TH/8-1

DIAMAGNETIC MHD EQUATIONS FOR PLASMAS WITH FAST FLOW AND ITS APPLICATION TO ELM ANALYSIS IN JT-60U AND JET-ILW

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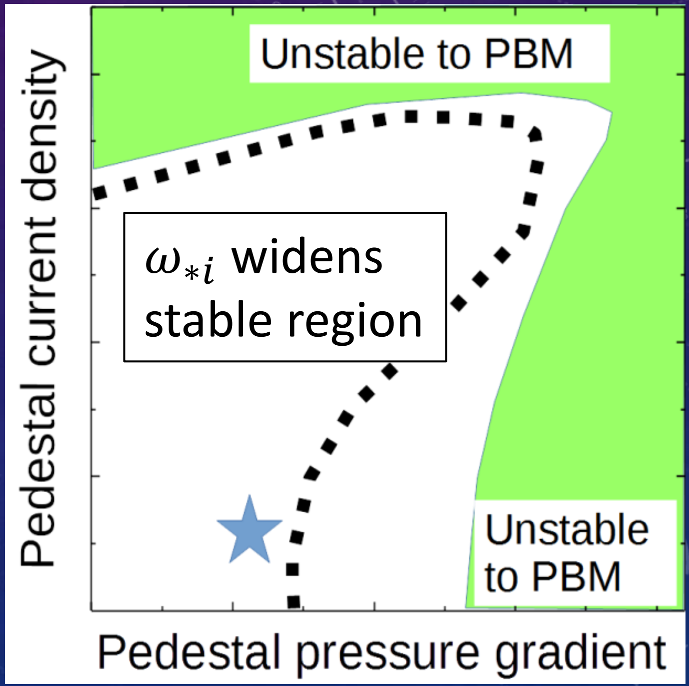
BACKGROUNDS

- Peeling-ballooning mode (PBM) with the toroidal mode number n is intermediate ($\sim$30) triggers the type-I ELM. [Snyder PoP2002 etc.]
- Results in JT-60U and JET-ILW imply higher-n modes sometimes trigger the ELM.[Aiba NF2011, Giroud PPCF2015 etc.]
- "Non-ideal" effects have impact on the stability to high-n MHD modes.
- Stable region becomes wider by the "ion diamagnetic drift (ω_{*i})" effect analyzing with the stability condition[Tang NF1980 etc.]

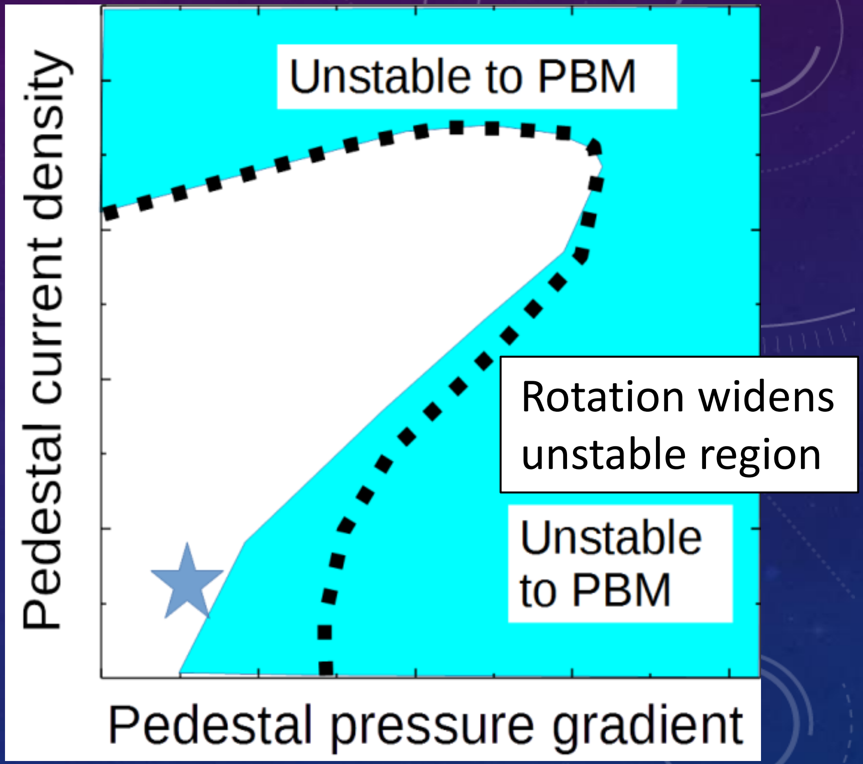
$$\gamma \geq 0.5\omega_{*i}.$$



Discrepancy between experiments and numerical analyses becomes larger.

ROTATION HAS DESTABILIZING EFFECTS ON MHD MODES

- Plasma rotation with shear can destabilize PBM. [Snyder NF2007, Aiba NF2009]
- This destabilization plays an important role on type-I ELM stability in JT-60U. [Aiba NF2010]
- Rotation can destabilize intermediate to high-n PBM.



How does rotation act on the PBM stability including the ω_{*i} effect?

DIAMAGNETIC MHD MODEL

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Fluid models for ELM stability analysis

$(v_E$: ExB drift vel. v_{thi}: ion thermal vel., Ω_i: Ion cyclotron freq.$)$

Diamagnetic MHD model [Aiba PPCF2016]:

$$v_E/v_{thi} \sim O(\delta^{\alpha}),\ \omega_0/\Omega_i \sim O(\delta^{1+\alpha}),\ 0<\alpha<0.5$$

$$m_i N\left(\left(\frac{\partial}{\partial t}+(\boldsymbol{V}_{MHD}\cdot\nabla)\right)(\boldsymbol{V}_E+V_{\parallel}\boldsymbol{b})+(\boldsymbol{V}_{*i}\cdot\nabla)\boldsymbol{V}_E\right)=\boldsymbol{J}\times\boldsymbol{B}-\nabla P.$$

$$\frac{\partial N}{\partial t}+(\boldsymbol{V}_{MHD}\cdot\nabla)N+N\nabla\cdot\boldsymbol{V}_{MHD}=0,$$

$$\frac{\partial P}{\partial t}+(\boldsymbol{V}_{MHD}\cdot\nabla)P+\Gamma P\nabla\cdot\boldsymbol{V}_{MHD}=0,\qquad \boldsymbol{E}+\boldsymbol{V}_{MHD}\times\boldsymbol{B}=0,$$

$$\boldsymbol{V}=\boldsymbol{V}_{MHD}+\boldsymbol{V}_{*i}=\boldsymbol{V}_E+V_{\parallel}\boldsymbol{b},\quad \boldsymbol{V}_E=\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2},\quad \boldsymbol{V}_{*i}=\frac{\boldsymbol{B}\times\nabla p_i}{eZNB^2},$$

