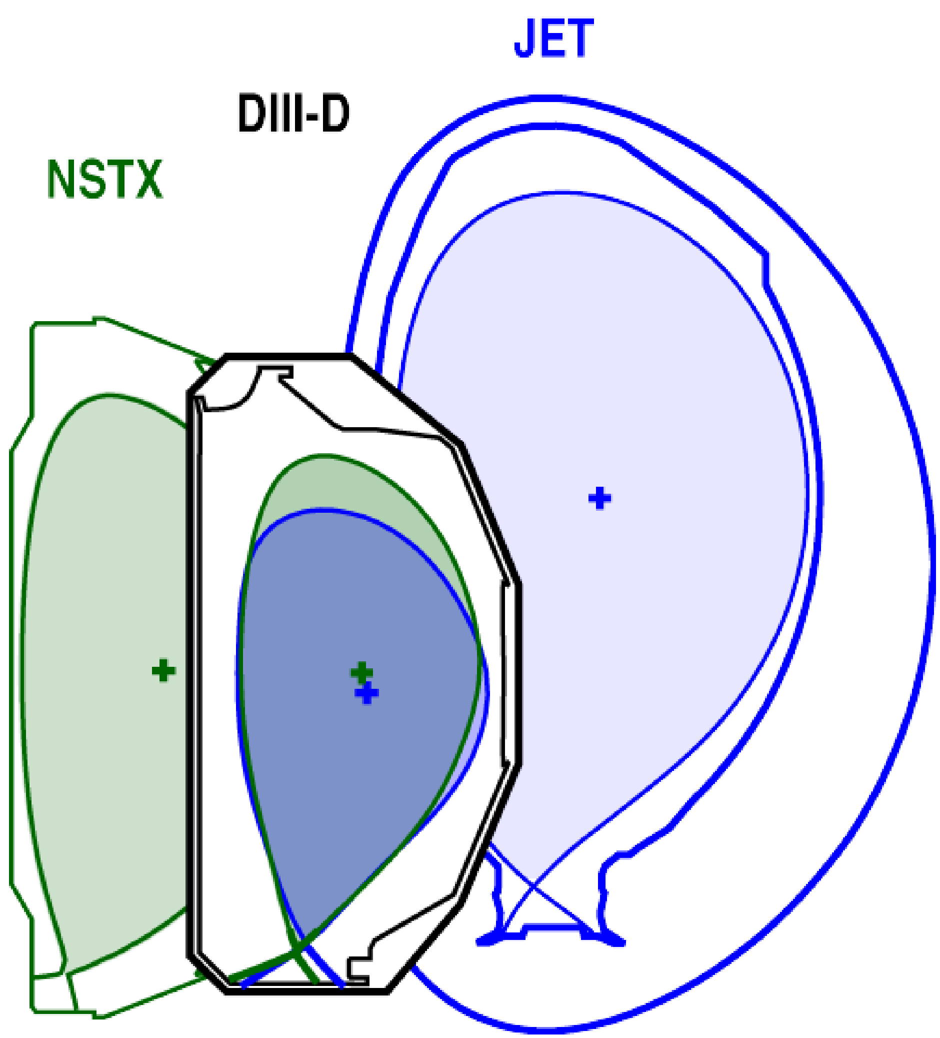
Cross-Machine Comparison of Resonant Field Amplification and Resistive Wall Mode Stabilization by Plasma Rotation

Presented by
H. Reimerdes



Presented at
Forty-Seventh Annual Meeting
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Columbia University

Cross-Machine Comparison of Resonant Field Amplification and Resistive Wall Mode Stabilization by Plasma Rotation

In collaboration with

DIII-D team including

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JET-EFDA contributors including

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NSTX team including

S.A. Sabbagh, J.M. Bialek, J.E. Menard, A.C. Sontag, W. Zhu, D.A. Gates, D. Mueller and R. Raman

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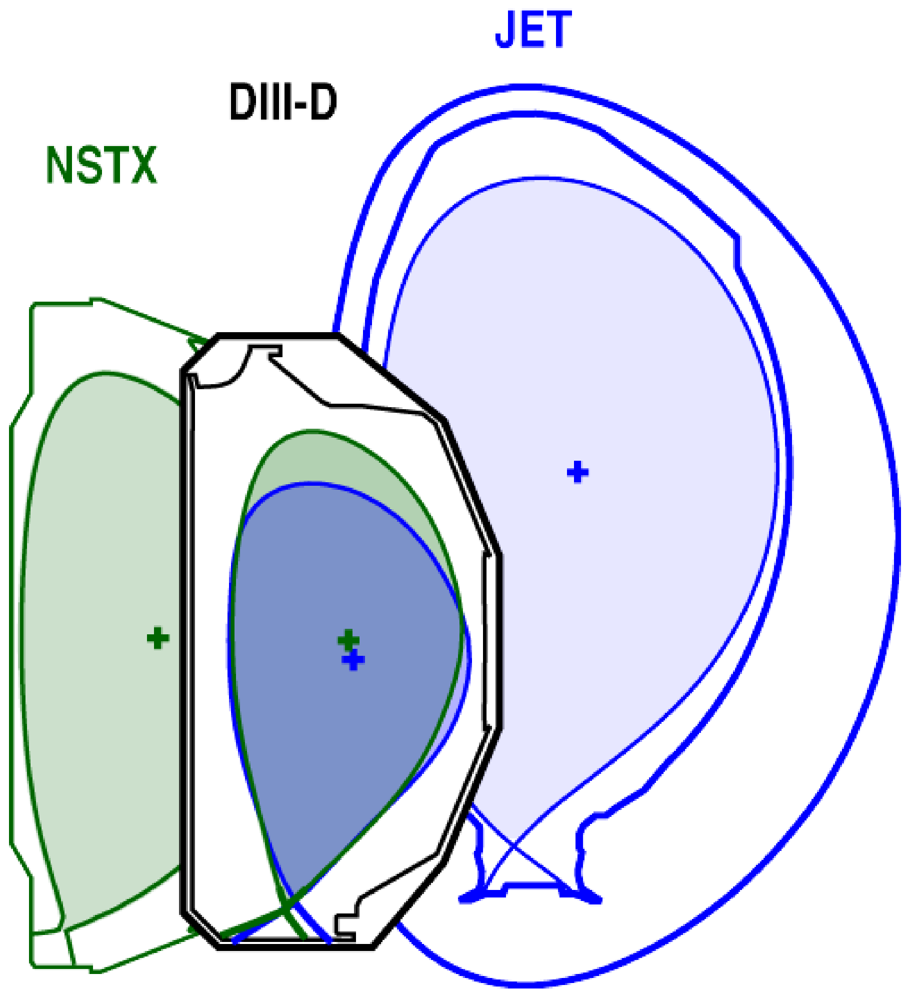
NSTX

Cross-machine comparison establishes universality of resistive wall mode stabilization by plasma rotation

- **Resistive wall mode (RWM) stabilization by plasma rotation has been studied up to high β_N**
  - **NSTX**: $\beta_N \leq 7.3$
  - **DIII-D**: $\beta_N \leq 4.3$
  - **JET**: $\beta_N \leq 3.7$
- **Recent DIII-D experiments demonstrate sustained $\beta_N \sim 4$ with active error field correction**
  - ➜ A.M. Garofalo invited talk, UI2, Friday 9:30AM
- **The devices vary in size and aspect ratio *A=R/a***



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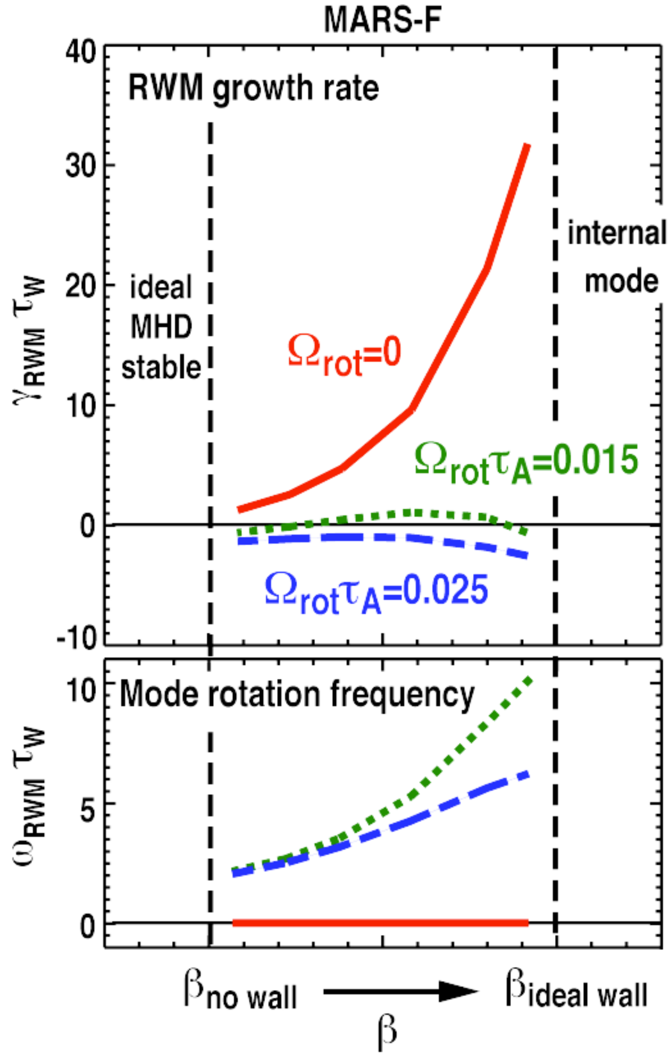
NSTX

Plasma rotation can stabilize RWM up to the ideal wall stability limit

- **Resistive Wall Mode (RWM):**
  - External kink mode whose growth is slowed by magnetic field penetration through the conducting wall
  - Quasi-static perturbation in a fast toroidal plasma flow: $\gamma_{RWM}, \omega_{RWM} \sim \tau_W^{-1} << \Omega_{rot}$
- **Stabilizing effect of plasma rotation first observed in DIII-D** [E.J. Strait et al, PRL 74 (1995)]
  - Stabilization requires a dissipation mechanism [A. Bondeson, D.J. Ward, PRL 72 (1994)]
- **Resonant field amplification (RFA):**
  - Externally applied resonant fields can excite the weakly damped RWM [A.H. Boozer, PRL 86 (2001)]



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Machine-size comparison between DIII-D and JET and aspect ratio comparison between DIII-D and NSTX

- **Machine size comparison: DIII-D and JET vary by a factor of 1.7**
  - Same resonant field amplification (RFA)
  - Same critical plasma rotation for RWM stabilization
    - Importance of q=2 surface for rotational stabilization

