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XP idea: Pedestal rotation shear enhancement with high-n NTV braking and 2nd NBI*

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(and maybe Rajesh… maybe)

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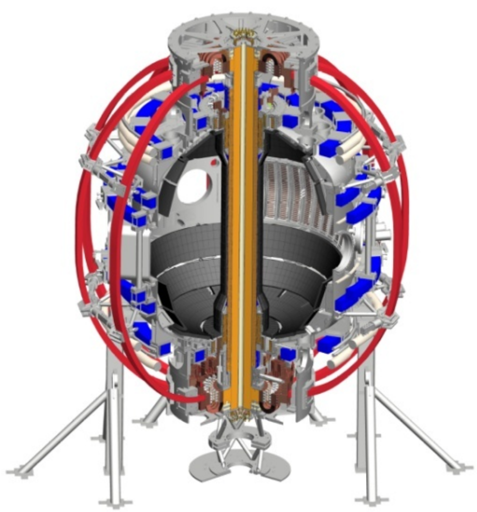

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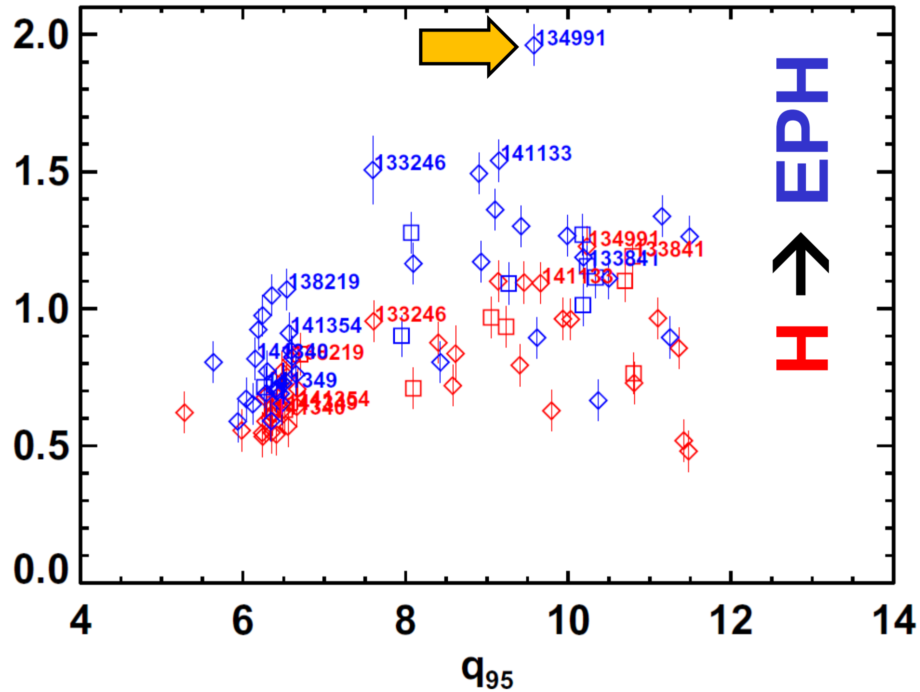
"Enhanced pedestal" H-modes (EPH) in NSTX have accessed H_{98} up to 1.5 (one case up to H_{98} =1.8-2)

