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3DST

New Understanding of Resonant Layer Response via Extended MHD

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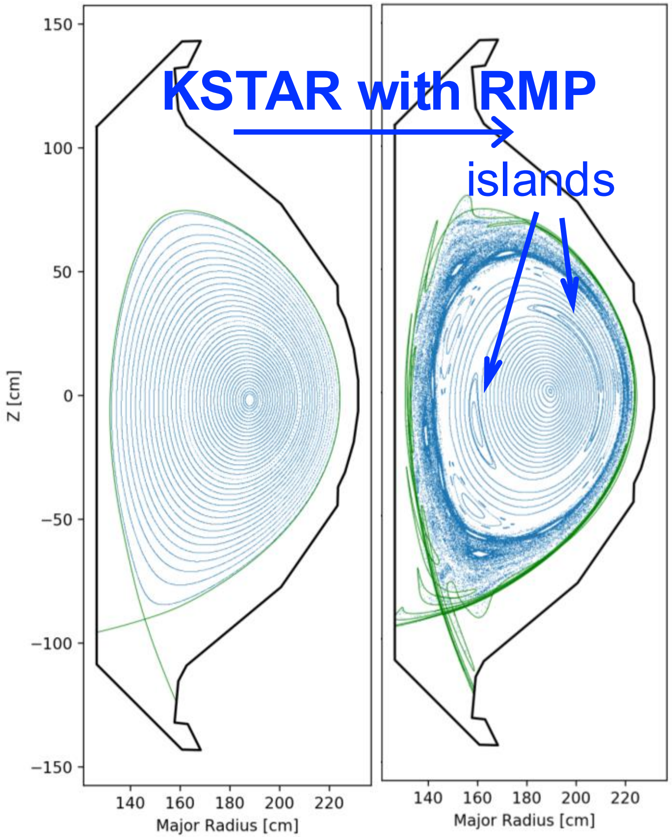
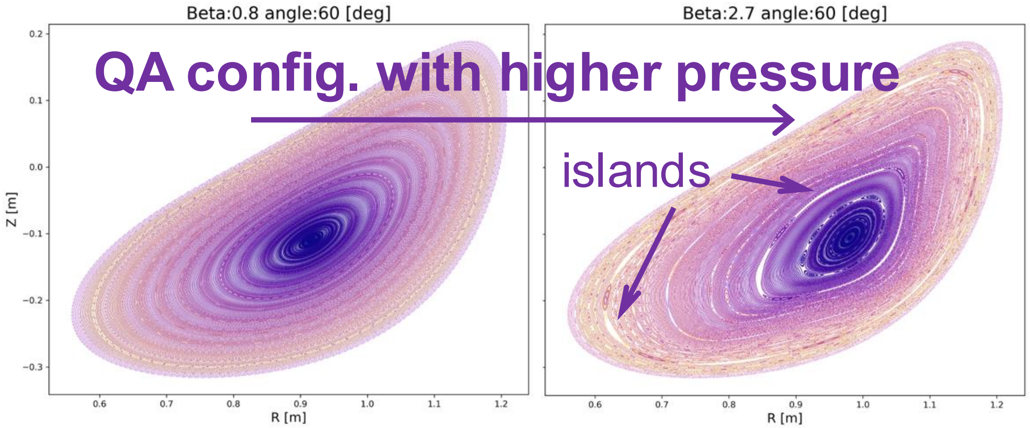
Mechanism of magnetic island opening in fusion plasmas



- Magnetic fusion needs good magnetic surfaces
- Unwanted magnetic islands must be prevented
- **Mechanism opening islands** must be understood
- Leading to our key question on field penetration



Overview

- Introduction to field penetration
  - As a key process in error field, tearing mode, 3D-edge control
- Modeling background
  - Two-fluid drift MHD framework
- New theory and modeling with extended MHD physics
  - **Strong density correlation with electron viscosity**
  - **Shielding by ion parallel flow near natural frequency**
- Implication to parameteric scaling and prediction
- Conclusion remarks

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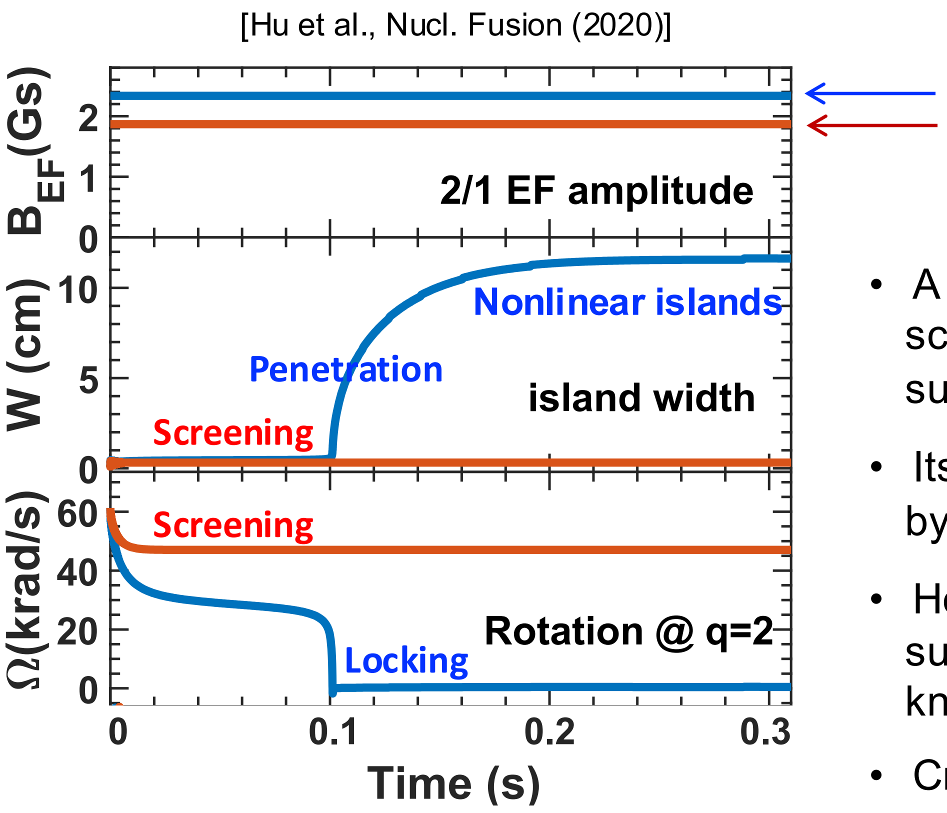
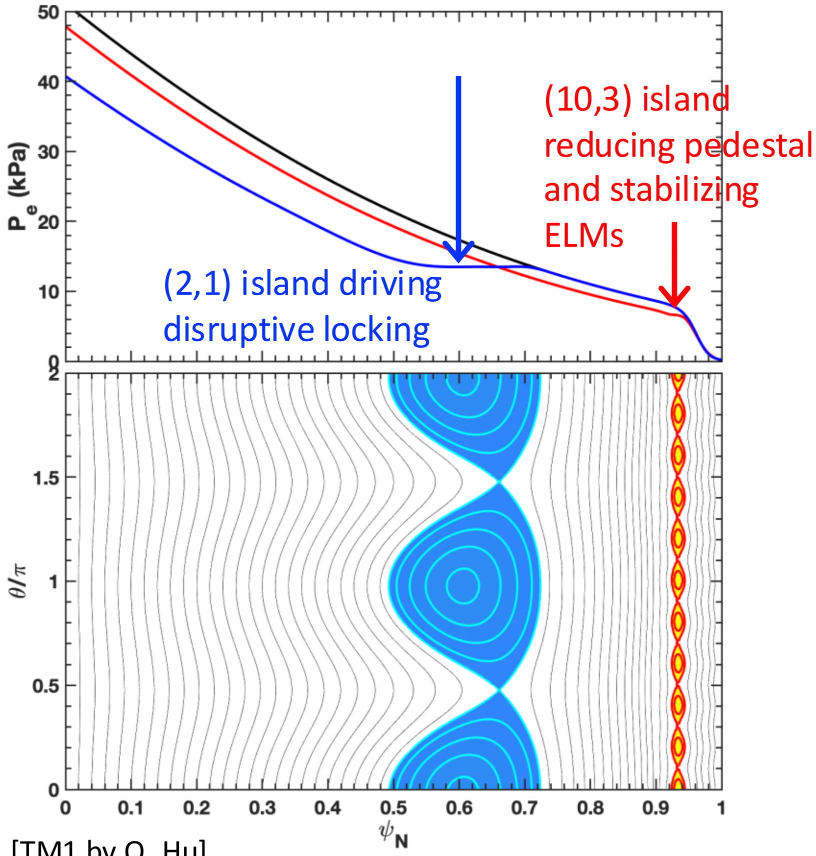
Field penetration is a bifurcation to large magnetic islands