- **Aspect ratio comparison: DIII-D and NSTX vary by a factor of 2**
  - Higher critical rotation at low aspect ratio explained by trapped particles not contributing to RWM stabilization
  - Alternatively, the RWM stabilization is determined by the sound wave velocity rather than the Alfvén velocity

- **Target plasmas designed for a large difference between no wall and ideal wall β limits rather than maximum β_N**

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Match parameters for the RWM drive and for the dissipation mechanism

- **Obtain the same external kink mode by matching the ideal MHD properties of the plasma:** shape, q-profile, pressure profile

- **Express RWM drive by the normalized gain in β**

$$C_\beta = \frac{\beta - \beta_{no\ wall}}{\beta_{ideal\ wall} - \beta_{no\ wall}} = \begin{cases} 0 \text{ at no wall limit} \\ 1 \text{ at ideal wall limit} \end{cases}$$

- **Stabilization models:**
  - ***Sound wave damping***: Fluid approximation, where RWM couples to sound waves, which are then ion Landau damped, described via a parallel viscous force
  - ***Kinetic* description** of inertia enhancement and ion Landau damping

➜ **Normalize plasma rotation frequency with inverse of Alfvén time**

$$\tau_A = R_0 \frac{\sqrt{\mu_0 n_e m_i}}{B_0}$$

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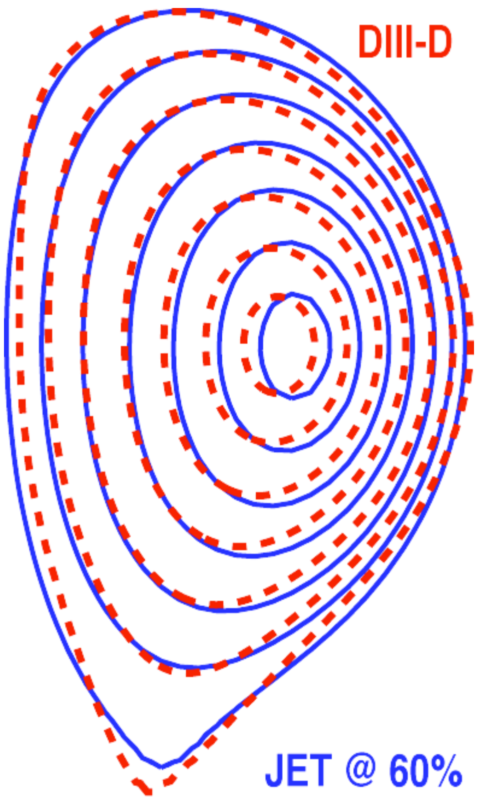
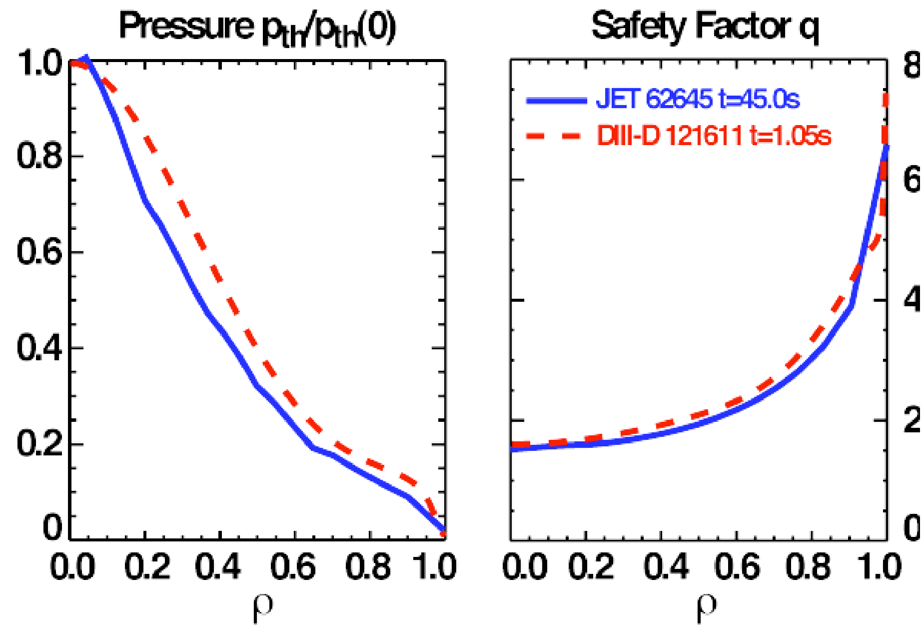
Matching shape and profiles leads to same ideal MHD no-wall stability limit in DIII-D and JET plasmas





- **ELMy H-mode target plasma**
  - $q_0 \approx 1.5$
  - q_{95} = 3.3 - 5.0
  - $\ell_i \approx$ 0.7 (DIII-D) / 0.95 (JET)

- **Ideal MHD no-wall stability limit:** – $\beta_{N,\text{no wall}} \sim 2.8\ \ell_i$ **in DIII-D and JET**

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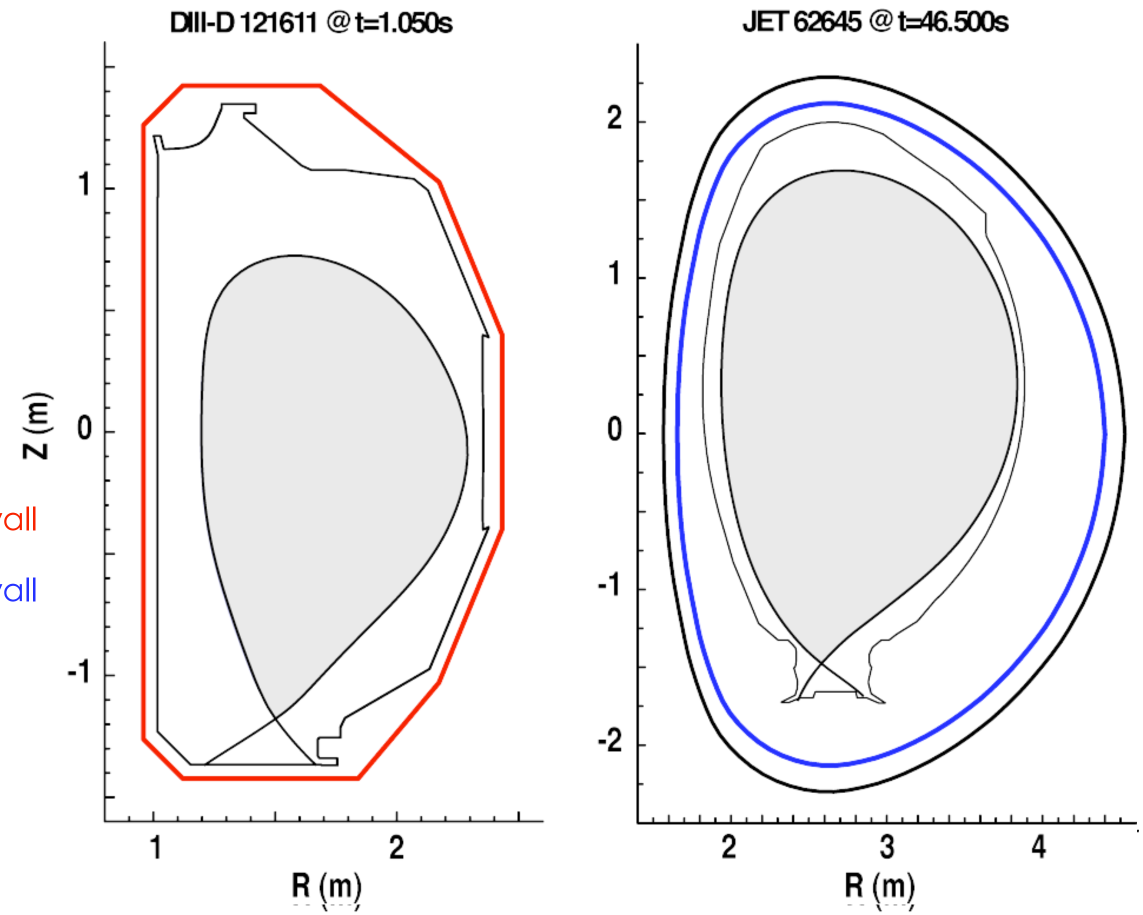
Wall-stabilized regime in DIII-D and JET varies due to different ℓ_i and wall geometry

- **No wall stability limit**
  DIII-D: $\beta_{N,no\ wall} \approx 2.0$
  JET: $\beta_{N,no\ wall} \approx 2.7$

- **Ideal wall stability limit**
  DIII-D: $\beta_{N,ideal\ wall} \approx 1.5\ \beta_{N,no\ wall}$
  JET: $\beta_{N,ideal\ wall} \approx 1.3\ \beta_{N,no\ wall}$



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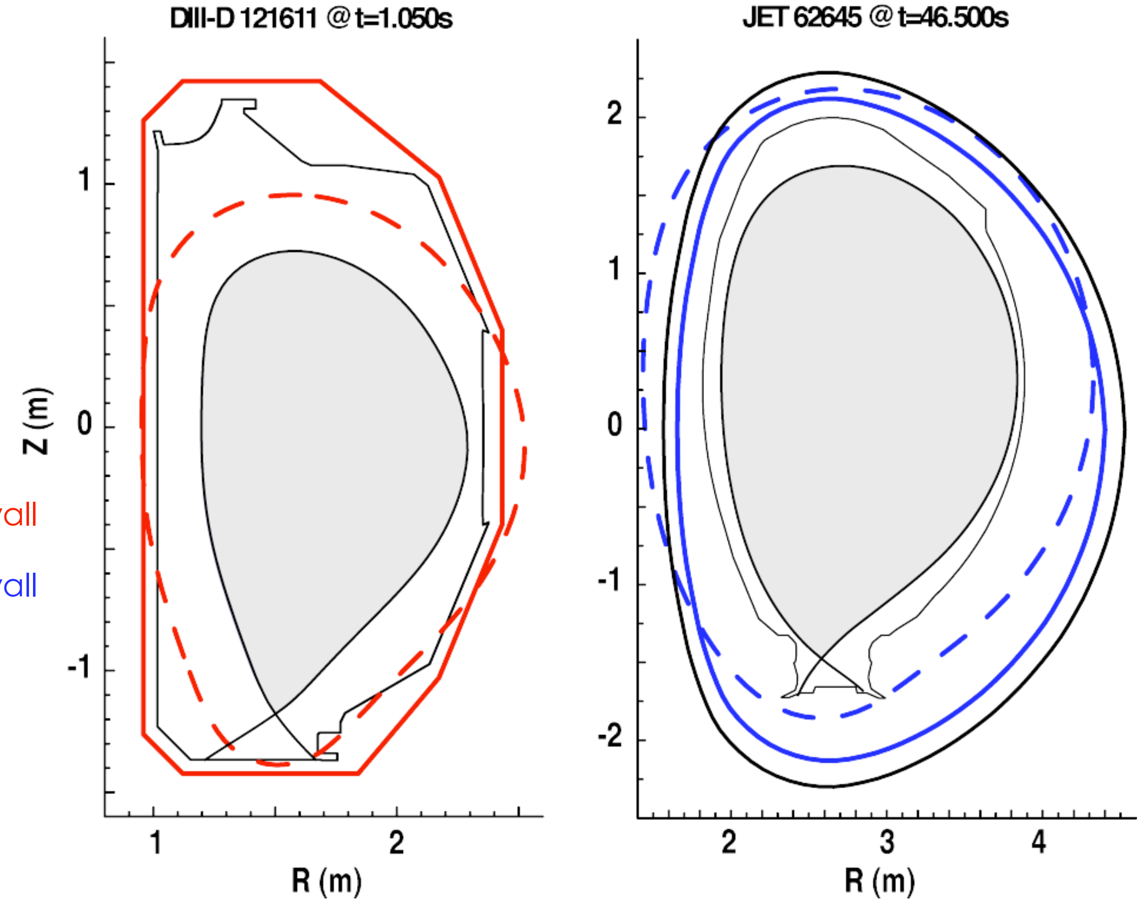