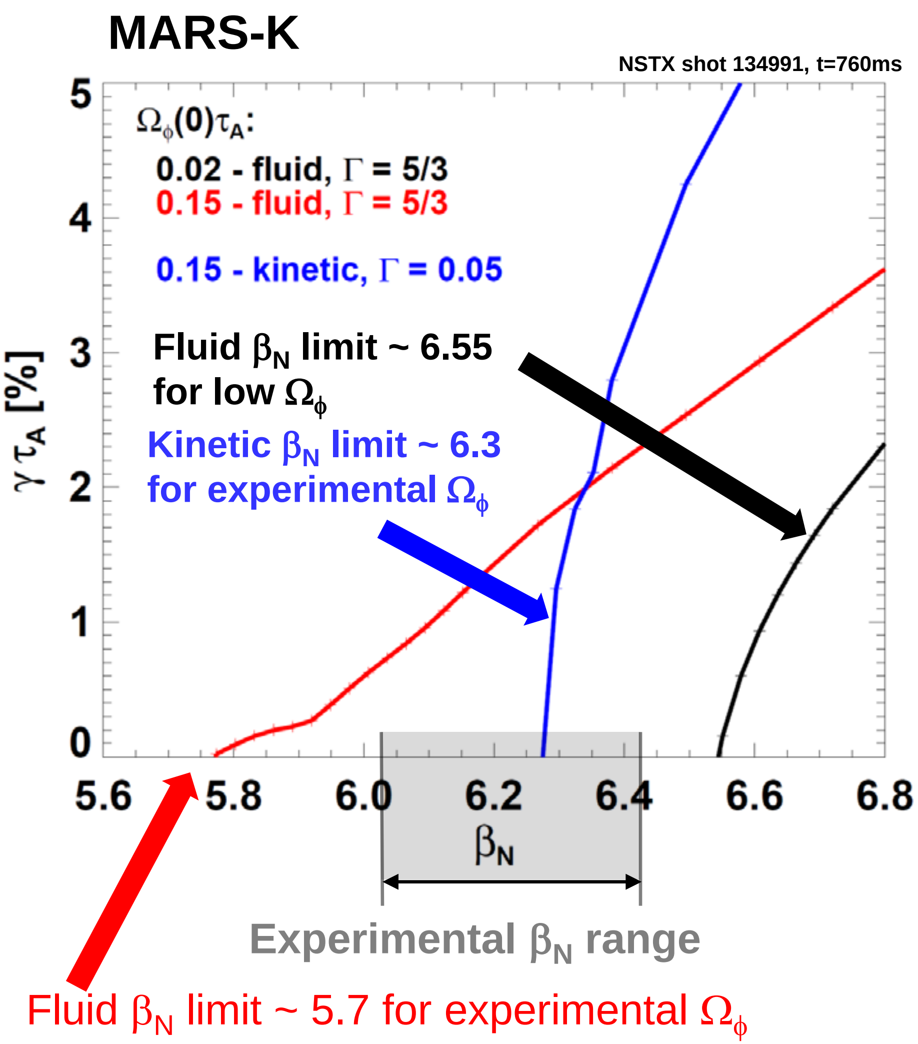
$H_{98y,2}$ (steady-state) $= W_{th} / P_{abs}\, \tau_{98y2}$



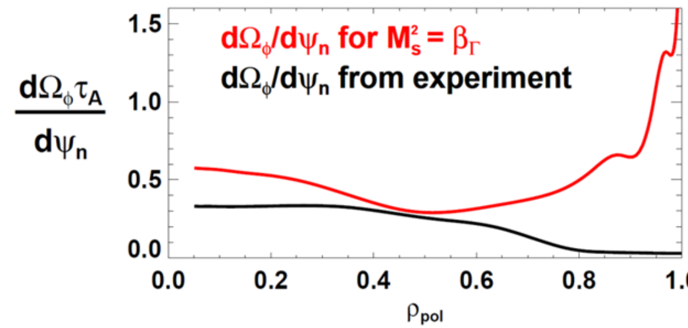
Gerhardt, NF 2014

- $H_{98} \leq 1.5$ with $\beta_N \sim 6$ and high non-inductive fraction = 60-70%
- Highest H_{98} in EPH appears to require:
  - **Strong edge rotation shear (3D fields/edge island?)**
  - Lithium wall coatings (lower edge recycling, ν^*)
- Often transient (EPH lost w/ ELM) – much more work needed to understand access and sustainment

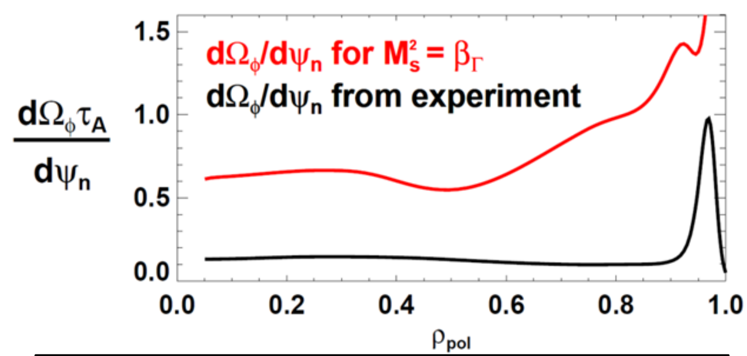
MARS-K and Chu analytic models for n=1 KH / kink show edge most stable location for high rotation shear