N: number density, $\boldsymbol{V}$: velocity, P: pressure, Γ: heat capacity ratio,

$\boldsymbol{E}$: electric field, $\boldsymbol{B}$: magnetic field, $\boldsymbol{J}$: plasma current, $\boldsymbol{b}\equiv\boldsymbol{B}/B$,

e: elementary charge, m_i: ion mass, Z: effective charge, p_i: ion pressure

EXTENDED FRIEMAN-ROTENBERG EQUATION

By introducing plasma displacement $\boldsymbol{\xi}$, the derived basic equations can be linearized as follows; an "extended Frieman-Rotenberg equation".

$$\rho_0 \frac{\partial^2 \xi}{\partial t^2} + 2\rho_0 \left(\boldsymbol{V}_{0,MHD} \cdot \nabla\right) \frac{\partial \xi}{\partial t} + \rho_0 \left(\boldsymbol{V}_{0,*i} \cdot \nabla\right) \frac{\partial \xi_\perp}{\partial t} = \boldsymbol{F}_{MHD} + \boldsymbol{F}_{*i},$$

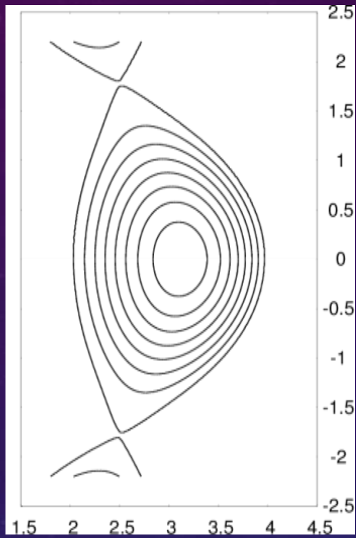
$$\begin{aligned} \boldsymbol{F}_{MHD} &= \boldsymbol{J}_0 \times \boldsymbol{B}_1 + (\nabla \times \boldsymbol{B}_1) \times \boldsymbol{B}_0 - \nabla P_1 \\ &\quad + \nabla \otimes \left[\rho_0 \boldsymbol{\xi} \otimes (\boldsymbol{V}_0 \cdot \nabla) \boldsymbol{V}_{0,MHD} - \rho_0 \boldsymbol{V}_0 \otimes \left(\boldsymbol{V}_{0,MHD} \cdot \nabla\right) \boldsymbol{\xi}\right], \\ \boldsymbol{F}_{*i} &= \frac{\rho_0}{2eZ_{eff} N_0 B_0^2} \{(\nabla \cdot (\boldsymbol{\xi} \times \nabla P_0) \boldsymbol{B}_0 - (\boldsymbol{B}_0 \cdot \nabla \mathrm{P}_0) \nabla \times \boldsymbol{\xi}) \cdot \nabla\} \boldsymbol{V}_{0,MHD,\perp} \\ &\quad + \nabla \otimes \left[\rho_0 \boldsymbol{\xi} \otimes \left(\boldsymbol{V}_{0,*i} \cdot \nabla\right) \boldsymbol{V}_{0,MHD} - \rho_0 \boldsymbol{V}_{0,*i} \otimes \left(\boldsymbol{V}_{0,MHD} \cdot \nabla\right) \boldsymbol{\xi}\right], \end{aligned}$$

Assumptions $\quad \nabla \cdot \boldsymbol{\xi} = 0, \quad (\boldsymbol{B} \cdot \nabla) \boldsymbol{\xi} \ll 1$

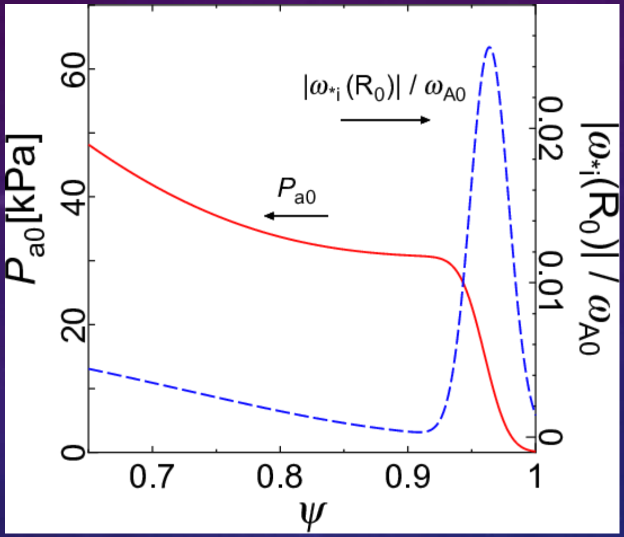
The MINERVA-DI code has been developed to solve this equation.

PBM STABILITY WITH $\boldsymbol{\omega_{*i}}$ IS ANALYZED IN A ROTATING TOKAMAK

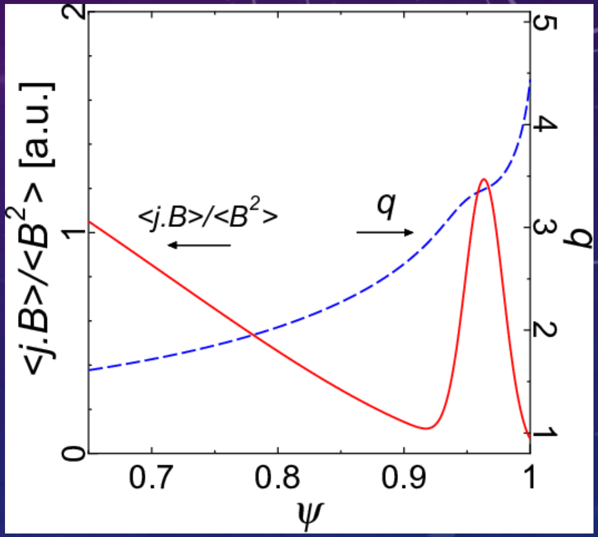
Contours of ψ



p and $|\omega_{*i}|$



$\langle \boldsymbol{j} \cdot \boldsymbol{B} \rangle$ and q



- PBM stability is analyzed in D-shaped (double-null) plasma.
- Density is assumed as $N = 5.0 \times 10^{19} [1/m^3]$.
- PBM stability is analyzed for $1 \leq n \leq 40$.