Local resonant (m=2,n=1) field at just *slightly different* amplitudes, leading to a very different consequence

- A resonant magnetic perturbation $\delta\vec{B}$ is screened by parallel currents $\delta\vec{j}_{\parallel}$ at the rational surface when its strength is insufficient
- Its electromagnetic torque $\delta\vec{j}_{\parallel} \times \delta\vec{B}$ is balanced by viscous torque
- However, $\delta\vec{B}$ can penetrate to the resonant surface when its strength reaches a threshold – known as **field penetration bifurcation**
- Creating large, nonlinear magnetic islands

Field penetration is the leading hypothesis for error-field driven disruption and RMP ELM suppression



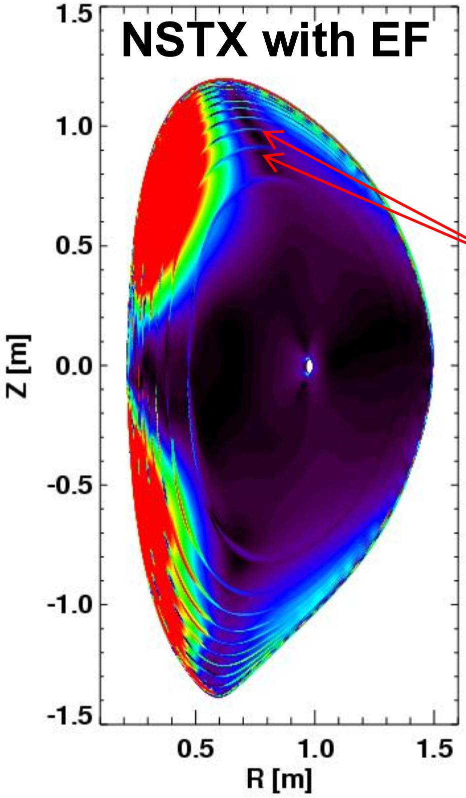
[TM1 by Q. Hu]

- Disruptive locked modes by intrinsic error field (EF) are created by field penetration in the core, by low (m,n) resonant field

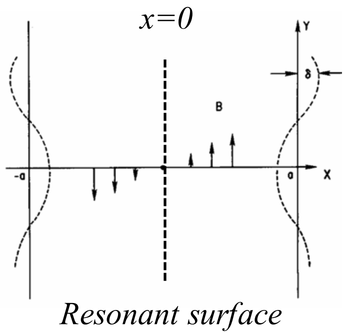
- RMP ELM suppression is believed to come with field penetration in the edge, by mostly high (m,n) resonant fields

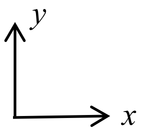
- These two represent core vs. edge, or bad vs. good side of non-axisymmetry, but share the key process in common – **Field penetration**

Boundary layer theory offers a unique way to gain fundamental understanding of complex MHD interplays in field penetration



- Field peneteration is a boundary layer phenomenon
  - Outer layer : Ideal MHD is dominant
  - Inner layer : Ideal MHD breaks down and all subsidary physics effects can come into a play
- Layer is narrow, with radial scale $\delta \sim S^{-1/3} < 10^{-3}$ in ITER
- Analytic theory is possible in slab representation, targeting physics understanding and verification for full simulation in the future





- $\hat{x} \propto \vec{\nabla}\psi$
- $\hat{y} \propto \vec{B} \times \vec{\nabla}\psi$
- $\hat{z} \propto \vec{B}$

As used in theory for islands since FKR (1963)

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Two-fluid drift-MHD adapted to explore layer response