- Low β / early MHD case
  - Ω' mode not stabilized kinetically



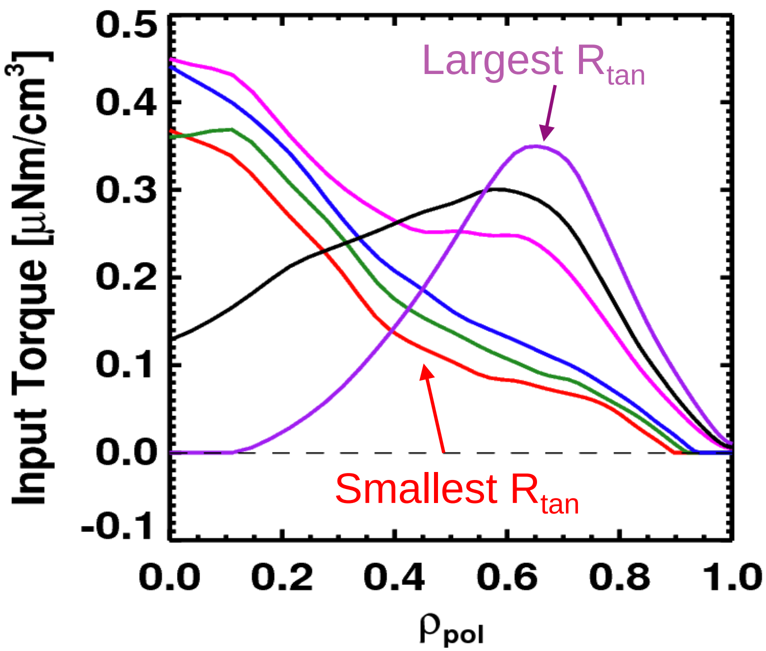
- High β / best EPH case
  - High edge Ω' stabilizing
  - Maximizes kinetic stabilization



Bottom line: put rotation shear in region of high q-shear

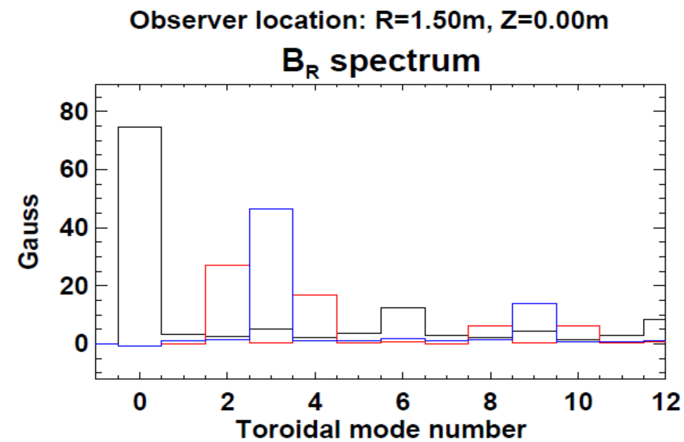
XP: Try broad/varied NBI deposition + vary outer gap and NTV (both DC and pulsed) – 0.75-1.5 days

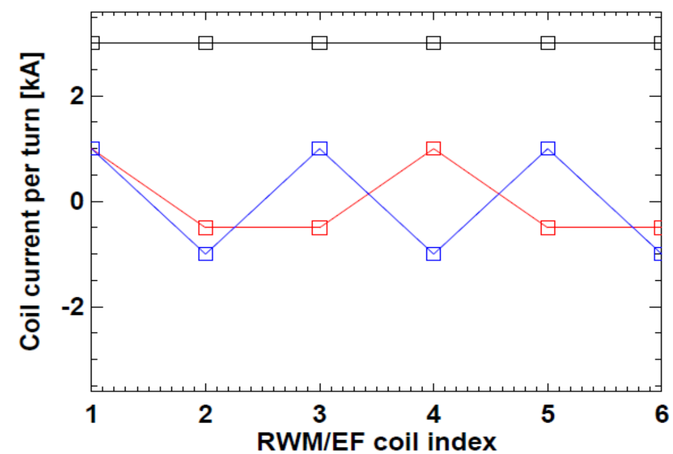
Torque Profiles From
6 Different NB Sources