ROTATION CAN MINIMIZE THE ω_{*i} EFFECT ON PBM

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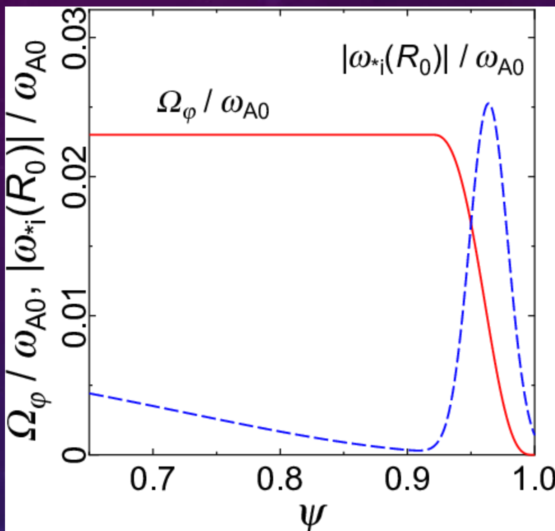
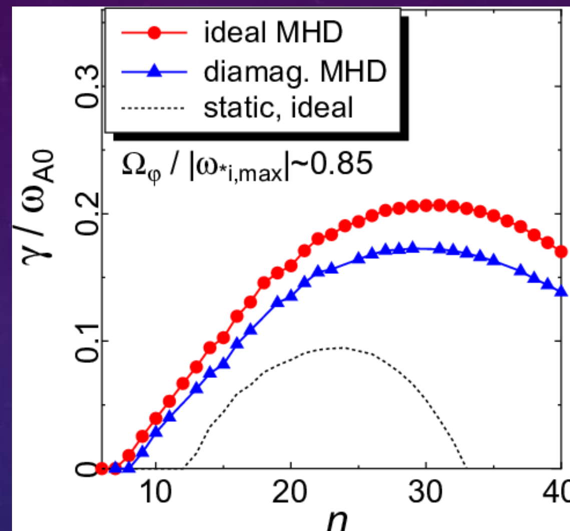
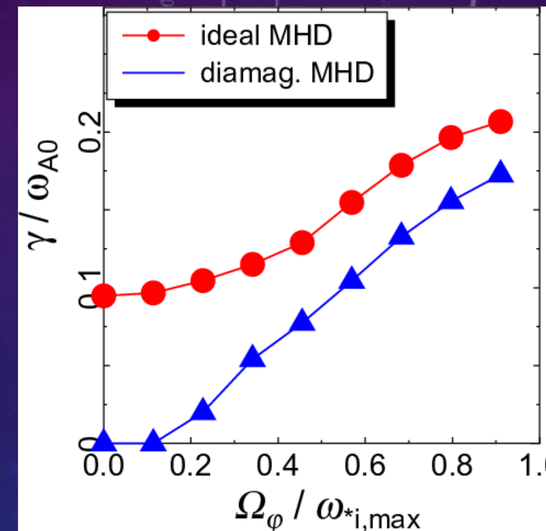
Ω_ϕ and $|\omega_{*i}|$



γ vs n



γ_{max} vs $\Omega_\phi / |\omega_{*i,max}|$



- Plasma rotation excites PBM, which is stabilized by ω_{*i} in static case.
- The threshold rotation frequency Ω_ϕ is smaller than ω_{*i}.
- When Ω_ϕ becomes comparable to ω_{*i}, PBM stability is not affected so much by ω_{*i}

⇒ Plasma rotation minimizes the ω_{*i} effect on PBM stability.

Type-I ELMy H-mode Discharge in JT-60U

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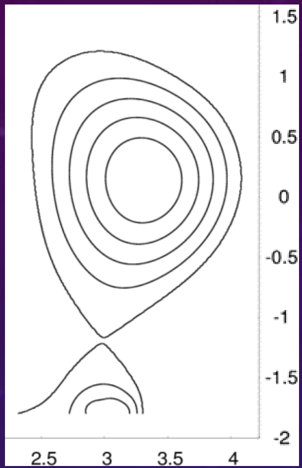
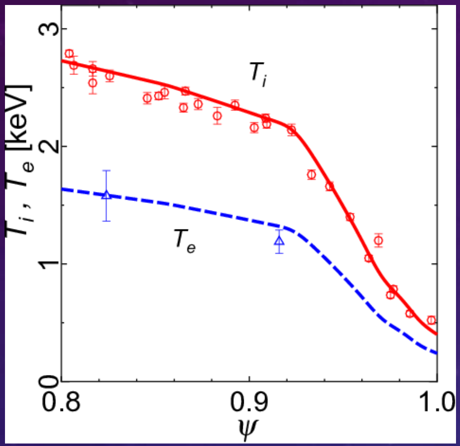
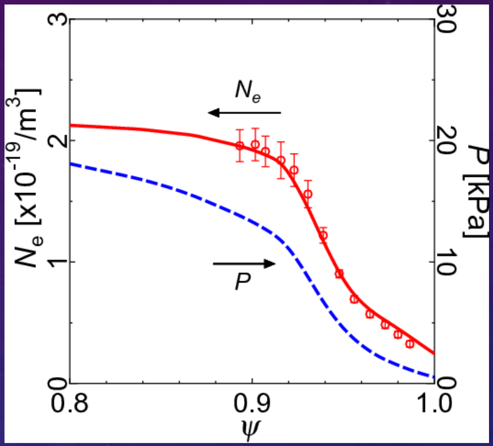


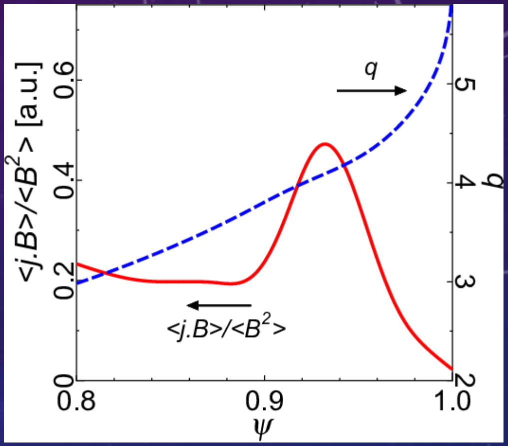
T_i ,T_e



N_e ,P



$j_{\parallel}$, q



- Plasma profiles were measured with CXRS $[T_i, \Omega_\phi(C)]$, LiBP $[n_e]$, TS $[T_e]$; note that T_e profile is assumed as $T_e = 0.6T_i$.
- Current density near pedestal is estimated as the bootstrap current j_{BS}.
- PBM stability is analyzed for $1 \leq n \leq 40$.