- Following two-fluid drift MHD formulation and including [Fitzpatrick et al., Phys. Plasmas (2005)]
  - First-order drifts and ion gyro-viscous tensor pressure $\left(\vec{\nabla} \cdot \overleftrightarrow{\Pi}_g\right)$
  - Phenomenological conductivity or (perpendicular diffusivity), electron/ion viscosity

$$m_i n_0 \left(\frac{\partial}{\partial t} + \vec{V} \cdot \vec{\nabla}\right) \vec{V} = \vec{j} \times \vec{B} - \vec{\nabla} p - m_i n_0 \frac{\tau}{1+\tau} \vec{V}_* \cdot \vec{\nabla} \vec{V}_\perp + \mu_i \nabla^2 \vec{V}_i + \mu_e \nabla^2 \vec{V}_e$$

$$\vec{E} + \vec{V} \times \vec{B} = \eta \vec{j} - \frac{1}{e n_0} \left(\vec{\nabla} p - \vec{j} \times \vec{B} - \frac{\tau}{1+\tau} (\hat{b} \cdot \vec{\nabla} p) \hat{b} - \mu_e \nabla^2 V_e\right)$$

$$\left(\frac{\partial}{\partial t} + \vec{V} \cdot \vec{\nabla}\right) p = -\gamma p (\vec{\nabla} \cdot \vec{V}) + \kappa \nabla^2 p$$

- Drift velocities: $\vec{V} = \vec{V}_E + V_\parallel \hat{b} = \vec{V}_i - \frac{\tau}{1+\tau} \vec{V}_* \left(= \vec{V}_e - \frac{\tau}{1+\tau} \vec{V}_* + \frac{\vec{j}}{e n_0}\right)$ $\quad \vec{V}_* = \frac{\hat{b} \times \vec{\nabla} p}{e n_0 B}$

4-(Scalar)-field model along with reduced MHD

- Reduced MHD: Take $(\hat{b} \cdot \vec{\nabla} \times)$ to remove compressional Alfven wave
- Force balance indicates $\boldsymbol{p} = p_0 - B_0 \boldsymbol{b_z}$
- $\vec{B} = \vec{\nabla}\boldsymbol{\psi} \times \hat{z} + (B_0 + \boldsymbol{b_z})\hat{z}$, $\vec{V} = \vec{\nabla}\boldsymbol{\phi} \times \hat{z} + \boldsymbol{V_z}\hat{z}$ in a slab lead to **4-field** $(\boldsymbol{\psi}, \boldsymbol{Z}, \boldsymbol{\phi}, \boldsymbol{V_z})$ equations

$*\boldsymbol{Z} \equiv \boldsymbol{b_z}/c_\beta\sqrt{1+\tau}$

$$\frac{\partial \psi}{\partial t} = [\phi, \psi] - [Z, \psi] + \eta J - \frac{\mu_e d_\beta (1+\tau)}{c_\beta} \nabla^2 \left(V_z + \frac{d_\beta}{c_\beta} J \right)$$

$$\frac{\partial Z}{\partial t} = [\phi, Z] + d_\beta^2 [J, \psi] + \left(c_\beta^2 \eta + \left(1 - c_\beta^2\right)\kappa \right) \nabla^2 Z + d_\beta c_\beta [V_z, \psi] + \mu_e d_\beta^2 \nabla^2 (U - \nabla^2 Z)$$

$$\frac{\partial U}{\partial t} = [\phi, U] - \frac{\tau}{2}(\nabla^2[\phi, Z] + [U, Z] + [\nabla^2 Z, \phi]) + [J, \psi] + \mu_i \nabla^2 (U + \tau \nabla^2 Z) - \mu_e \nabla^2 (U - \nabla^2 Z)$$

$$\frac{\partial V_z}{\partial t} = [\phi, V_z] + \frac{c_\beta}{d_\beta}[Z, \psi] + \mu_i \nabla^2 V_z + \mu_e \nabla^2 (V_z + \frac{d_\beta}{c_\beta} J)$$

$J = \nabla^2 \psi, U = \nabla^2 \phi,\quad c_\beta = \sqrt{\beta/(1+\beta)},\ d_\beta = c_\beta d_i/\sqrt{1+\tau}$ $\quad$ *Ion skin depth* $d_i = \sqrt{m_i/n_0 e^2 \mu_0}/a$

$*\ Poisson\ Braket\ [A, B] \equiv \hat{z} \cdot (\vec{\nabla} A \times \vec{\nabla} B)$ $\quad$ $*\ (t, \nabla, B, \eta, \mu_{i,e}, \kappa)$ *are properly normalized with* a, V_A

Resonant field response is characterized by a single quantity "Δ_{in}" in boundary layer theory

- Boundary layer theory with a small parameter $\epsilon \sim S^{-1/3}$ shows that resonant layer response $(\tilde{\psi}, \tilde{Z}, \tilde{\phi}, \tilde{V}_z) \propto e^{i(m\theta - n\phi)}$ is characterized by a single quantity:

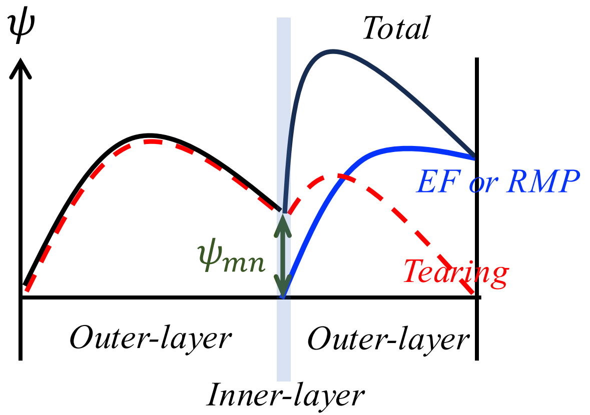
$$\Delta_{in}(\omega, Q, Q_i, Q_e, c_\beta, C, D, P_i, P_e)$$

* *Normalized $\vec{E} \times \vec{B}$* ***rotation*** $\boldsymbol{Q}$, *ion (electron)* ***diamagnetic rotation*** $\boldsymbol{Q_{i(e)}}$, ***beta*** $\boldsymbol{c_\beta}$, ***conductivity (diffusivity)*** $\boldsymbol{C}$, ***ion gyroradius*** $\boldsymbol{D}$, ***ion (electron) viscosity*** $\boldsymbol{P_{i(e)}}$

- Asymptotic matching to global outer-layer response (mostly ideal 3D MHD)

$$\lim_{X\to\infty} \Delta_{in} \rightarrow \left[\frac{\partial}{\partial x} \ln \psi\right]_-^+ \leftarrow \lim_{x\to 0} \Delta_{\mathrm{out}} \left(= \frac{\Delta_{\mathrm{ext}}}{\psi_{mn}} + \Delta'\right)$$

External drive $\propto \delta B_{mn}$ *Tearing mode index*



- Giving growth ω for tearing modes, or seed island size ψ_{mn} driven by external EF or RMP
  - As a function of $Q, Q_i, Q_e, c_\beta, C, D, P_i, P_e$