- Try most tangential beams to broaden torque deposition profile
- Vary gap to vary edge braking and NBI deposition

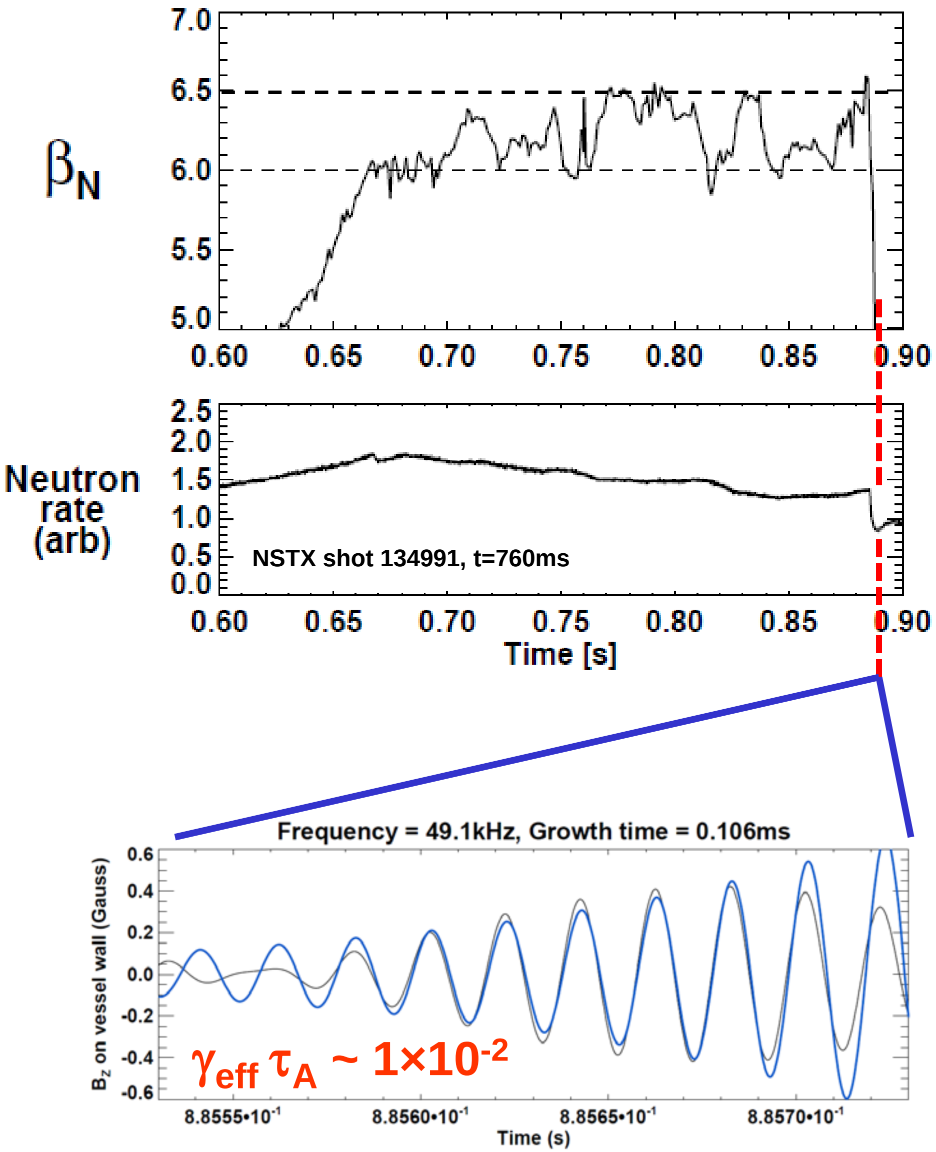
- Vary NTV n=2+4, 3, 6, amplitude, DC, pulsed