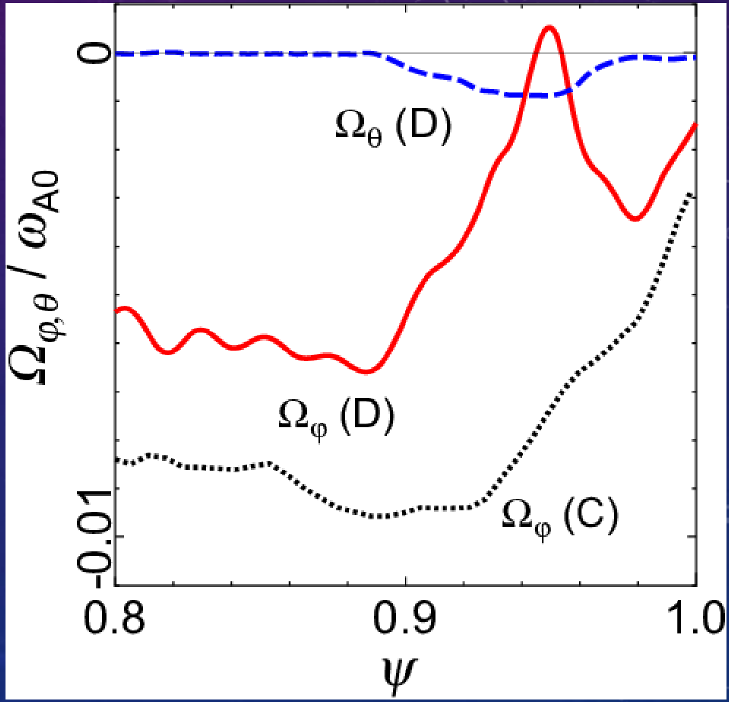
ROTATION PROFILE IS DETERMINED BASED ON THE NEOCLASSICAL THEORY

- Deuterium rotation profile is evaluated based on the neoclassical theory with MI by CHARROT code [Honda NF2013].

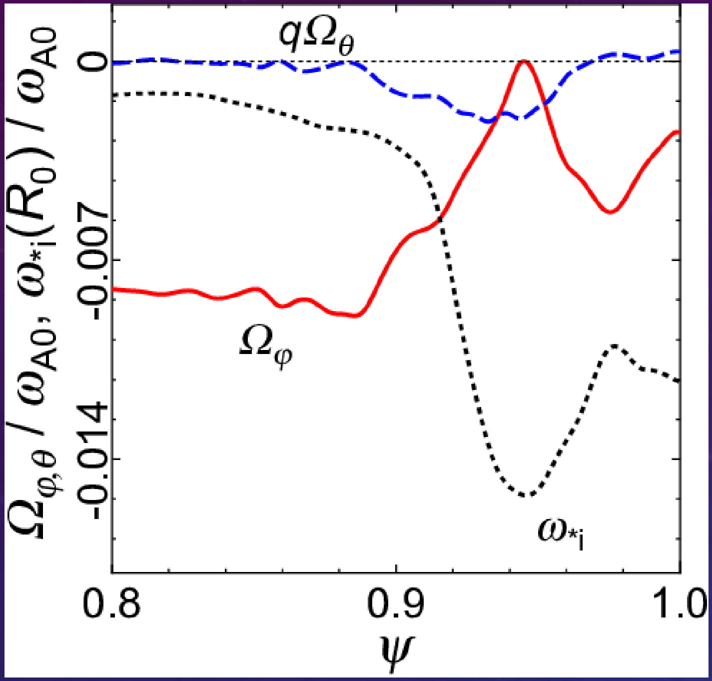
- CHARROT determines the profile by calculating radial electric field through radial force balance equation with measured $\Omega_{\phi,imp}, T_{imp}$, and N_{imp} evaluated with Z_{eff}.

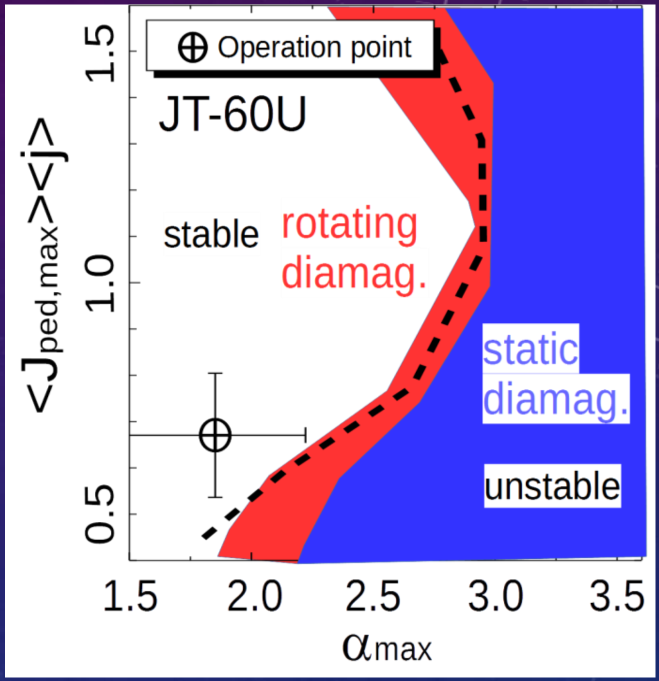
- Both toroidal and poloidal rotation are taken into account in the stability analysis; slow poloidal rotation is assumed.

Profiles of $\Omega_{\phi}(C), \Omega_{\phi}(D), \Omega_{\theta}(D)$



PLASMA ROTATION COUNTERACTS ω_{*i} EFFECT ON PBM STABILITY BOUNDARY IN JT-60U





- Stabilizing effect due to ω_{*i} pushes the stability boundary away from the operation point.
- Rotation realizes to bring back the boundary near the operation point.

How about in JET-ILW plasmas?

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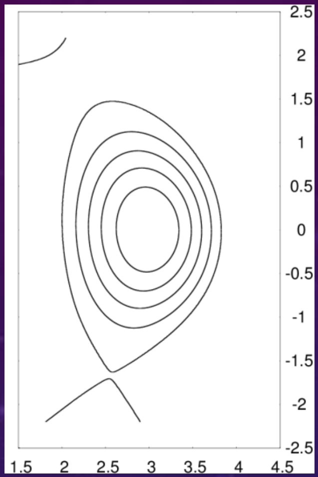
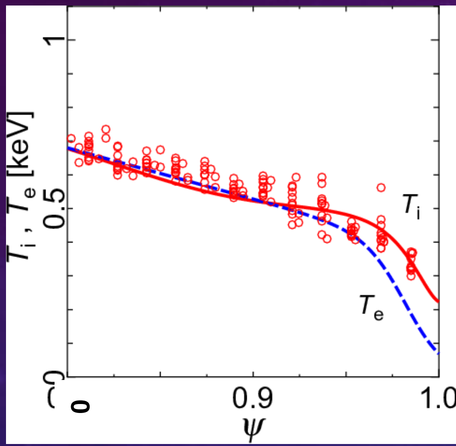
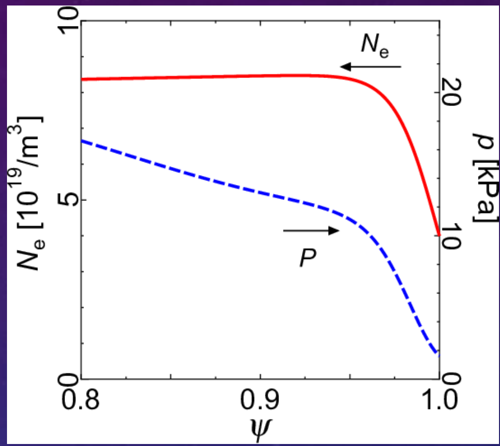