Field penetration occurs when torque balance breaks down

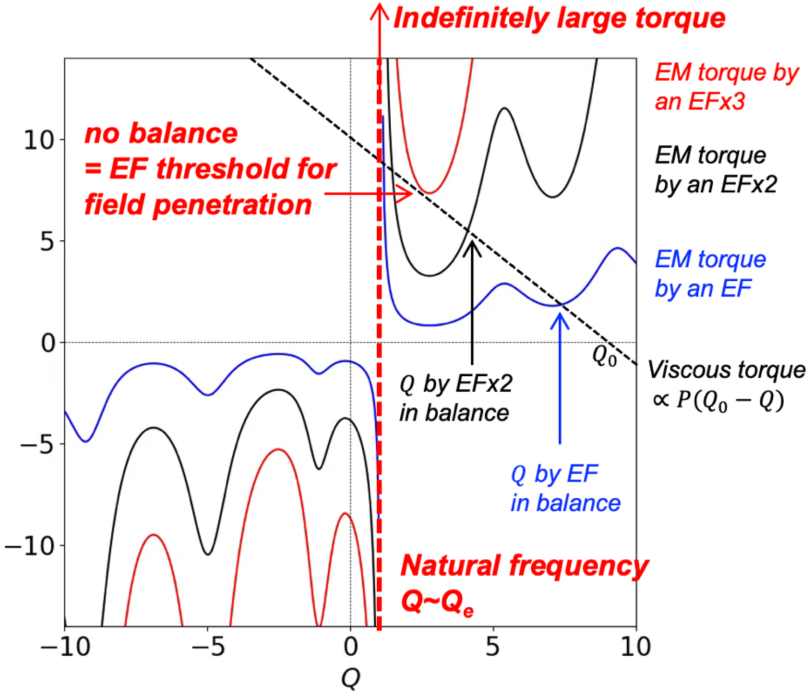
- In the presence of external 3D fields (EF or RMP), electromagnetic $\delta\vec{j}_{\parallel} \times \delta\vec{B}$ torque is induced

$$\tau_{\phi} = -\frac{k}{2}\mathrm{Im}(\Delta_{in})|\psi_{mn}|^2 \propto \mathrm{Im}\left(\frac{1}{\Delta_{in}}\right)$$

- **Field penetation**: When viscous torque cannot make a balance against $\delta\vec{j}_{\parallel} \times \delta\vec{B}$ torque, (ψ_{mn}, τ_{ϕ}) becomes indefinitely large near **natural frequency $Q \sim Q_e$**, breaking linear framework with nonlinear islands

- **Field penetration threshold** can be estimated when this torque balance is no longer possible

$$\delta_c = \left[\frac{\delta B_{mn}}{B_{\phi}}\right]^2_{crit} \approx \max\left[\frac{2P(Q_0 - Q)}{S\ \mathrm{Im}(1/\hat{\Delta})}\right] \quad {}^{*}\hat{\Delta} = \epsilon\Delta_{in}$$



Earlier theory already identified 10 distinct regimes

- Earlier theory explored layer response analytically (Cole) and numerically (Park) by ignoring electron viscosity and ion parallel flow [Cole et al., Phys. Plasmas (2006)] [Park, Phys. Plasmas (2022)]

Fourier transform from $\tilde{F} = (\tilde{\psi}, \tilde{\phi}, \tilde{Z}, \tilde{V}_z)$ to $\bar{F} = (\bar{\psi}, \bar{\phi}, \bar{Z}, \bar{V}_z)$ by $\bar{F}(p) = \int_c \tilde{F}(X)\, e^{ipX} dX$

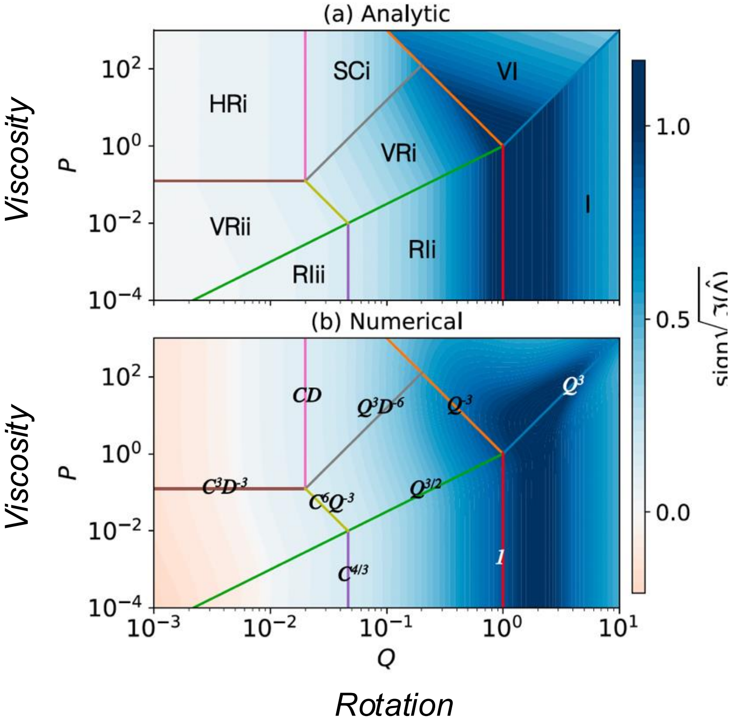
$$i(Q - Q_e)\bar{\psi} = \frac{d(\bar{\phi} - \bar{Z})}{dp} - p^2\bar{\psi} - \cancel{p^4 P_e \frac{D^2}{c_\beta^2}(1+\tau)\bar{\psi}},$$

$$i(Q - Q_i)p^2\bar{\phi} = \frac{d(p^2\bar{\psi})}{dp} - Pp^4(\bar{\phi} + \tau\bar{Z}) - \cancel{P_e p^4(\bar{\phi} - \bar{Z})}.$$

$$iQ\bar{Z} - iQ_e\bar{\phi} = -D^2\frac{d^2(p^2\bar{\psi})}{dp^2} - c_\beta^2 p^2\bar{Z} + \cancel{c_\beta^2\frac{d\bar{V}_z}{dp}} + \cancel{P_e D^2 p^4(\bar{\phi} - \bar{Z})},$$

$$\cancel{iQ\bar{V}_z + iQ_e\bar{\psi} = \frac{d\bar{Z}}{dp} - (P + P_e)p^2\bar{V}_z + P_e\frac{D^2}{c_\beta^2}p^4\bar{\psi}.}$$

HR: Hall-Resistive, SC: Semi-Collisional, RI: Resistive-Inertial, VR: Visco-Resistive, VI: Visco-Inertial, I: Inertial, (i: First, ii: Second)