- **Effective conformal wall:** $d_c \approx 0.45a$ (DIII-D) $d_c \approx 0.55a$ (JET)

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DIII-D and NSTX develop common target with a substantial wall-stabilized regime

- **Profiles are not well matched due to aspect ratio effects**

- **No wall stability limit**

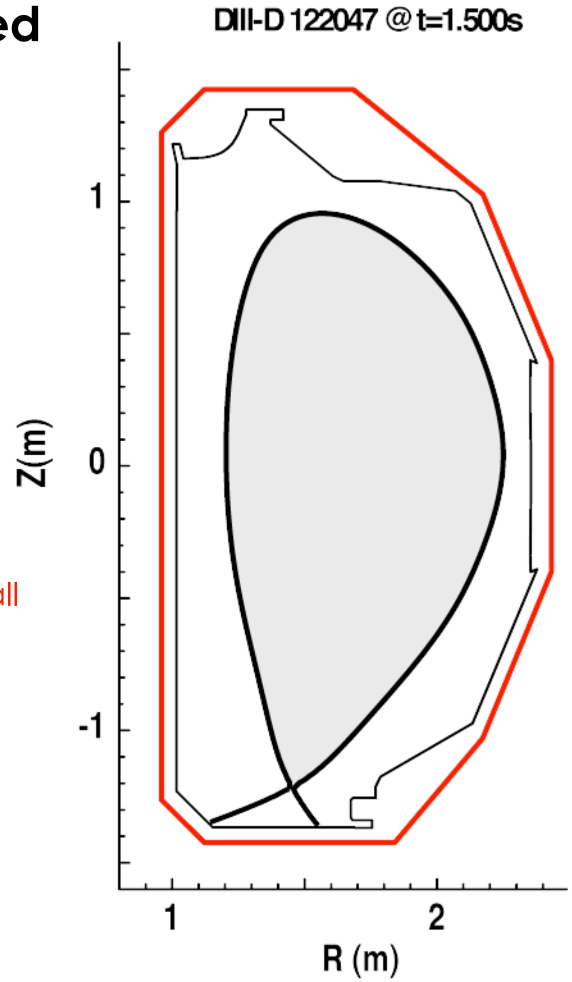
  DIII-D: $\beta_{N,no\ wall} \approx 2.0$

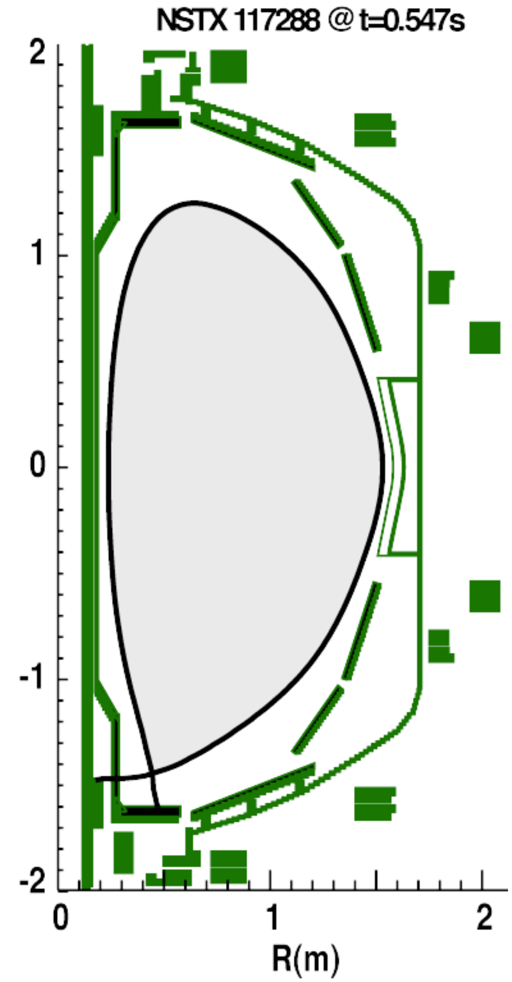
  NSTX: $\beta_{N,no\ wall} \approx 4.0\text{-}4.8$

- **Ideal wall stability limit**

  DIII-D: $\beta_{N,ideal\ wall} \approx 1.5\ \beta_{N,no\ wall}$

  NSTX: $\beta_{N,ideal\ wall} \approx 1.3\text{ -}1.5\ \beta_{N,\ no\ wall}$





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DIII-D and NSTX develop common target with a substantial wall-stabilized regime

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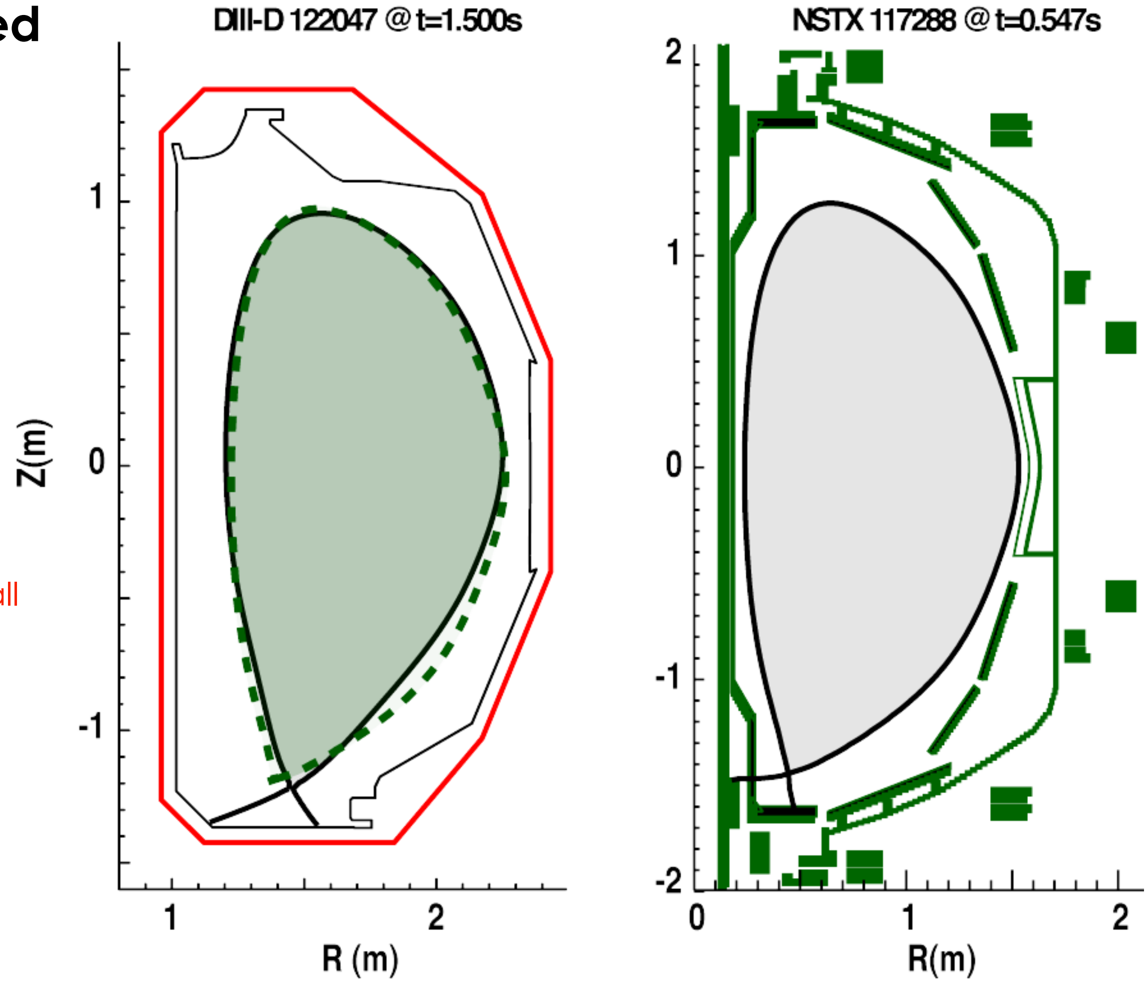

Machine-size comparison between DIII-D and JET and aspect ratio comparison between DIII-D and NSTX