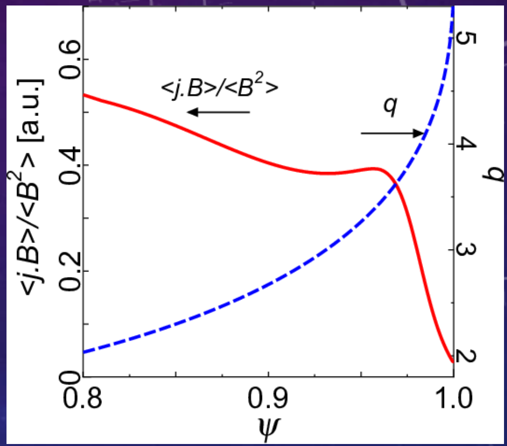
T_i, T_e



N_e, P

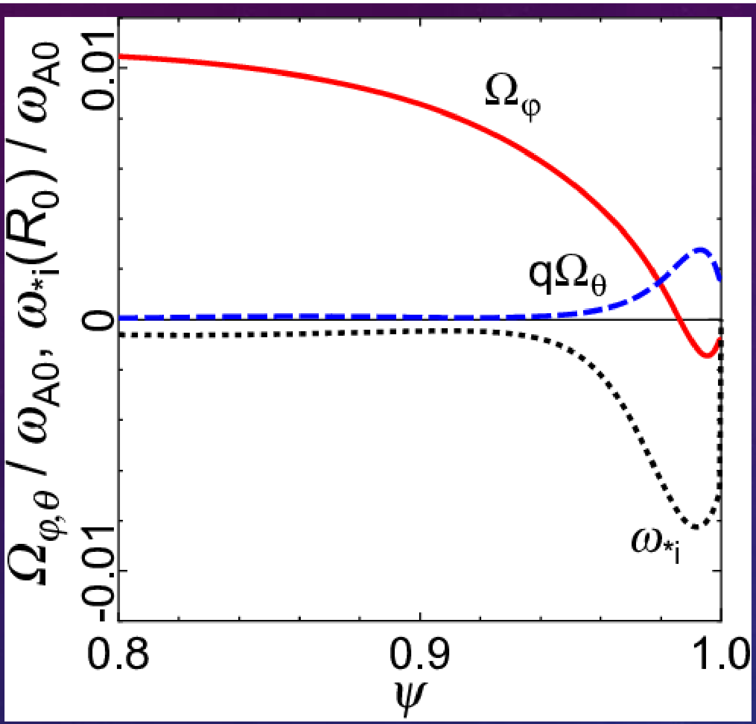


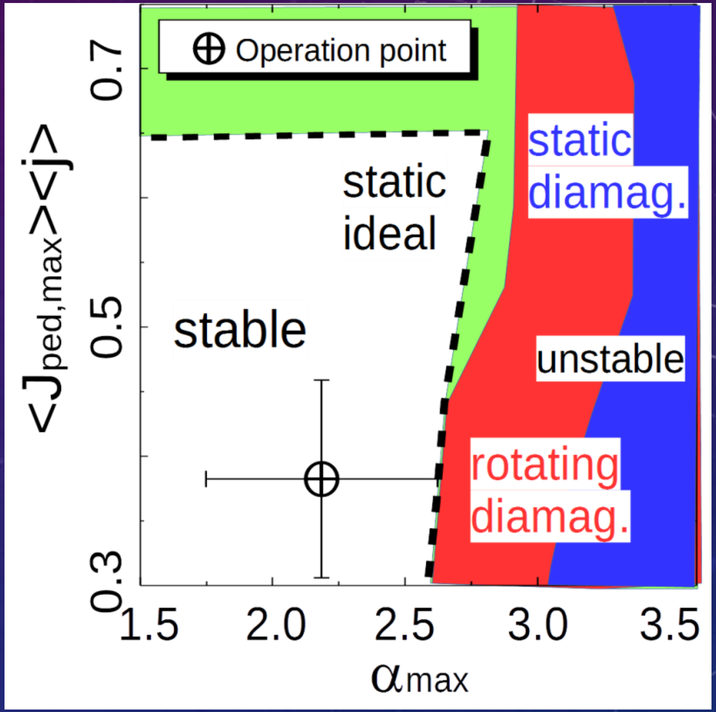
$j_{\|}, q$



- Plasma profiles were measured with CXRS $[T_i, \Omega_\phi(C)]$, HRTS$[n_e, T_e]$.
- Deuterium rotation and j_{BS} profiles are estimated with CHARROT.
- High density reduces j_{BS} due to increasing collisionality.
- The stability of $2 \le n \le 100$ modes is analyzed numerically.

Plasma Rotation can Bring PBM Stability Boundary near Operation Point in JET-ILW



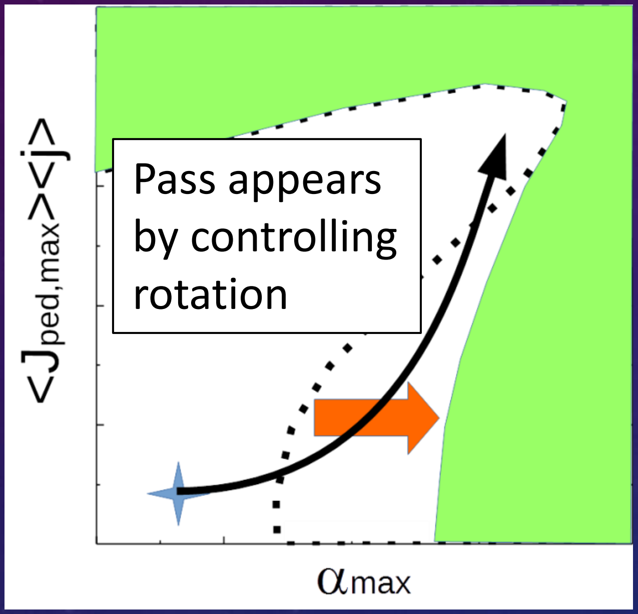


Plasma rotation minimizes the ω_{*i} stabilizing effect on PBM, and brings back the boundary near the operation point.