Earlier theories reveal complexity but still without reproducing key observations of field penetration

$$\delta_c \propto n_e^{\alpha_n} B_\phi^{\alpha_B} R_0^{\alpha_R} \omega^{\alpha_\omega}$$

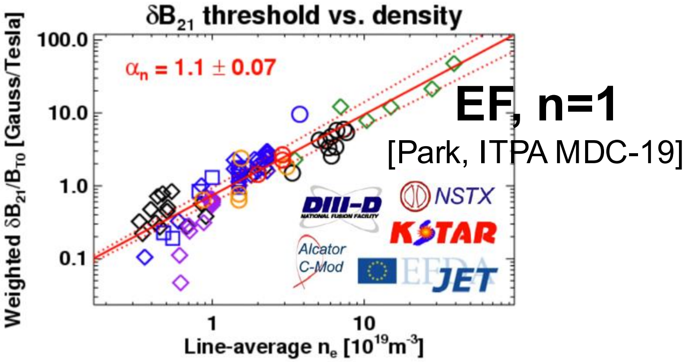
- Most well-known observation is strong density scaling (as well as inverse B_ϕ scaling and rotation scaling) of field penetration threshold

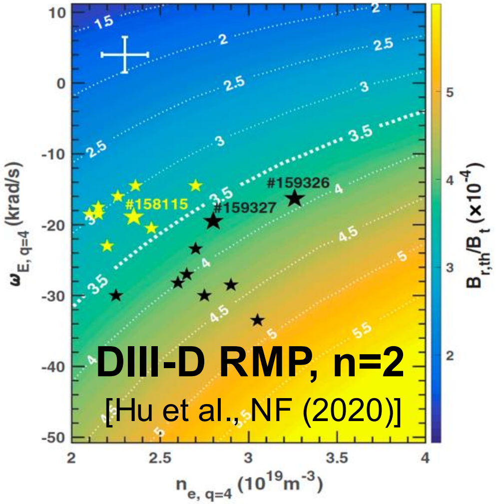
$$\alpha_{n,EF\ or\ RMP} = 0.55\sim1.1$$

- In theory, most relevant regimes for operating or future tokamaks are Semi-collisional (SCi) or Hall-Resistive (HRi), but its density scaling is too week

$$\alpha_{n,SCi\ or\ HRi} = 0.25$$

- Nonlinear or toroidal effects? Still, there are missing physics in linear regimes





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Theory has been successfully extended with electron viscosity

- Earlier methods through a single 2nd ODE extended with electron viscosity

$$\frac{d}{dp}\left[\frac{p^2}{\underbrace{\frac{D^2(\tau+1)P_e}{c_\beta^2}}_{\text{From parallel Ohm's law}}p^4+p^2+i(Q-Q_e)}\frac{dY}{dp}\right]-p^2G(p)Y=0,$$

[J. Waybright and J.-K. Park, Phys. Plasmas (2024)]

[Y. Lee et al., Phys. Plasmas (2025)]

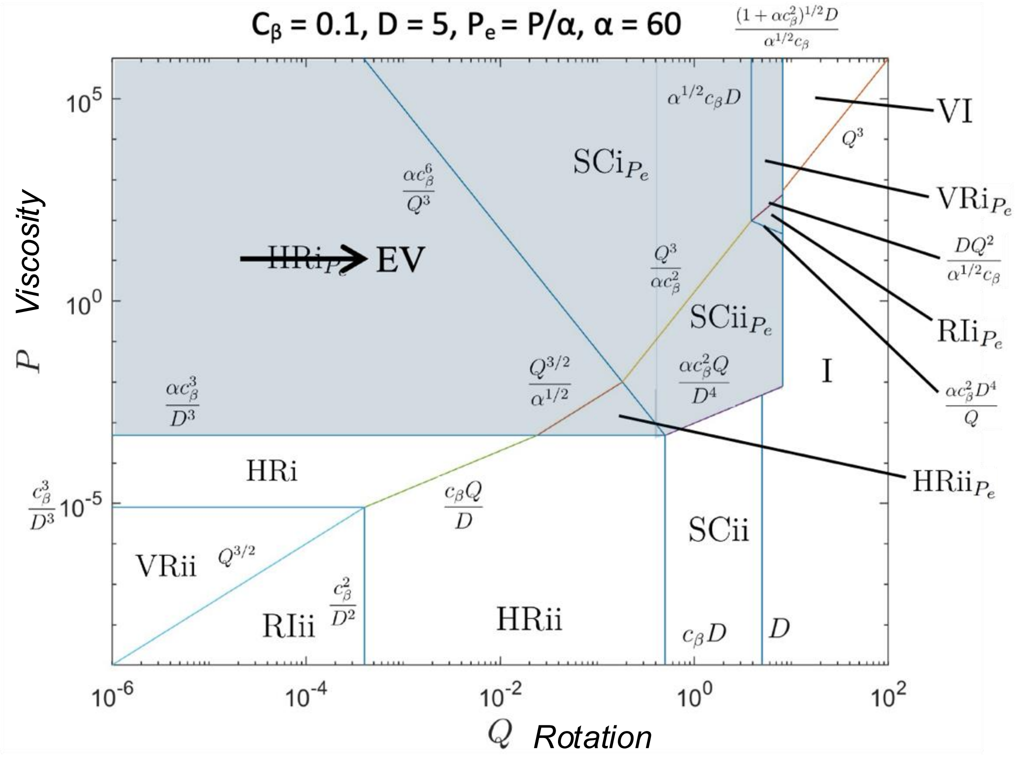
$$G(p)=\frac{\overbrace{PP_eD^2(\tau+1)p^6+\left(iP_eD^2(Q-Q_i)+Pc_\beta^2\right)p^4}^{\text{From the curl of Ohm's law}}+i(c_\beta^2+P)(Q-Q_i)p^2-Q(Q-Q_i)}{PD^2(\tau+1)p^4+\left(i(Q-Q_i)D^2+c_\beta^2\right)p^2+i(Q-Q_e)}.$$