Backup

Experimental characteristics of highest-β_N MHD



- β_N = 6-6.5 sustained for 2-3τ_E
  - Oscillations from ELMs and bottom/limiter interactions
  - Possible small RWM activity
  - Only small core MHD (steady neutron rate)
- f = 50kHz mode causes 35% β_N drop ending high-β phase
  - Mode grows very fast (~100μs)
  - n-number difficult to determine
  - Possible that mode has n > 1

Analytic model of rotational-shear destabilization is being compared to MARS results and experiment

Model: low rotation, high rotation shear (Ming Chu, Phys. Plasmas, Vol. 5, No. 1, (1998) 183)

1. Ideal interchange criterion including rotation shear:

$$D_{\mathrm{I},\Omega} = D_{\mathrm{I}} + \frac{1}{4}(M_a^2 + A) + \frac{\beta_\Gamma M_s^2}{F(\beta_\Gamma - M_s^2)} \times \left[D_{\mathrm{I}} + \frac{1}{2}\left(\frac{1}{2} - H\right)\right]^2 > 0$$

Ideal interchange index w/o rotation

Glasser, Greene, Johnson – Phys. Fluids (1975) 875

2. Kelvin-Helmholtz criterion:

$$M_s^2 > \beta_\Gamma$$

β_Γ = compressional Alfvén wave β

$$\beta_\Gamma = \frac{\Gamma p}{\Gamma p + p'^2(\langle B^2/|\nabla V|^2\rangle/\Lambda^2 F)}$$

M_a = (shear) Alfvén wave excitation Mach number

$$M_a^2 = \frac{1}{\Lambda^2}\boxed{\left(\frac{\partial\Omega}{\partial V}\right)^2}\frac{\rho M \chi'^2}{(2\pi)^2}$$

M_s = sound Alfvén wave excitation Mach number

$$M_s^2 = \frac{\chi'^2 \boxed{(\partial\Omega/\partial V)^2} \langle B^2\rangle \rho F}{p'^2 \langle B^2/|\nabla V|^2\rangle (2\pi)^2}$$

Rotation shear

destabilizes Alfvén wave directly *or* through sound wave coupling

MARS-K: self-consistent linear resistive MHD including toroidal rotation and drift-kinetic effects

- **Perturbed single-fluid linear MHD:**

Y.Q. Liu, et al., Phys. Plasmas 15, 112503 2008

$$(\gamma + in\Omega)\xi = \mathbf{v} + (\xi \cdot \nabla\Omega)R^2\nabla\phi$$

$$\rho(\gamma + in\Omega)\mathbf{v} = \mathbf{j}\times\mathbf{B} + \mathbf{J}\times\mathbf{Q} - \nabla\cdot\mathbf{p}$$

$$\boxed{+\rho\left[2\Omega\hat{\mathbf{Z}}\times\mathbf{v} - (\mathbf{v}\cdot\nabla\Omega)R^2\nabla\phi\right] - \nabla\cdot(\rho\xi)\Omega\hat{\mathbf{Z}}\times\mathbf{V}_0}$$

$$(\gamma + in\Omega)\mathbf{Q} = \nabla\times(\mathbf{v}\times\mathbf{B}) + (\mathbf{Q}\cdot\nabla\Omega)R^2\nabla\phi - \nabla\times(\eta\mathbf{j})$$

$$(\gamma + in\Omega)p = -\mathbf{v}\cdot\nabla P - \Gamma P\nabla\cdot\mathbf{v} \qquad \mathbf{j} = \nabla\times\mathbf{Q}$$

- **Drift-kinetic effects in perturbed anisotropic pressure *p*:**

$$\mathbf{p} = p\mathbf{I} + p_{\|}\hat{\mathbf{b}}\hat{\mathbf{b}} + p_{\perp}(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}})$$

$$p_{\|}e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma M v_{\|}^2 f_L^1$$

$$p_{\perp}e^{-i\omega t + in\phi} = \sum_{e,i}\int d\Gamma \frac{1}{2} M v_{\perp}^2 f_L^1$$

$$f_L^1 = -f_\epsilon^0 \epsilon_k e^{-i\omega t + in\phi}\sum_{m,l,u} X_m^u H_{ml}^u \lambda_{ml} e^{-in\tilde{\phi}(t) + im\langle\dot{\chi}\rangle t + il\omega_b t}$$

$$H_L = \frac{1}{\epsilon_k}\left[M v_{\|}^2 \vec{\kappa}\cdot\xi_{\perp} + \mu(Q_{L\|} + \nabla B\cdot\xi_{\perp})\right]$$