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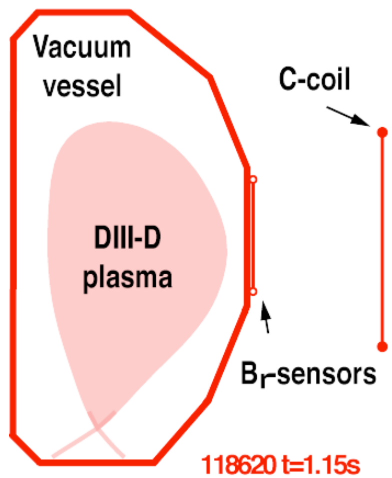
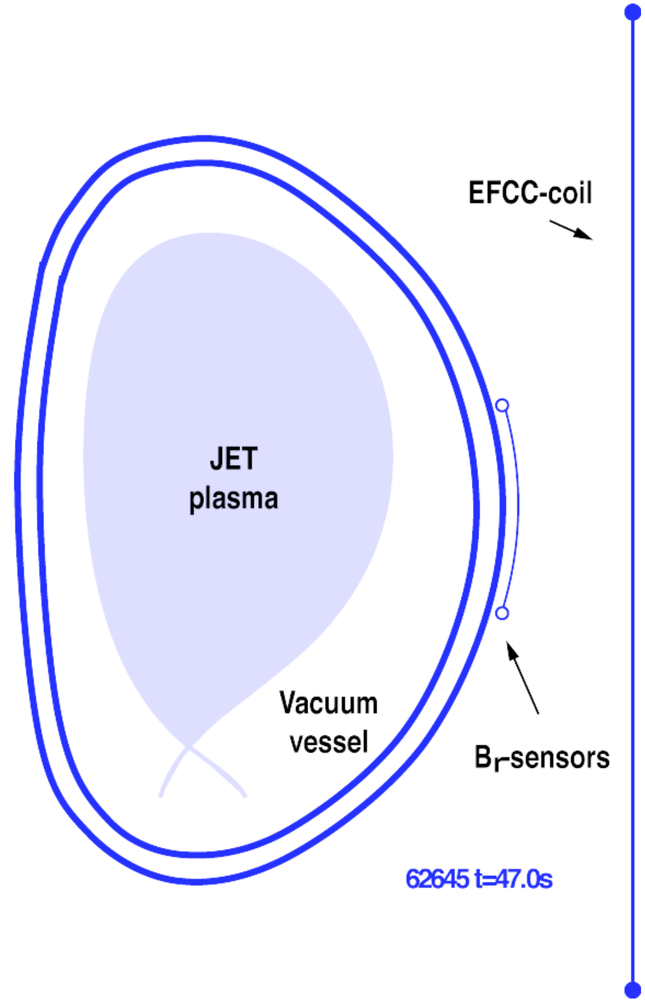
DIII-D and JET plasmas probed using non-axisymmetric external control coils with similar geometry

- Apply resonant field pulses B^{ext} with one pair of external control coils (predominantly n=1)
- Detect plasma response B^{plas} with toroidal arrays of B_r sensors





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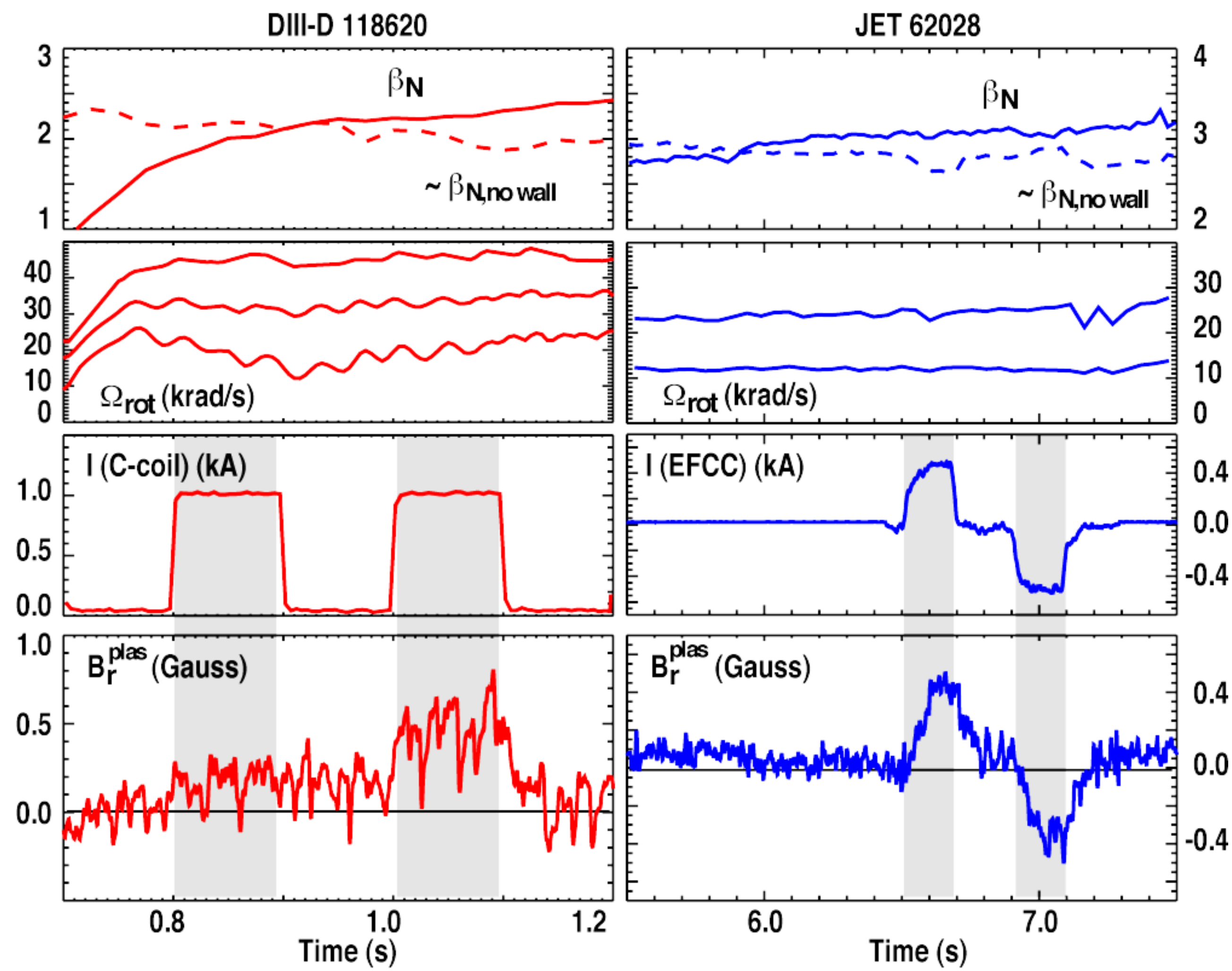
High-β plasmas respond to externally applied *n*=1 perturbations

- Beta exceeds no-wall limit
- Plasma rotation provides RWM stabilization
- Probe plasma with externally applied *n*=1 field
- RFA leads to plasma response detected at the (toroidal) node of the applied field



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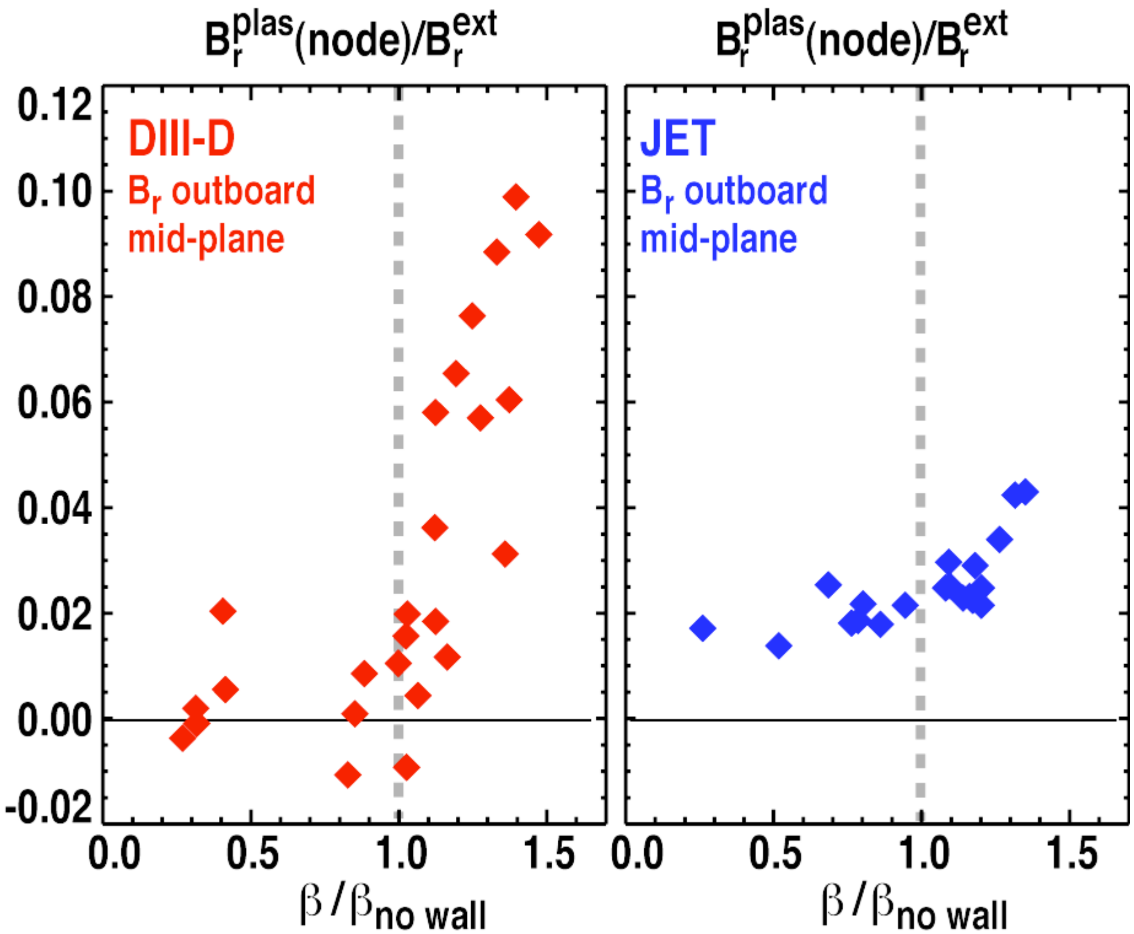
RFA in DIII-D and JET increase significantly once β exceeds no wall stability limit

- **Increase of RFA for $\beta > \beta_{no\text{-}wall}$ consistent with previous observations in DIII-D and NSTX** [A.C. Sontag et al, Phys. Plasmas (2005)]
  - Low β response in JET differs from DIII-D

- **Measured amplification in DIII-D twice as large as in JET**



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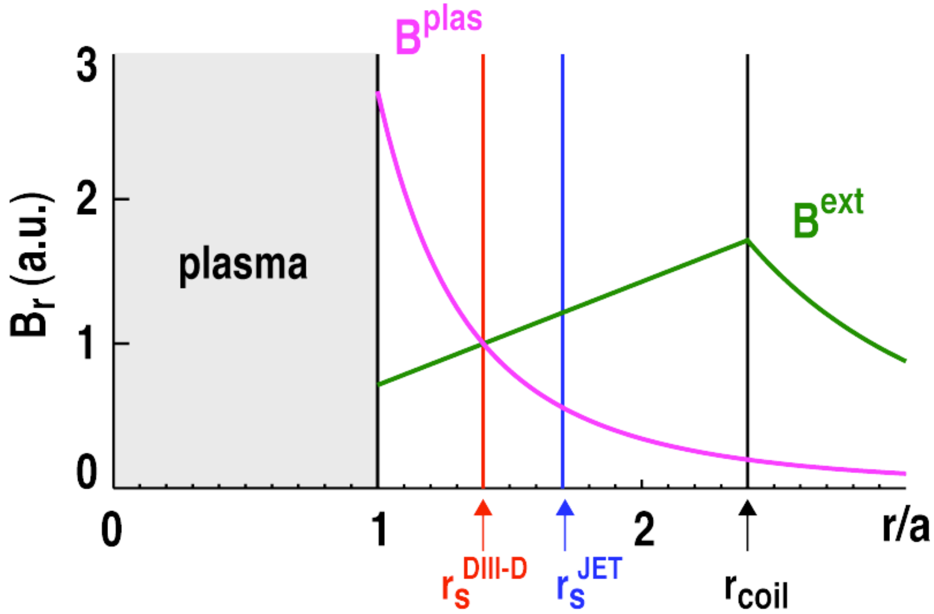
Comparison of RFA measurements has to account for geometry of magnetic fields and sensor locations