- Identifying two new regimes and reproducing **strong density scaling**, indicating key mechanism may be viscosity rather than (or in addition to) nonlinearity or toroidicity

$$\hat{\Delta}_{SCiPe}=\frac{3\Gamma(1/4)i^{7/4}\pi c_\beta^{1/2}(Q-Q_e)(Q-Q_i)^{3/4}}{8\Gamma(7/4)D^2(\tau+1)P_e^{1/4}}. \longrightarrow \delta_{c,SCiPe}\sim \boldsymbol{n_e^{0.625}}B_\phi^{-1.626}R_0^{-0.75}$$

$$\hat{\Delta}_{EV}=\frac{3i\pi\Gamma(5/8)c_\beta^{5/4}(Q-Q_e)}{8^{3/4}\Gamma(11/8)D^{5/4}(\tau+1)^{5/8}P_e^{1/4}}. \longrightarrow \delta_{c,EV}\sim \boldsymbol{n_e^{0.69}}B_\phi^{-0.75}R_0^{0.125}$$

Small electron viscosity can change resonant response strongly through delicate balance in generalized Ohm's law



- Electron viscosity can change response strongly even with classical assumption $P_e = P_i\sqrt{m_e/m_i}$
- It is because electron dynamics is in delicate balance, as represented by generalized Ohm's law
  - Electron viscosity should be compared with resistivity, flow, Hall term, in Ohm's law, rather than ion viscosity
- Can play even more important role when electron viscosity is anomalous

New analytic prediction has also been numerically verified

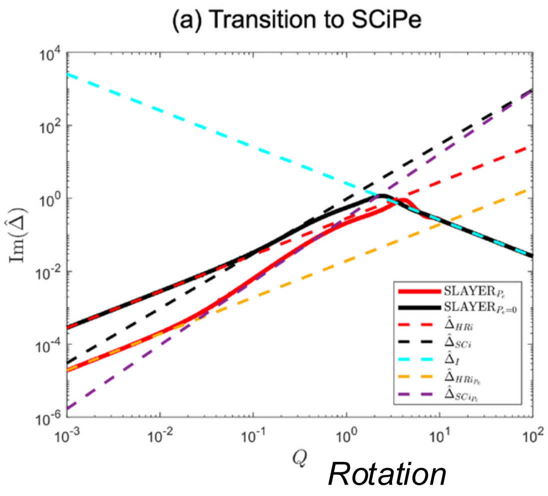
- 2^{nd} order linear ODE with exponential solution behavior → 1^{st} order nonlinear ODE with algebraic solution behavior by Riccati $W = (p/Y)(dY/dp)$

$$\frac{dW}{dp} = W\left(\frac{\frac{4D^2p^3(\tau+1)P_e}{c_\beta^2} + 2p}{\frac{D^2p^4(\tau+1)P_e}{c_\beta^2} + i(Q-Q_e) + p^2} - \frac{1}{p}\right) - \frac{W^2}{p} + pG(p)\left(\frac{D^2p^4(\tau+1)P_e}{c_\beta^2} + i(Q-Q_e) + p^2\right)$$

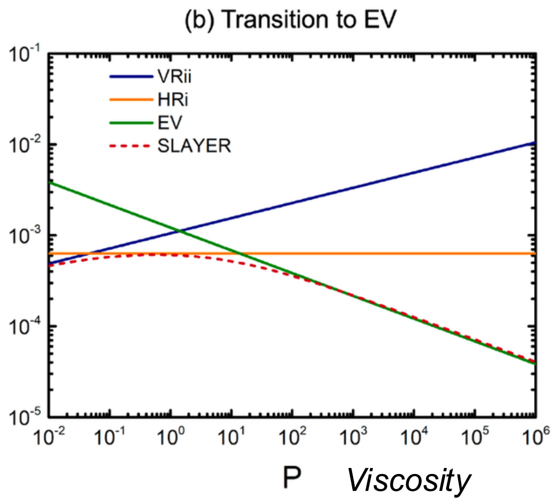
- As implemented in SLAYER code and used for verification

- Each asymptotic regimes are precisely reproduced by SLAYER computation

[J. Waybright et al., Phys. Plasmas (2024)]



[Y.S. Lee et al., Phys. Plasmas (2025)]



Ion parallel flow effects require full numerical integration

- Last piece is ion parallel flow perturbation – requiring full integration in either

In configuration space or *In Fourier space*

$$i(Q-Q_e)\tilde{\psi} = iX(\tilde{\phi}-\tilde{Z}) + \frac{d^2\tilde{\psi}}{dX^2} - (1+\tau)P_e\left(\frac{d^2\tilde{V}_z}{dX^2} + \frac{D^2}{c_\beta^2}\frac{d^4\tilde{\psi}}{dX^4}\right),$$

$$iQ\tilde{Z} = iQ_e\tilde{\phi} + iD^2X\frac{d^2\tilde{\psi}}{dX^2} + ic_\beta^2X\tilde{V}_z + \left(c_\beta^2 + (1-c_\beta^2)K\right)\frac{d^2\tilde{Z}}{dX^2} + P_eD^2\left(\frac{d^4\tilde{\phi}}{dX^4} - \frac{d^4\tilde{Z}}{dX^4}\right),$$

$$i(Q-Q_i)\frac{d^2\tilde{\phi}}{dX^2} = iX\frac{d^2\tilde{\psi}}{dX^2} + P\left(\frac{d^4\tilde{\phi}}{dX^4} + \tau\frac{d^4\tilde{Z}}{dX^4}\right) + P_e\left(\frac{d^4\tilde{\phi}}{dX^4} - \frac{d^4\tilde{Z}}{dX^4}\right),$$

$$\boxed{iQ\tilde{V}_z = -iQ_e\tilde{\psi} + iX\tilde{Z} + (P+P_e)\frac{d^2\tilde{V}_z}{dX^2} + P_e\frac{D^2}{c_\beta^2}\frac{d^4\tilde{\psi}}{dX^4}.}$$

$$i(Q-Q_e)\bar{\psi} = \frac{d(\bar{\phi}-\bar{Z})}{dp} - p^2\bar{\psi} - p^4P_e\frac{D^2}{c_\beta^2}(1+\tau)\bar{\psi},$$

$$i(Q-Q_i)p^2\bar{\phi} = \frac{d(p^2\bar{\psi})}{dp} - Pp^4(\bar{\phi}+\tau\bar{Z}) - P_ep^4(\bar{\phi}-\bar{Z}).$$

$$iQ\bar{Z} - iQ_e\bar{\phi} = -D^2\frac{d^2(p^2\bar{\psi})}{dp^2} - c_\beta^2p^2\bar{Z} + c_\beta^2\frac{d\bar{V}_z}{dp} + P_eD^2p^4(\bar{\phi}-\bar{Z}),$$