Rotation plays an important role on the ELM stability in JT-60U and JET-ILW.

DISCUSSION FOR GETTING HIGH PEDESTAL ROBUSTLY IN ITER

Stability diagram determined with ω_{*i} and rotation.



- Trajectory during pedestal build-up doesn't intersect with the stability boundary => O.K..
- In case trajectory intersects with the boundary, we have to consider how to avoid the situation as the JET-ILW case.
- To make the pass to the corner,
  - ✓ Increasing j_{ped} by reducing collisionality
  - ✓ Seeding low-Z impurity [Dunne EX/3-5, Giroud EX/P6-3]
  - ✓ Increasing core pressure [Urano EX/3-4, Chapman EX3-6]
  - ✓ Minimizing rotation [this work]

Predicting rotation and analyzing the pedestal stability with the rotation help to obtain high pedestal robustly in ITER.

SUMMARY

- Diamagnetic MHD model has been developed to analyze ion diamagnetic drift effect on peeling-ballooning (PBM) stability in rotating plasmas.
- An extended Frieman-Rotenberg equation has been derived from the diamagnetic MHD model.
- MINERVA-DI code was developed to solve the equation.
- It is found that plasma rotation can minimize the ion diamagnetic drift (ω_{*i}) effect on PBM stability.
- Minimization of ω_{*i} effect by rotation plays an important role on PBM stability in both JT-60U and JET-ILW.
- Stability analysis including ω_{*i} and rotation helps to realize high pedestal performance robustly in ITER.

APPENDIX

APPROXIMATIONS USED FOR SIMPLIFYING THE DRIFT MHD MODEL

We simplify the model with Frieman-Rotenberg formalism.

Approximations:

1. In Faraday's law, non-ideal term is neglected.

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \boldsymbol{E} = -\nabla \times \left(\boldsymbol{V}_{MHD} \times \boldsymbol{B} + \frac{1}{eN} \nabla p_{e\parallel} \right)$$

This approximation can be justified when

   a. Rotation is enough slow compared to ion thermal velocity.

   b. Density N or temperature T is constant in a plasma

   c. Functional form of N is proportional to that of T.

2. Magnetic field varies slowly $\nabla \times (\boldsymbol{b}/B) \ll 1$.
This helps to change the continuity equation as follows.

$$\left.\frac{DN}{Dt}\right|_{MHD} + N\nabla \cdot \boldsymbol{V}_{MHD} = 0$$

POLOIDAL ROTATION CAN AFFECT EDGE MHD STABILITY

Difference of the mode freq. $n\omega$ from the Doppler-shifted freq. $\boldsymbol{k}\cdot\boldsymbol{v}$ is essential for destabilizing edge MHD modes.[Aiba NF2011].

$$\boldsymbol{k}\cdot\boldsymbol{v} = -\imath n\Omega_\phi + \imath m\Omega_\theta$$

Ω_ϕ: Toroidal rotation Freq., Ω_θ: Poloidal Rotation freq.
n: Toroidal mode num., m: poloidal mode num.

For the Fourier harmonics which satisfy $m - nq = 0$, $m\Omega_\theta \sim n\Omega_\phi$ even when $v_\theta = (nr/mR)v_\phi \sim 0.1 v_\phi$ if $q = 3$ and $R/r \sim 3.3$.

$$= \imath\Omega_\parallel(\boldsymbol{k}\cdot\boldsymbol{B}/B) - \imath n\Omega_{E\times B}$$

$\Omega_\parallel$: Freq. parallel to $\boldsymbol{B}$
$\Omega_{E\times B}$: Freq. perp. to $\boldsymbol{B}$

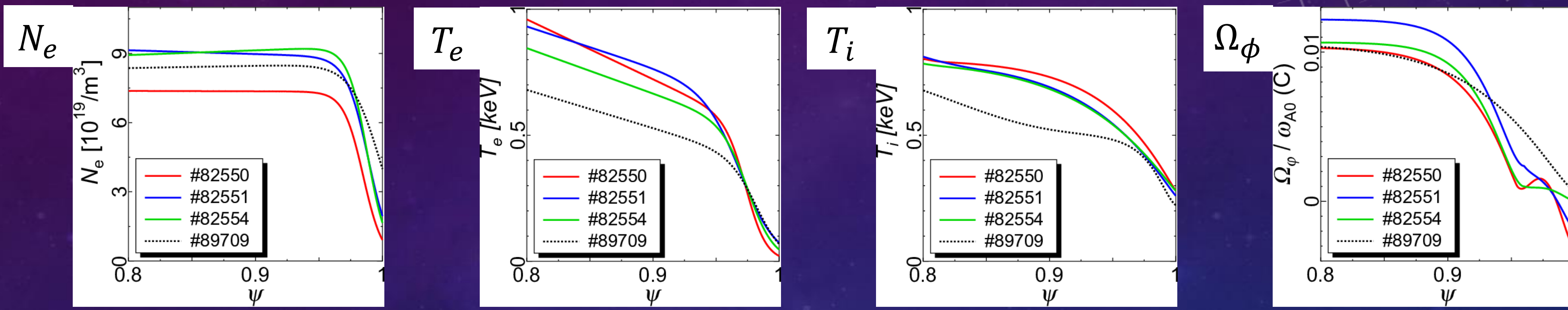
Near rational surfaces, $\boldsymbol{k}\cdot\boldsymbol{v} \sim 0 \rightarrow \Omega_{E\times B}$ will be important.

MINERVA(-DI) can identify the poloidal rotation effect on MHD stability (at present, poloidal rotation effect on equilibrium is neglected.)

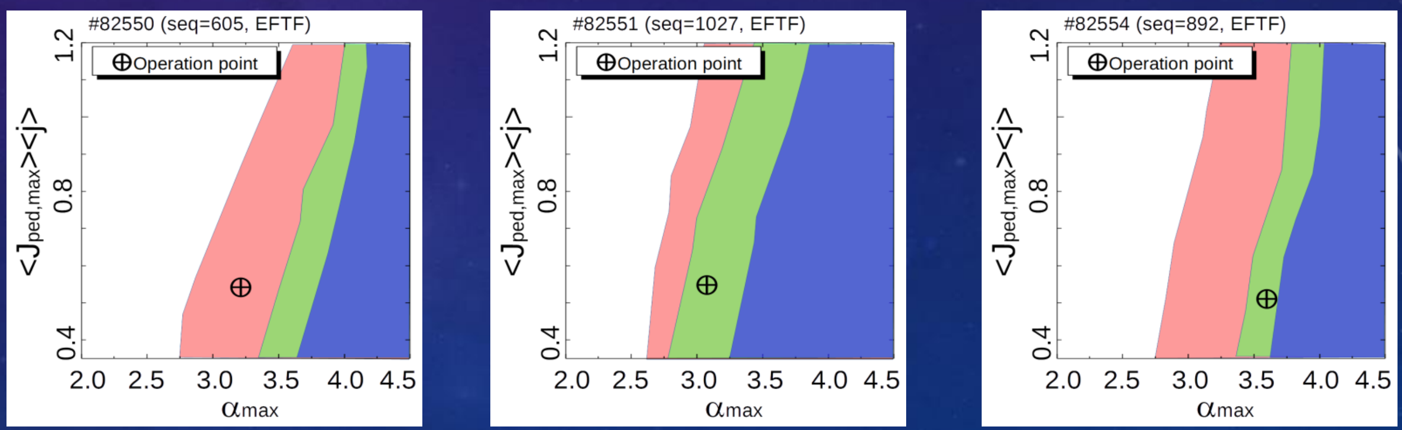
Re-evaluate stability diagram with not only Ω_ϕ but also Ω_θ.