- **Similar geometry of applied fields in DIII-D and JET**
- **Similar geometry of plasma perturbation in DIII-D and JET**
- **Radial decay of external field and plasma response cause radial dependence of B^{plas}/B^{ext}**
  - Cylindrical approximation

$$\frac{B_a^{plas}/B_a^{ext}}{B_s^{plas}/B_s^{ext}} = (r_s/a)^{2m}$$

  - Assume effective poloidal mode number m=2 at outboard midplane



	DIII-D	JET
a (m)	0.54	0.95
r_s (m)	0.74	1.61
$(r_s/a)^4$	**3.5**	**8.25**

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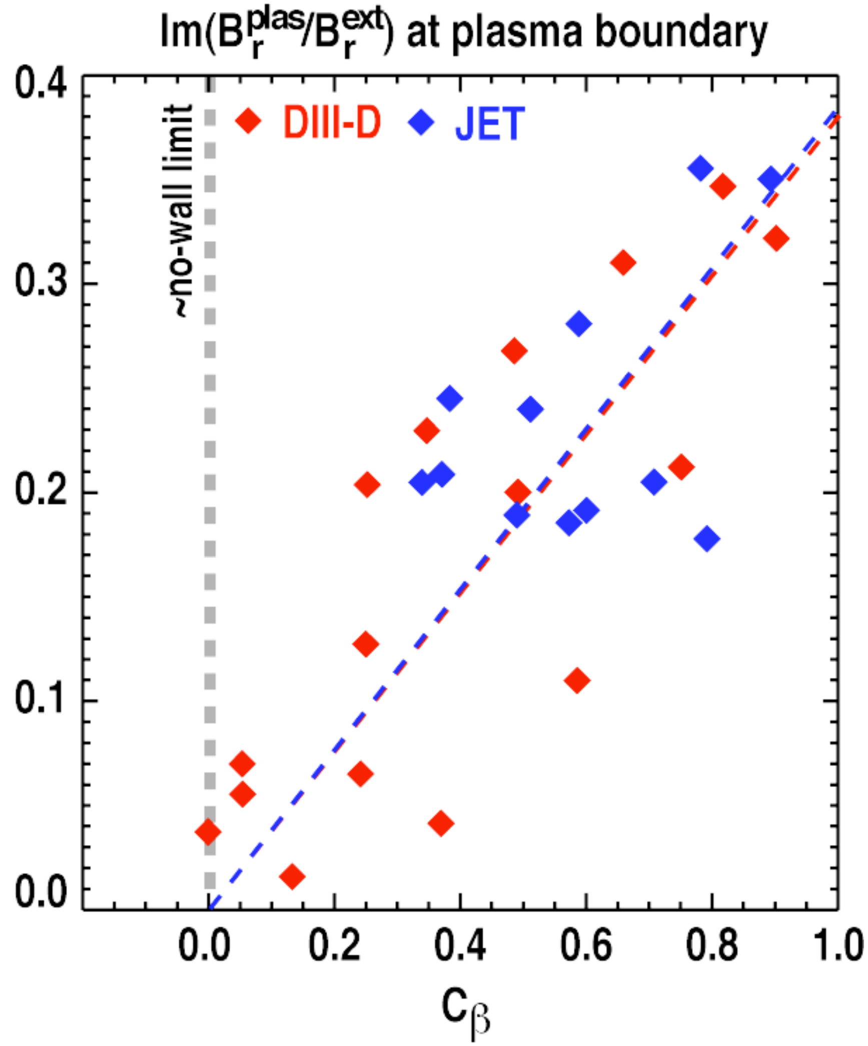
RFA magnitudes at the plasma boundary in DIII-D and JET are in quantitative agreement

- **Map RFA to the same location, e.g. plasma boundary**
- **RWM drive described by normalized gain over no wall limit C_β**



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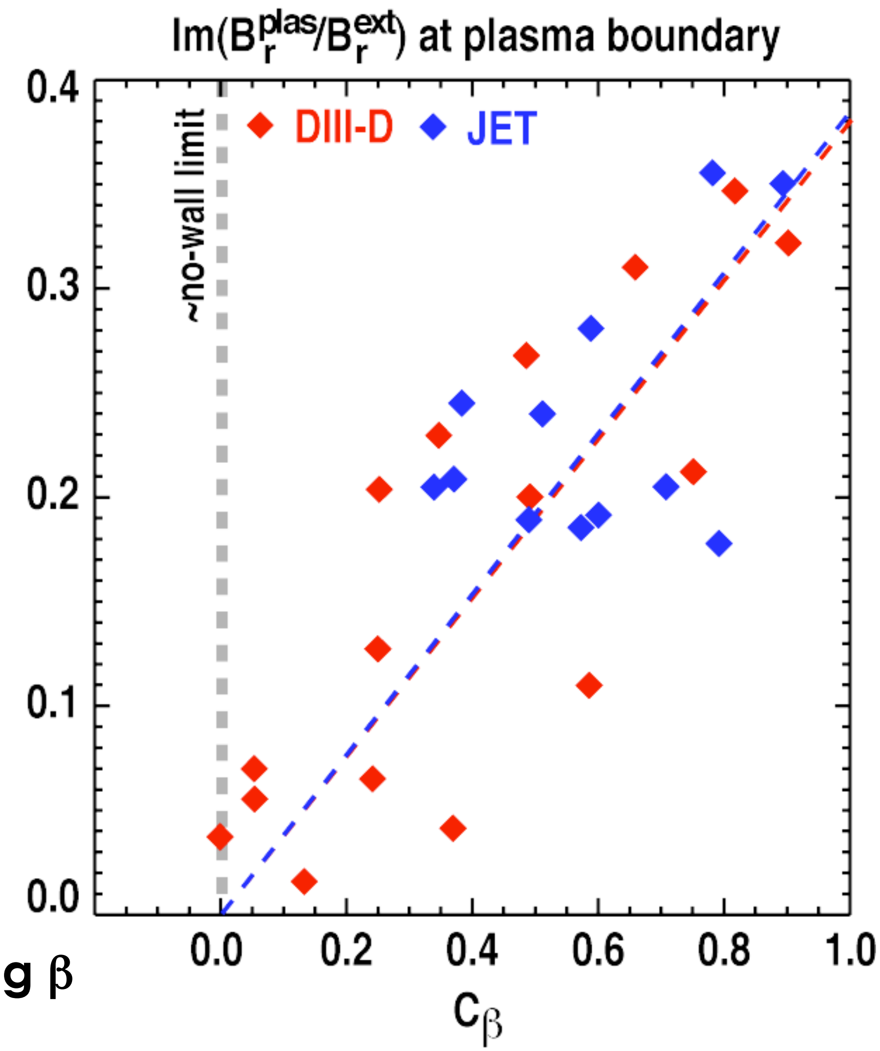
RFA magnitudes at the plasma boundary in DIII-D and JET are in quantitative agreement

- **Map RFA to the same location, e.g. plasma boundary**
- **RWM drive described by normalized gain over no wall limit C_β**
- **Link quantitative agreement of RFA to RWM damping rate $-\gamma_{RWM}$**

$$\frac{B_s^{plas}\,(\text{node})}{\left|B_s^{ext}\right|} \propto \frac{\omega_{RWM}\tau_W}{\left(\gamma_{RWM}\tau_W\right)^2 + \left(\omega_{RWM}\tau_W\right)^2}$$

➜ **RWM in DIII-D and JET equally damped by plasma rotation**

➜ **Weaker RWM damping with increasing β**



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Machine-size comparison between DIII-D and JET and aspect ratio comparison between DIII-D and NSTX

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Braking of plasma rotation needed for RWM onset

- **NBI torque in NSTX, DIII-D and JET is usually provides sufficient rotation for RWM stabilization**
- **Increase drag by applying non-axisymmetric fields**
  - Neoclassical toroidal viscosity (NTV)
    [Shaing, Phys. Plasmas 10, 1443 (2003)] : $T_{NTV} \propto (\delta B/B)^2$
- **Non-linear RWM onset**
  - Magnetic braking: $\frac{d}{dt}\Omega_{rot} \propto \delta B^2$
  - RWM dispersion relation: $\gamma_{RWM}\tau_W = f(\Omega_{rot})$
  - Evolution of perturbed field (RFA and RWM): $\tau_W\left(\frac{d}{dt}\delta B - \gamma_{RWM}\delta B\right) = \delta B^{ext}$

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Magnetic braking leads to non-linear RWM onset

- Apply *n*=1 field

- Plasma rotation decreases

- Onset of fast growth is preceded by increasing RFA

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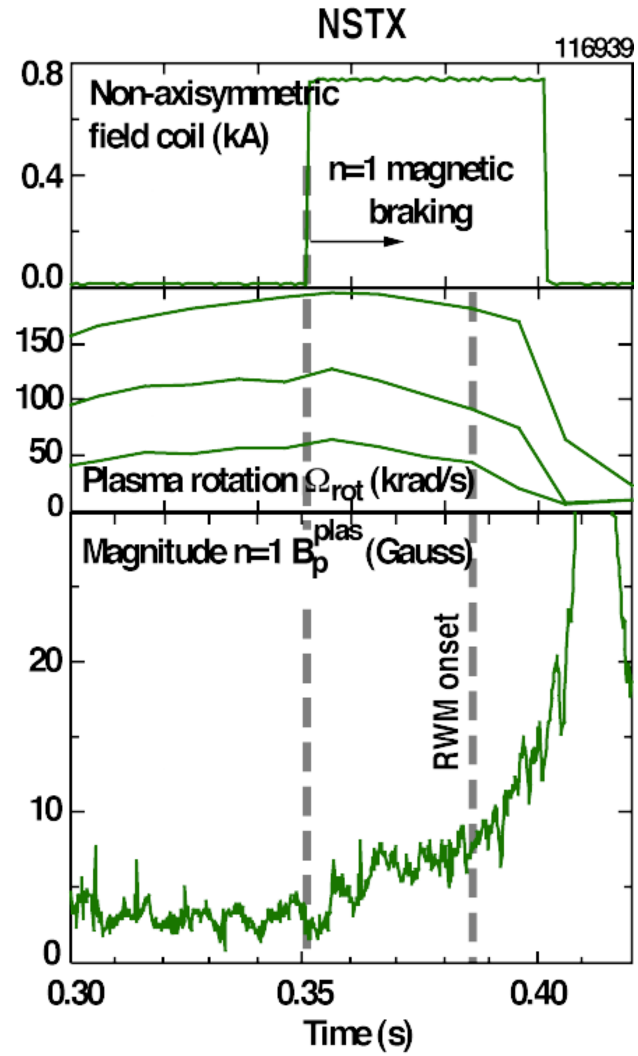
- Critical rotation Ω_{crit} measured at onset of fast growth