- Rotation and rotation shear effects:
- Mode-particle resonance operator:

Diamagnetic

$$\lambda_{ml} = \frac{n[\omega_{*N} + (\hat{\epsilon}_k - 3/2)\omega_{*T} + \omega_E] - \omega}{n(\langle\omega_d\rangle + \omega_E) + [\alpha(m + nq) + l]\omega_b - i\nu_{\text{eff}} - \omega}$$

Precession ExB Transit and bounce Collisions

- Fast ions: analytic slowing-down f(v) model – isotropic or anisotropic

This talk

- Include toroidal flow only: $\mathbf{v}_\phi = \mathbf{R\Omega_\phi(\psi)}$ and $\boldsymbol{\omega}_\mathbf{E} = \boldsymbol{\omega}_\mathbf{E}(\psi)$

Real part of complex energy functional provides equation for growth-rate useful for understanding instability sources

Dispersion relation

$$\delta K + \delta W = 0$$

Kinetic energy

$$\delta K = \frac{1}{2}\int d^3x \rho (\gamma + in\Omega)^2 \left|\vec{\xi}_\perp\right|^2$$

Potential energy

$$\delta W = -\frac{1}{2}\int d^3x\, \mathbf{F}\cdot\xi_\perp^*$$

$$\delta K_1 = -\frac{1}{2}\int d^3x \rho \left|\vec{\xi}_\perp\right|^2$$

Growth rate equation: mode growth for $\delta W^{re} < 0$

$$\left(\gamma^{re}\right)^2 = \left(\delta W_K^{re} + \delta W_F^{re} + \delta W_{vb} + \delta W_{rot}^{re}\right) / \delta K_1$$

$$\delta W_K = -\frac{1}{2}\int d^3x \mathbf{F}^K \cdot \xi_\perp^* \qquad \mathbf{F}^K = -\nabla\cdot\mathbf{p}^{\text{kinetic}}$$

$$\delta W_{rot} = \delta W_\Omega + \delta W_{d\Omega} + \delta W_{cf} + \delta K_2$$

$$\delta W_F^p = -\frac{1}{2}\int d^3x \mathbf{F}^p \cdot \xi_\perp^*$$
$$= \frac{1}{2}\int d^3x \left[(\xi_\perp\cdot\nabla P)\nabla\cdot\xi_\perp^* + \Gamma P|\nabla\cdot\xi|^2 - \Gamma P(\nabla\cdot\xi)(\nabla\cdot\xi_\parallel^*)\right] + S_F^p$$

$$\delta W_F^j = -\frac{1}{2}\int d^3x \mathbf{F}^j \cdot \xi_\perp^* = \frac{1}{2}\int d^3x |Q|^2 + S_F^j$$

$$\delta W_F^Q = -\frac{1}{2}\int d^3x \mathbf{F}^Q \cdot \xi_\perp^* = \frac{1}{2}\int d^3x \left[J_\parallel \hat{\mathbf{b}}\cdot\xi_\perp^* \times \mathbf{Q}_\perp - \frac{Q_\parallel}{B}(\xi_\perp^*\cdot\nabla P)\right]$$

$$S_F^p = -\frac{1}{2}\int [(\xi_\perp\cdot\nabla P) + \Gamma P \nabla\cdot\xi]\,\xi_\perp^*\cdot d\mathbf{s}$$

$$S_F^j = \frac{1}{2}\int B Q_\parallel \xi_\perp^* \cdot d\mathbf{s}$$

Coriolis - Ω

$$\delta W_\Omega = \frac{1}{2}\int d^3x \left[-2\rho\Omega(\gamma + in\Omega)\mathbf{Z}\times\vec{\xi}_1\cdot\vec{\xi}_\perp^*\right]$$

Coriolis - dΩ/dρ

$$\delta W_{d\Omega} = \frac{1}{2}\int d^3x R\left(2\rho\Omega\left(\vec{\xi}_1\cdot\nabla\Omega\right)\vec{\xi}_{\perp\mathbf{R}}^*\right)$$