VALIDATION STUDY OF THE NEW MODEL FOR ELM STABILITY ANALYSIS IN JET-ILW

To confirm the validity of the new model for analyzing ELM stability in JET-ILW, stability diagrams were made in several shots.



Red: unstable w/o ω_{*i} in static plasmas
Blue: unstable with ω_{*i} in static plasmas
Green: unstable with ω_{*i} in rotating plasmas



In any cases, the diamagnetic MHD model is the best to obtain the boundary near the operation point.

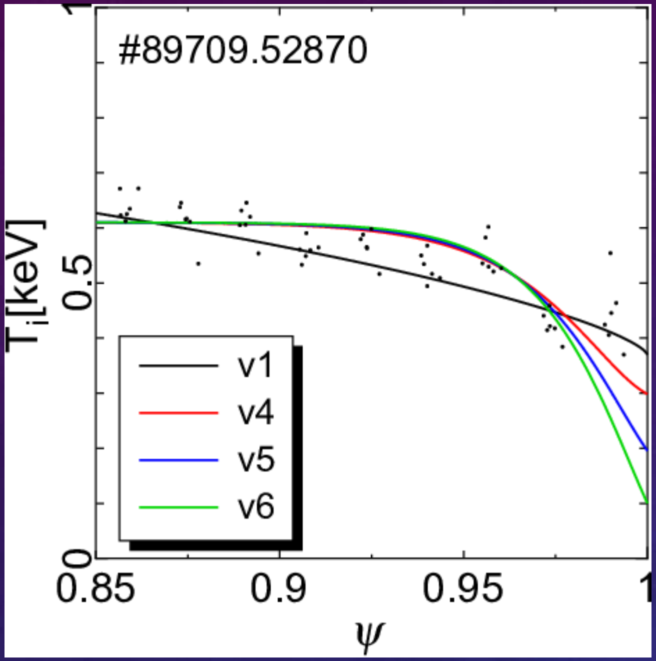
SENSITIVITY STUDY OF STABILITY ON T_i PROFILE (1)

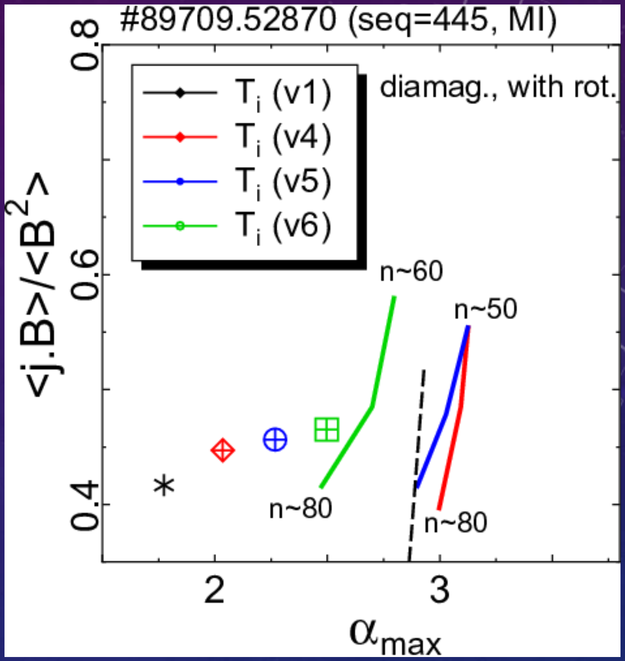
The stability with ω_{*i} and rotation is affected by T_i profile, because

1. increase of ω_{*i} due to
$$\omega_{*i} = \frac{n}{e_i n_i}\frac{dp_i}{d\psi}.$$
2. Increase of v_θ due to neoclassical theory as
$$v_\theta \propto \frac{1}{Z_i}\frac{dT_i}{d\psi}.$$

Since ω_{*i} stabilizes PBM but Ω_θ destabilizes it, it is necessary to understand the sensitivity of stability on T_i profile.

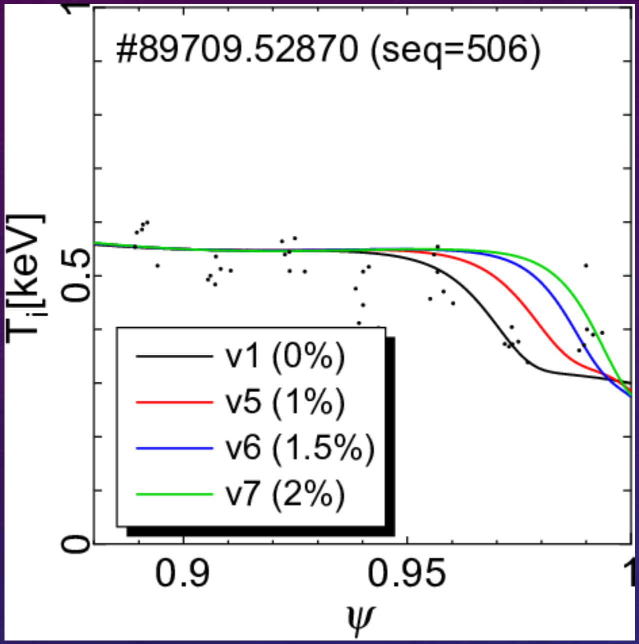
SENSITIVITY STUDY OF STABILITY ON T_i PROFILE (2)