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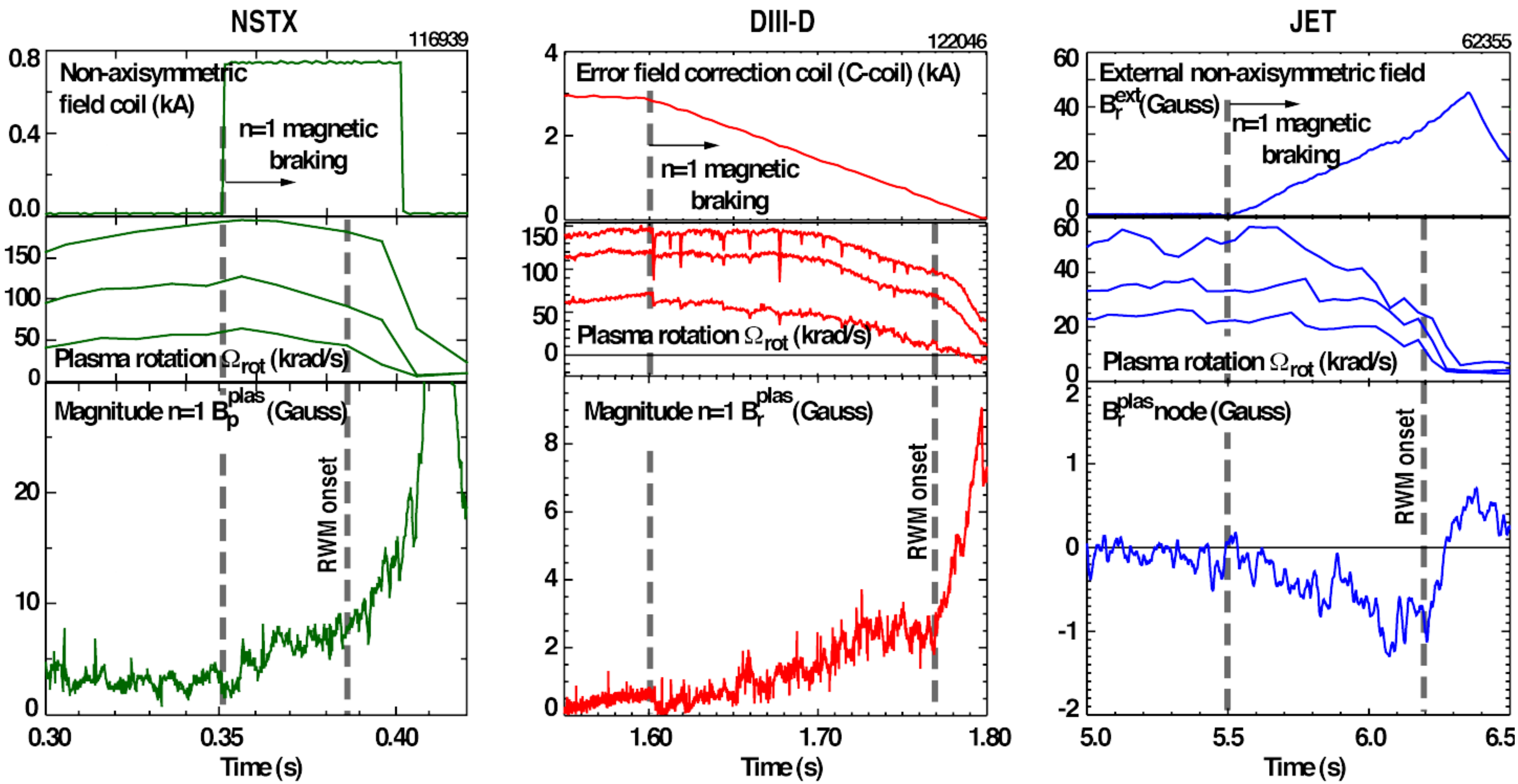
Time of marginal stability determined from start of fast mode growth



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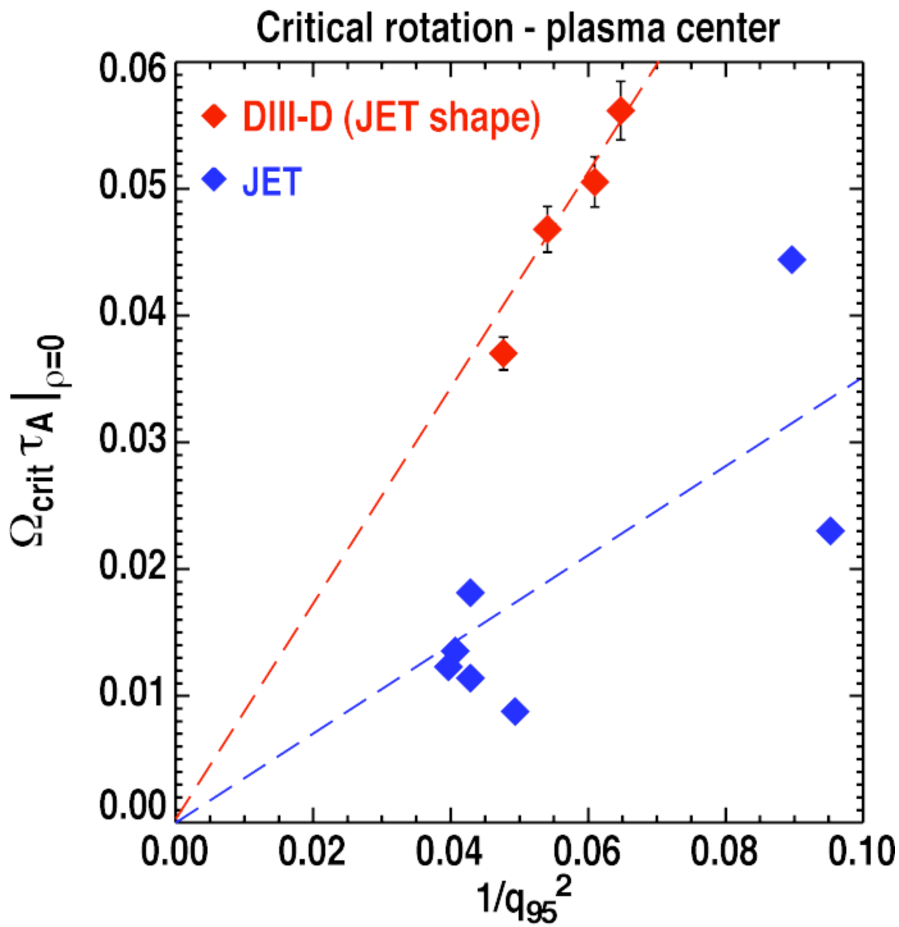
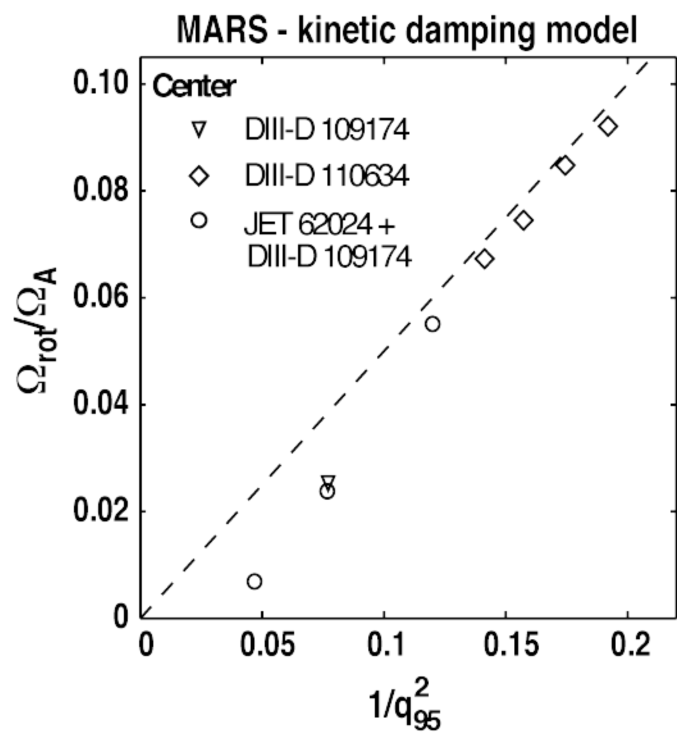
NSTX

Critical rotation in the center of DIII-D and JET plasmas decreases with increasing q_{95}





- **q_{95}-dependence consistent with MARS-F predictions**
  - ➜ Y.Q. Liu, next talk

