- First time dynamical validation of the model in the RFP

-- One of the more detailed tests of the model in any concept (multiple plasmas, various plasma conditions)

-- Bolsters confidence in the model, generic to the RFP and tokamak

Possible future work

-- QSH plasmas occur over a fairly wide parameter range

-- We hope to, for example,

(a) examine braking in He plasmas, PPCD

(b) measure flow velocity profile (CHERs)

(c) measure/verify internal perturbation from eddy currents

-- Suggestions welcome