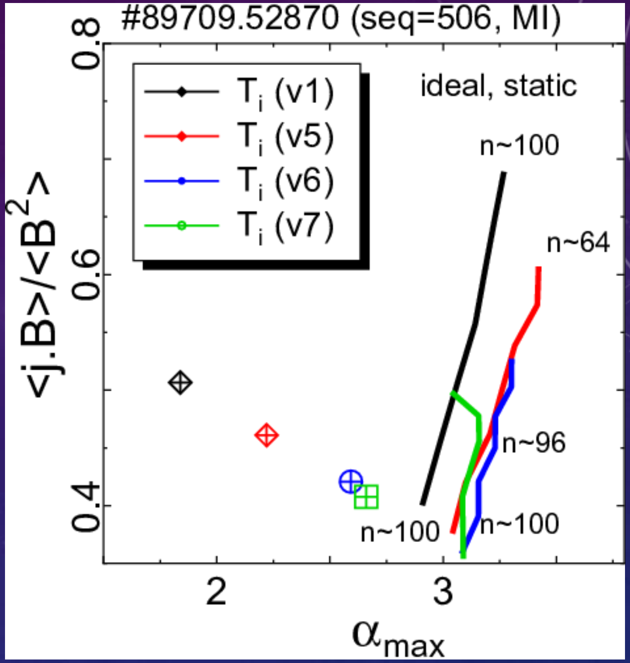




- Plasma toroidal rotation contributes to shift back the boundary to the lower α_{max} side.
- In particular, with T_i (v6), the boundary moves close to the O.P. (within 10%).
- The stability is sensitive to T_i profile near very edge; $T_{i,sep} = 200\text{eV}$ (v5), 100eV (v6).

SENSITIVITY STUDY OF STABILITY ON T_i PROFILE (3)





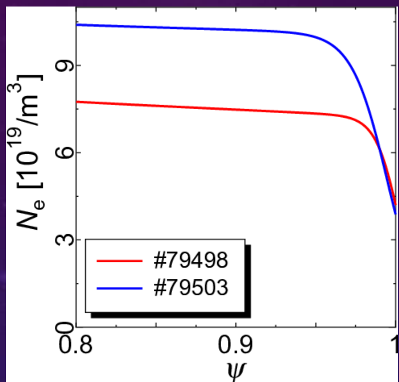
- By shifting the T_i profile outward, the α_{max} value increases due to that both $\frac{dT}{d\psi}$ and $\frac{dn}{d\psi}$ become large at the same radial position.
- The stability boundaries with different T_i profiles are similar to each other, but the O.P. moves to higher α_{max} side.

=> The difference between the O.P. and boundary becomes smaller as the T_i profile is shifted outward.

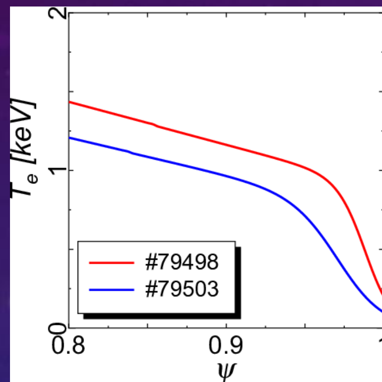
ELM STABILITY ANALYSIS IN JET-C WITH NEW MODEL (1)

The difference in stability determined with conventional and new methods was confirmed in JET-C; stability in JET-C has been well-explained with conventional method.

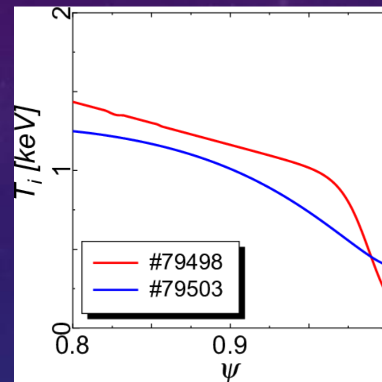
N_e



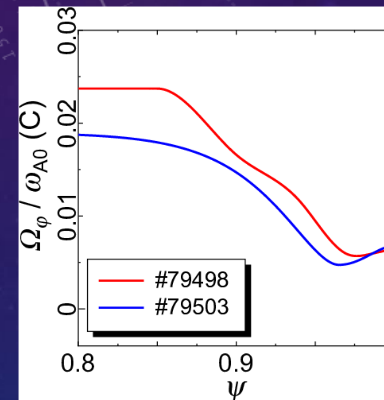
T_e



T_i



Ω_ϕ



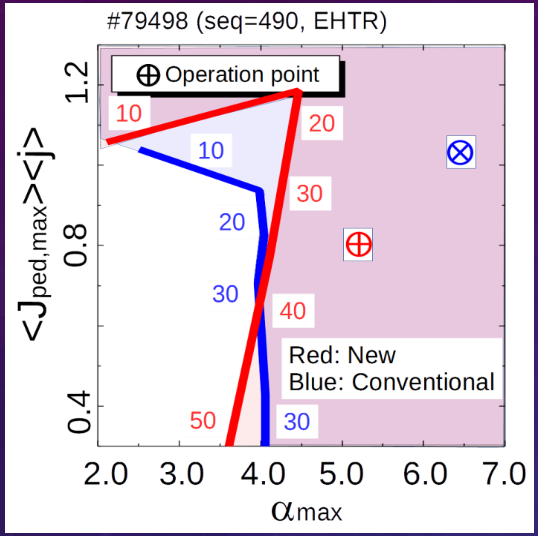
Conventional method:

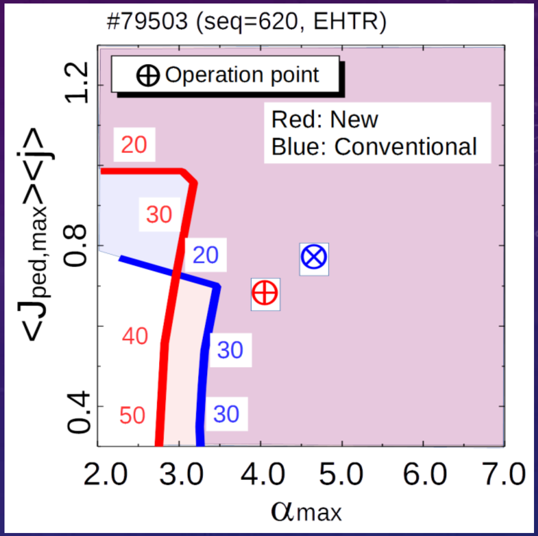
- Ideal stability in static plasma.
- Maximum n number analyzed is $n_{max} = 30$.
- Sauter model determines pedestal BS current with $T_i = T_e$.

New method:

- Diamagnetic stability with ω_{*i} and rotation.
- Maximum n number analyzed is $n_{max} = 100$.
- MI model determines pedestal BS current with measured T_i.

ELM stability analysis in JET-C with new model (2)





New method agrees well with experiments, and shows the difference from the conventional method as follows.

- #79498 (low density)
  - ✓ boundary is similar to the conventional one.
  - ✓ operation point approaches to the boundary.
- #79503 (high density)
  - ✓ Boundary and operation point shift to lower α_{max} side.