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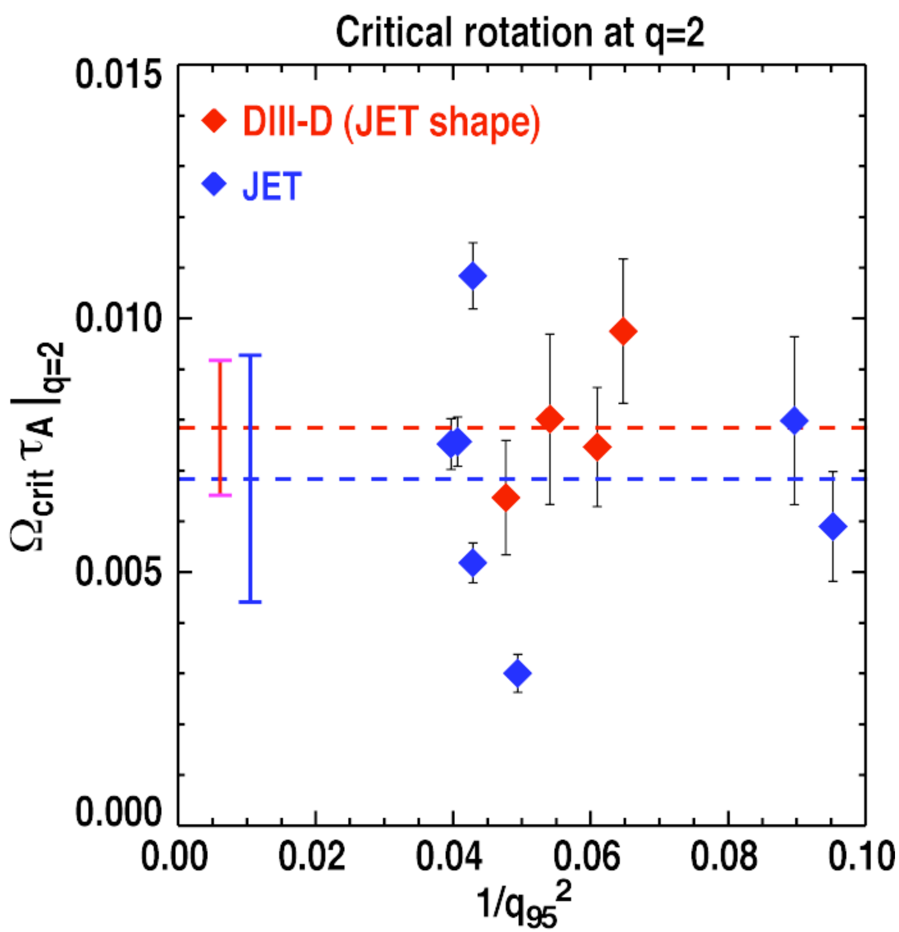
Evaluating Ω_{crit} at q=2 removes q_{95}-dependence and leads to quantitative agreement between DIII-D and JET



- **q_{95}-dependence caused by q-surfaces moving inwards towards higher rotation**
  - Stabilization mechanism depends on local q, e.g. kinetic damping [A. Bondeson and M.S. Chu, Phys. Plasmas (1996)],

$$\Omega_{crit} \propto 1/q^2$$

- **Quantitative agreement in DIII-D and JET indicates prominent role of q=2 surface**
  - Consistent with predictions for sound wave damping [D. Gregoratto, et al, Plasma Phys. Control. Fusion (2001)]
- **Variations of JET data partially caused by β-dependence**

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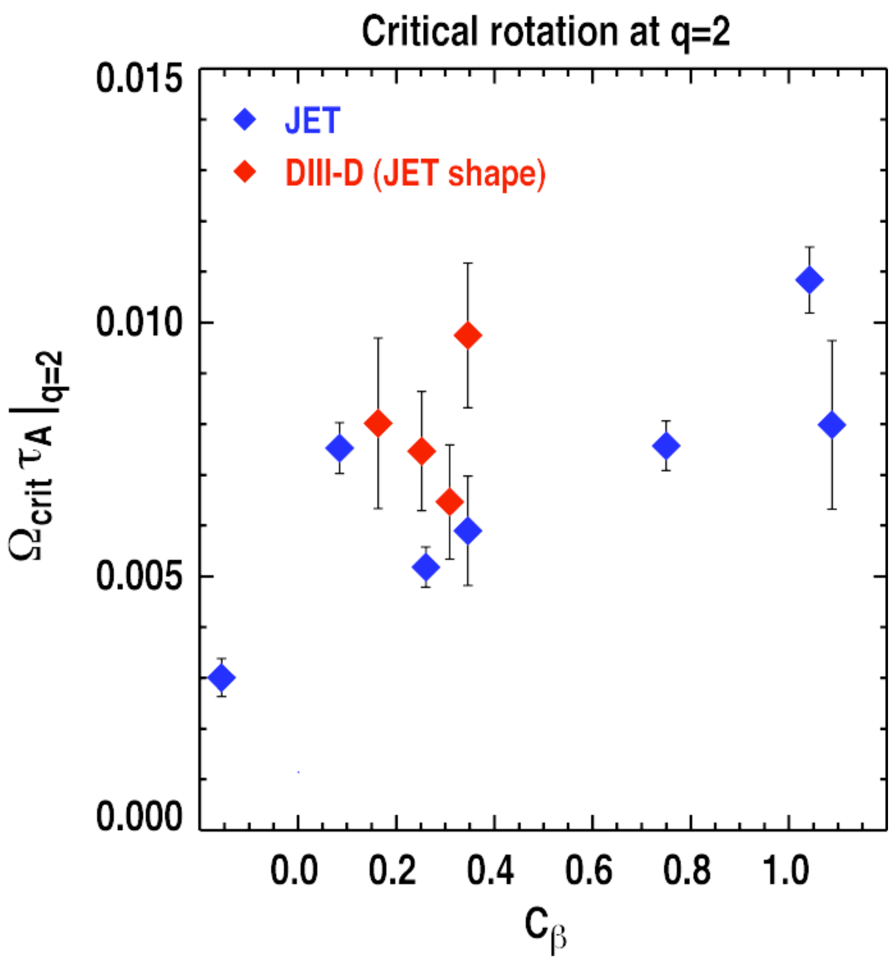
Ω_{crit} has weak β-dependence

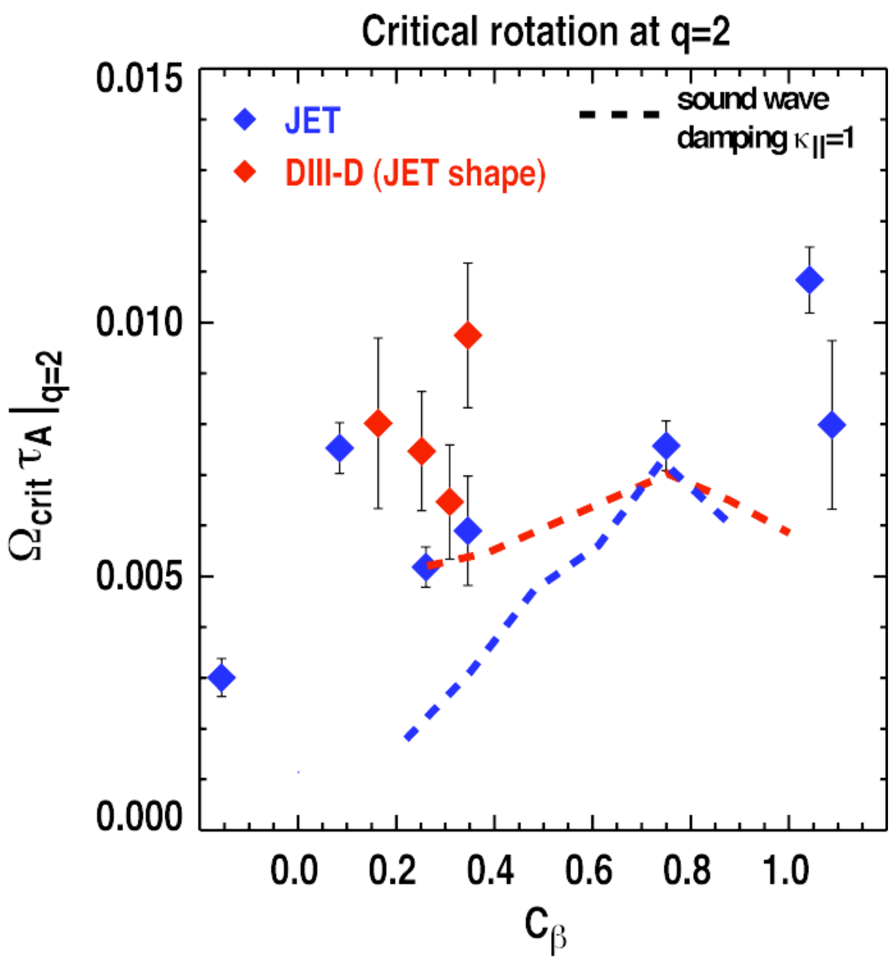
- **Beta-dependence of Ω_{crit} can account for some of the scatter of the measurement**
- **Consistent with increase of RFA with β**



Ω_{crit} has weak β-dependence

- **Beta-dependence of Ω_{crit} can account for some of the scatter of the measurement**
- **Consistent with increase of RFA with β**

- **Value of Ω_{crit} consistent with predictions (using MARS-F) for**
  - Sound wave damping



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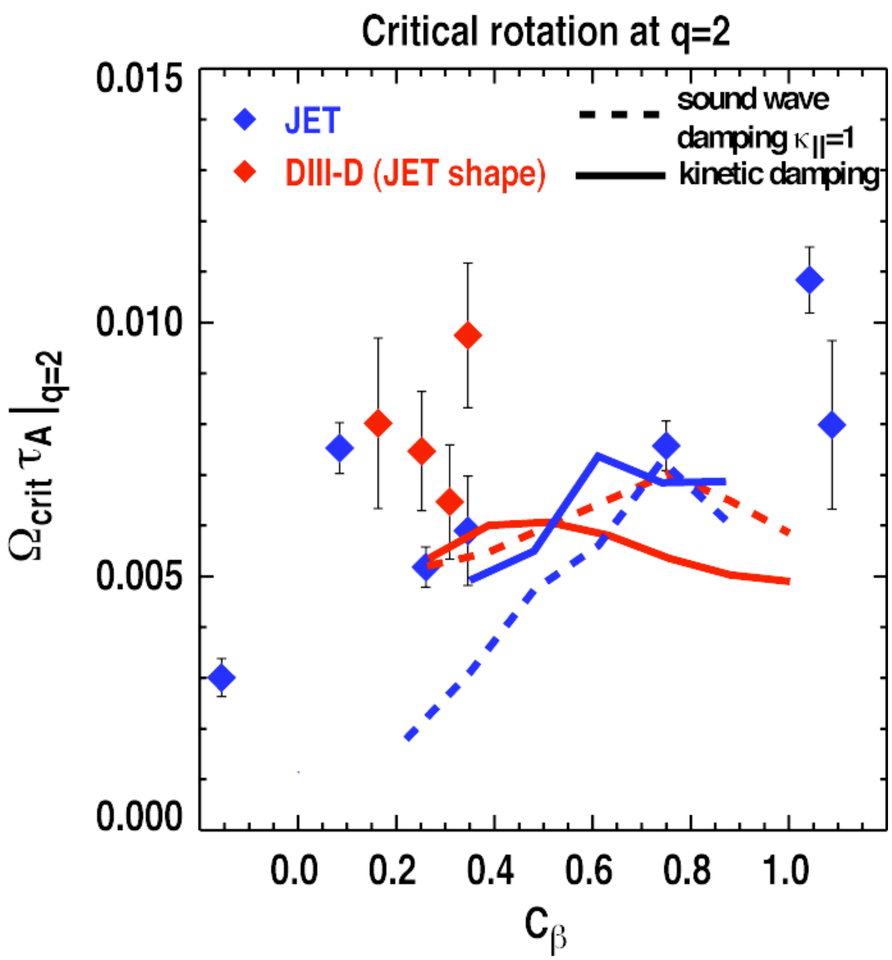
- **Value of Ω_{crit} consistent with predictions (using MARS-F) for**
  - Sound wave damping
  - Kinetic damping