Centrifugal

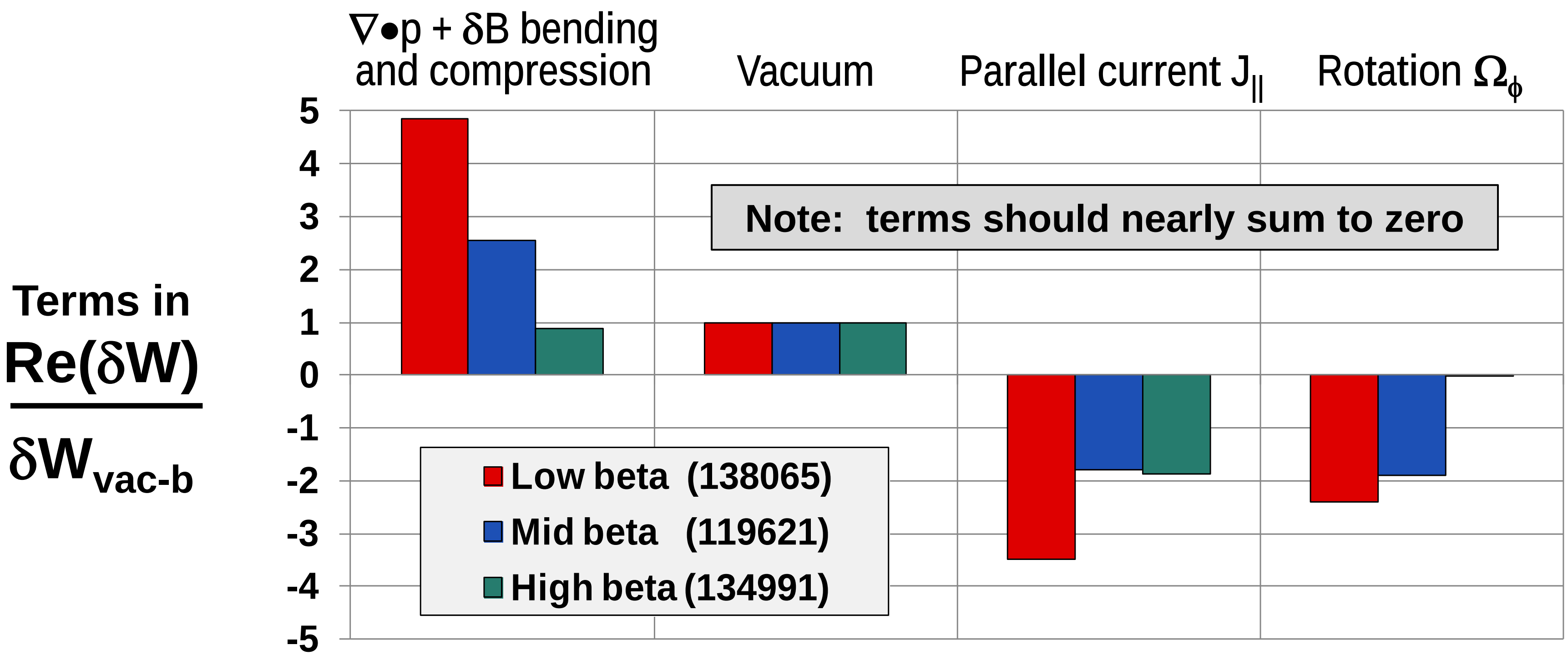
$$\delta W_{cf} = \frac{1}{2}\int d^3x R\Omega^2\nabla\bullet\left(\rho\vec{\xi}_1\right)\vec{\xi}_{\perp\mathbf{R}}^*$$

Differential kinetic

$$\delta K_2 = -\frac{1}{2}\int d^3x\rho(\omega + n\Omega)^2\left|\vec{\xi}_\perp\right|^2$$

Energy analysis near marginal stability elucidates trends from growth-rate scans

- All cases: field-line bending+compression balances primarily ∇p



- **Low β: $J_{||}$ (low q shear) and high Ω_ϕ strongly destabilizing**
- **Mid β: Reduced destabilization from $J_{||}$ & Ω_ϕ increases β limit**
- **High β: Large Ω_ϕ' at edge minimizes Ω_ϕ drive → highest β**