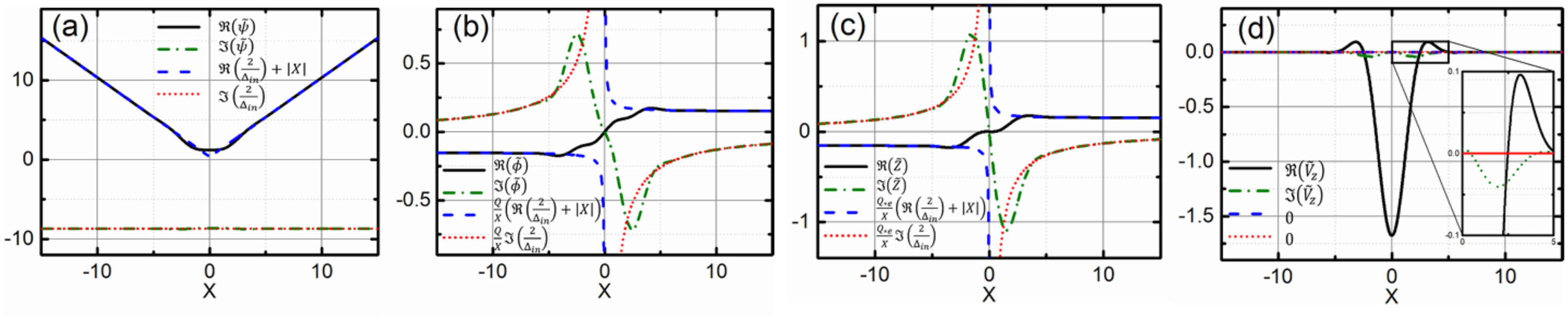
$$\boxed{iQ\bar{V}_z + iQ_e\bar{\psi} = \frac{d\bar{Z}}{dp} - (P+P_e)p^2\bar{V}_z + P_e\frac{D^2}{c_\beta^2}p^4\bar{\psi}.}$$

- A full solver for these high-order ODE system has also been successfully developed
  – In configuration space first by Y. S. Lee [Y. Lee et al., Nucl. Fusion (2024)]
  – Recently in Fourier space by R. Fitzpatrick's group [Private communication]

Fully reconstructed solution via Riccati matrix transformation clearly illustrates boundary phenomena across layer

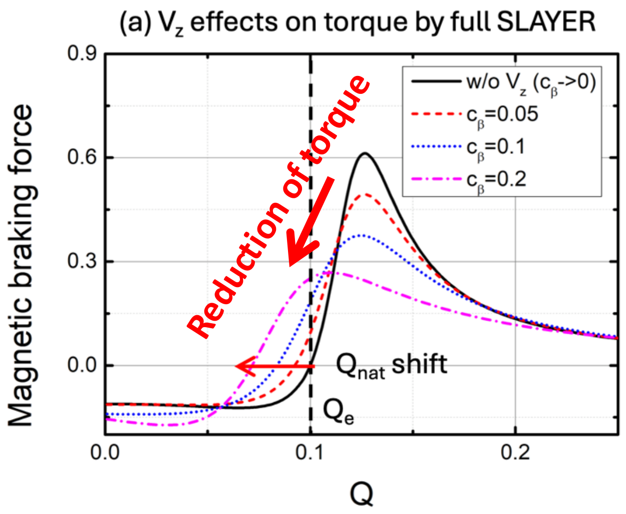
- Solution steepness in $X \in (0, \infty)$ has been controlled by Riccati matrix transformation [Y. Lee et al., Nucl. Fusion (2024)]
- This enables the full solution reconstruction in configuration space, elucidating boundary layer phenomena

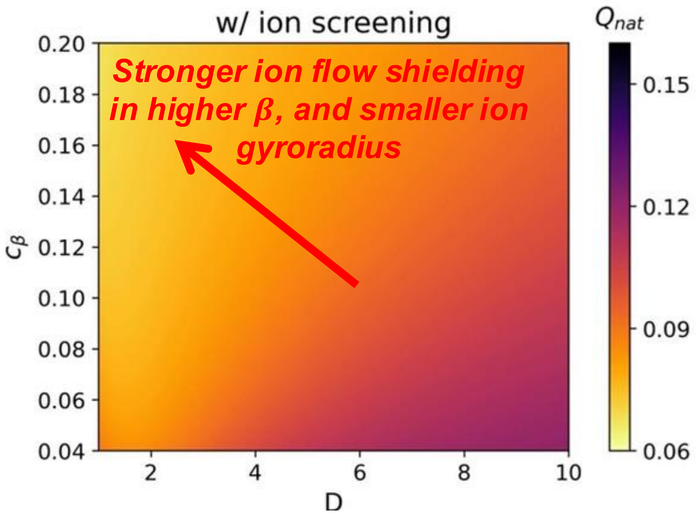
$\boldsymbol{\psi}$ $\boldsymbol{Z}$ $\boldsymbol{\phi}$ $\boldsymbol{V_z}$



Ion parallal flow can shield field penetration strongly in high β

- Linear regime in low Q has $\Delta_{in} \propto (Q - Q_e)$, resulting $\tau_\phi \propto \mathrm{Im}\,(1/\Delta_{in}) \to \infty\ as\ Q \to Q_e$
- Singularity point is called **natural frequency** $Q_{nat} = Q_e$, leading to the concept of field penetration to nonlinearly growing islands
- Turns out that ion parallel flow removes singularity by strong screening, especially in high-β reactor conditions





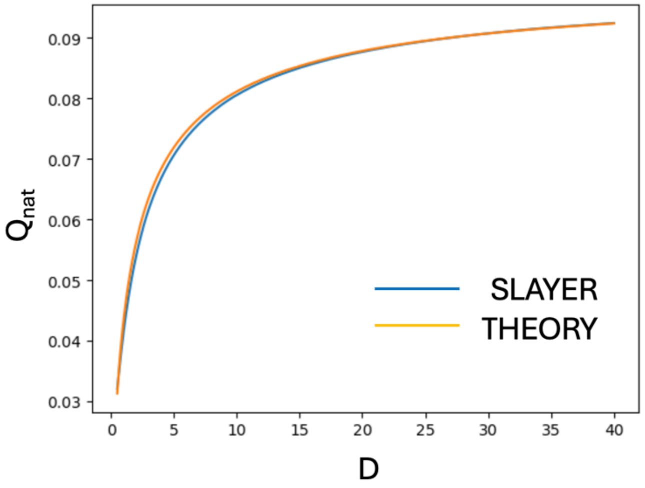
New analytic theory with multiple-layer breakdown verifies ion parallel flow screening and natural frequency shift

- Extended asymptotic matching with multiple layers has been developed
- For example, in HRi regime:

High-order correction by ion parallel flow

$$\hat{\Delta}_{HRiVz} = i\pi(Q-Q_e)\left(2\frac{\Gamma(3/4)}{\Gamma(1/4)}\left(\frac{c_\beta^2}{(1+\tau)D^2}\right)^{1/4} + (2^{7/4})\overbrace{\frac{4}{5}\frac{\Gamma(13/8)}{\Gamma(3/8)}(1+\tau)P\frac{Q}{Q-Q_e}\left(\frac{c_\beta^2}{(1+\tau)D^2P^2}\right)}^{\text{High-order correction by ion parallel flow}}{}^{5/8}\right)$$

(b) Comparison for natural frequency Q_{nat}



[On the courtesy of J. Waybright (PU)]

- Incredible agreement verifies strong ion flow screening
- Also verifying surprising implication – **There may be no field penetration at all in high-β reactor conditions** - to be validated in experiments

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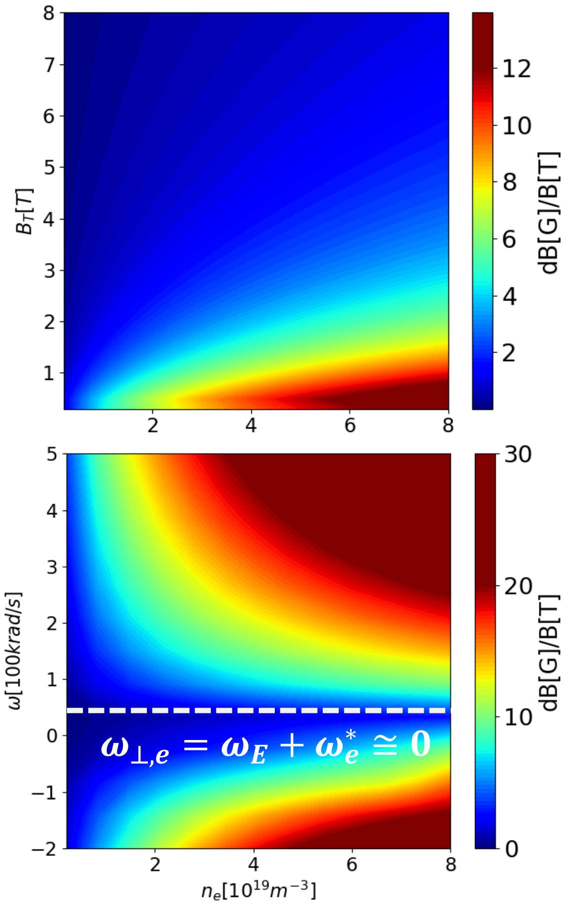
Extended MHD elevates overall density and B_ϕ scaling

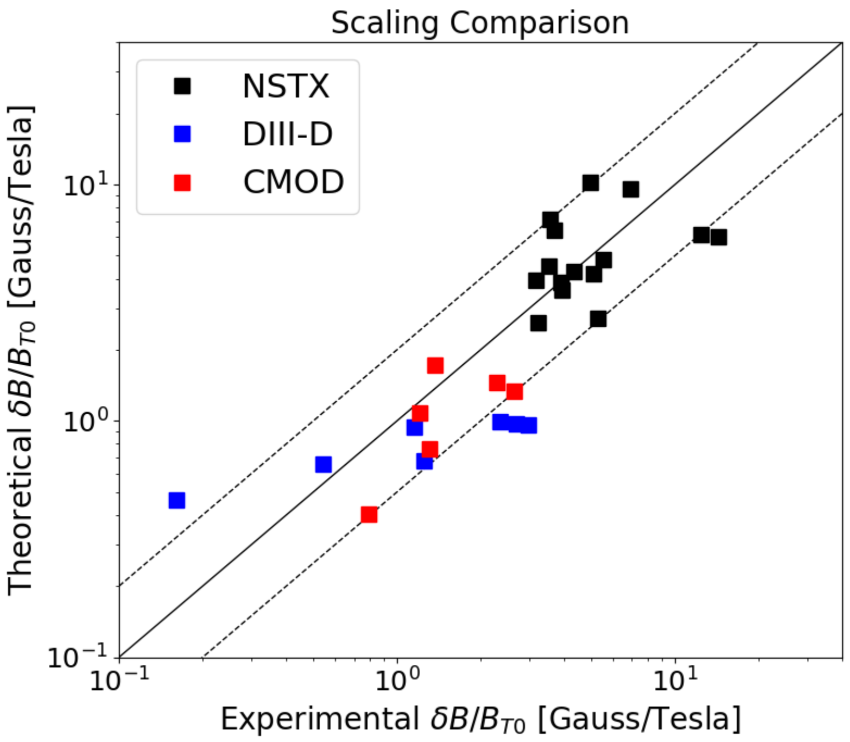
- Layer conditions can be under transition regimes and regimes are not always clearly separable in reality
- Full SLAYER computation for parametric scaling in wide experimental conditions
  - $3 \times 10^{18} m^{-3} < n_e < 8 \times 10^{19} m^{-3}, 0.3\mathrm{T} < \mathrm{B}_\phi < 8\mathrm{T},$ $-200\mathrm{krad/s} < \omega_\phi < 500\mathrm{krad/s}$
  - Separating rotation and viscosity (=constant) as an independent variable
- Scaling becomes favorable to experiments, although inter-parameter relation must be carefully accounted

$$\delta_c \sim n_e^{0.82} B_\phi^{-1.07} \omega_{\perp,e}^{0.79}$$



Applications to ITPA EF threshold database show feasibility

- A set of EF locked mode threshold data having TS diagnostics in Ohmically heated plasmas is tested with SLAYER
  - In order to minimize uncertainties in externally driven torque
  - With assumption of viscosity $P = 3.0$, $\omega_E = 0, n_i = n_e, T_i = T_e$
- Initial testing shows a possibility of good field penetration threshold prediction
- SLAYER with electron viscosity and ion parallel flow will also be tested for data with profiles and transport coefficients



Concluding remarks

- Two-fluid drift-MHD analytic theory extended with electron viscosity and parallel ion flow offers new insights for field penetration to magnetic islands
- Key findings:
  - Electron viscosity can enhance positive density correlation for field penetration threshold, better aligned with empirical scaling
  - Parallel ion flow perturbation becomes more important in high-β reactor conditions and can substantially shield resonant field along with shifted natural frequency
- These new findings are verified numerically, which is being tested against empirical scaling and EF database for validation
- Future work will also include the effects of NTV effects, directly incorporating anisotropic tensor, as its effects can be important in low-collisionality conditions