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Critical rotation in NSTX exceeds critical rotation in DIII-D

- q_{95}-dependence in NSTX similar to DIII-D and JET

↓

- Evaluate Ω_{crit} at the same value of q

- NSTX critical rotation $\Omega_{crit}\tau_A$ at same q always equal or higher
  - Rotation for $q \geq 3$ close to zero

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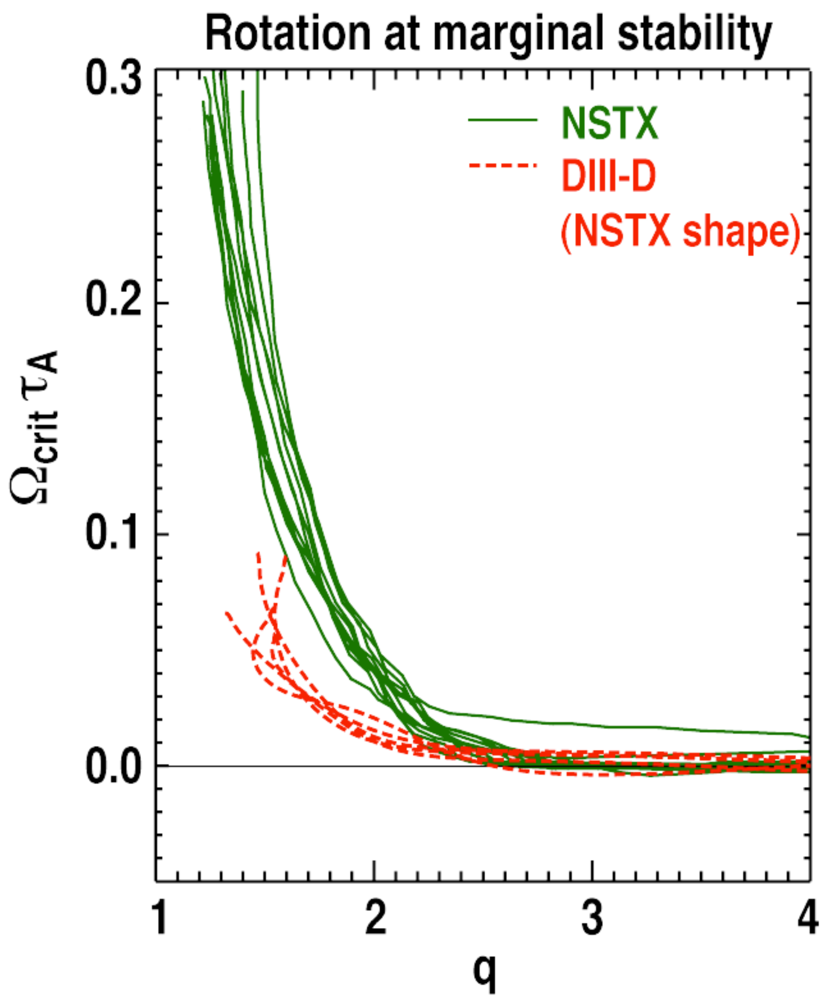
  - Single resonant surface can be sufficient for RWM stabilization

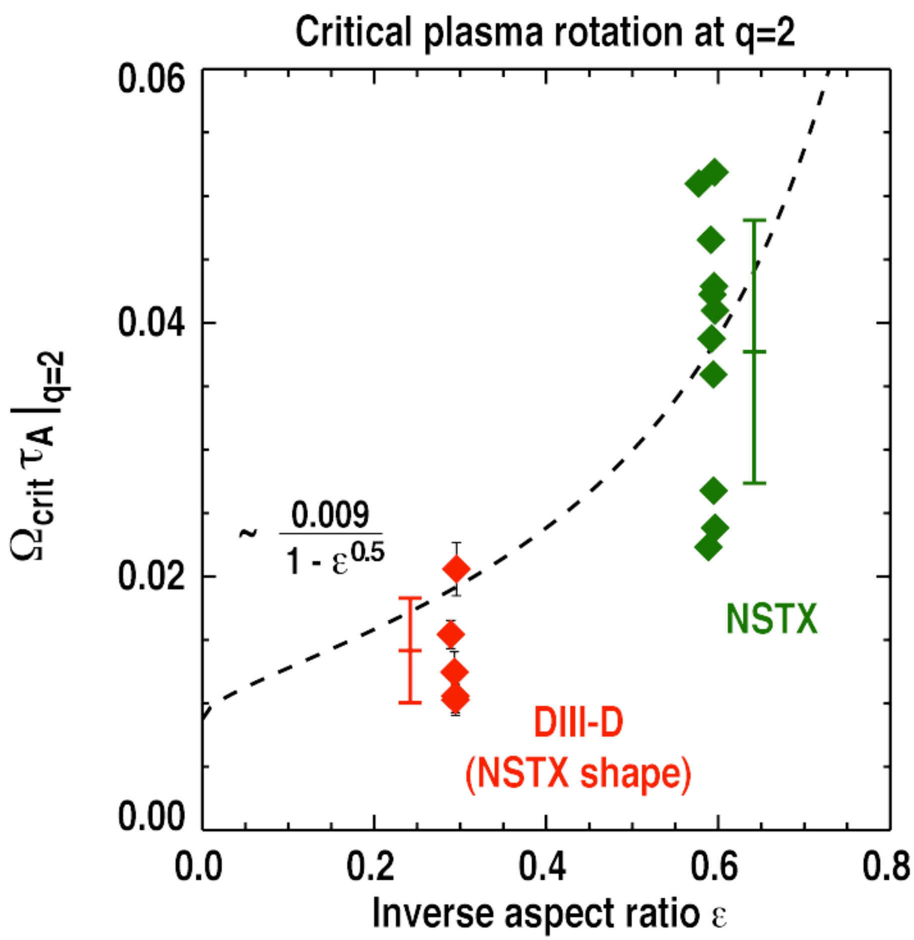


Aspect ratio dependence suggests that trapped particles do not contribute to RWM stabilization

- **Ion Landau damping significantly reduced for trapped particles**
  - Assume that only passing particles contribute to RWM stabilization

$$\Omega_{crit}\tau_A \propto \frac{1}{1-\sqrt{\varepsilon}}$$

- **Observed doubling of $\Omega_{crit}\tau_A$ consistent with stabilization by passing particles only**
  - Effect included in the kinetic but not in the sound wave damping model



Alternatively - RWM damping could be determined by sound wave velocity

- **Coupling to sound waves depends on sound time**

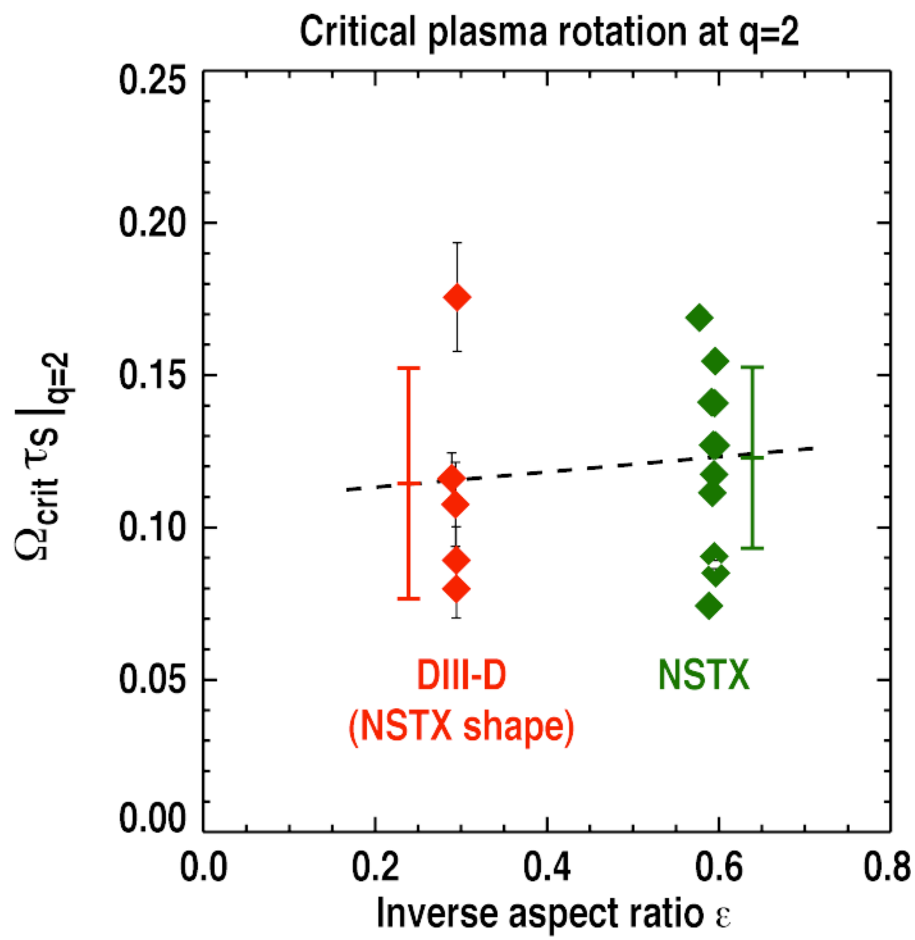
$$\tau_S = R_0 \sqrt{\frac{m_i}{k_B T_e + k_B T_i}}$$

- **Alfvén time and sound time linked via β**

$$\frac{\tau_A}{\tau_S} \propto \beta^{1/2} \propto \left(\varepsilon \beta_N / q_{95}\right)^{1/2}$$

  – Link is broken by aspect ratio

- **Normalization on sound time removes aspect ratio dependence**



Comparison of NSTX, DIII-D and JET establishes universality of RWM stabilization by plasma rotation

- **q_{95}-dependence of $\Omega_{crit}\tau_A$ explained by re-location of *q*-surfaces**
  - RWM stabilization depends on the local *q*
- **Quantitative agreement of $\Omega_{crit}\tau_A$ evaluated at *q*=2 in DIII-D and JET**
  - Physics determined by ideal MHD drive and normalized rotation
  - *q*=2 surface plays prominent role in stabilization mechanism
- **Quantitative agreement of RFA in DIII-D and JET**
  - Increase of RFA above $\beta_{no\ wall}$ in qualitative agreement with NSTX
  - RFA is manifestation of a weakly damped RWM
- **Aspect ratio dependence of $\Omega_{crit}\tau_A$ in DIII-D and NSTX explained by trapped particles not contributing to RWM stabilization**
  - Alternatively, the stabilization is determined by the sound wave velocity rather than the Alfvén wave velocity

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