Stabilization of kink/peeling modes by coupled rotation and ion diamagnetic drift effects in QH-mode plasmas in DIII-D and JT-60U

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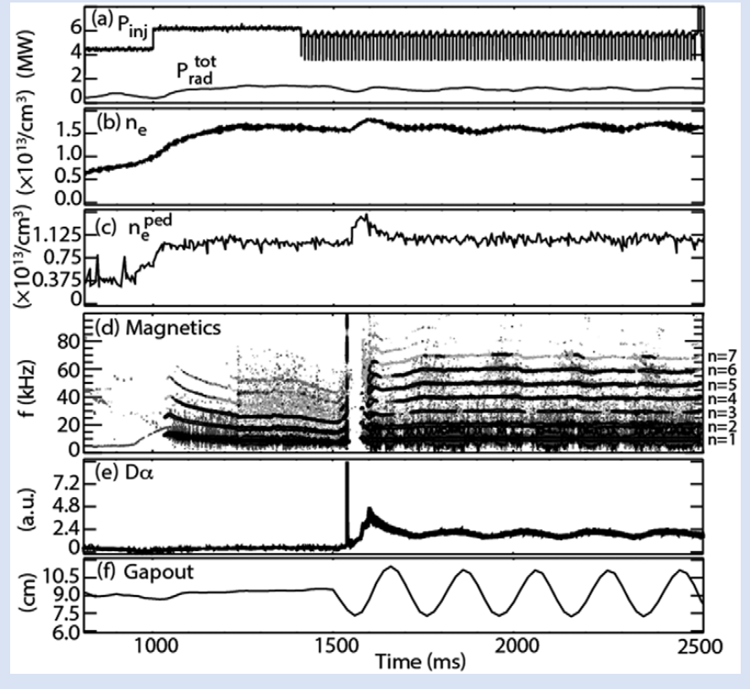
ABSTRACT/CONCLUSION

- MHD stability in the QH-modes with EHO in DIII-D and JT-60U has been investigated with the extended MHD code MINERVA-DI.
- It was found the kink/peeling mode, responsible for triggering EHO, is stabilized when considering the plasma rotation and the ion diamagnetic drift (ω_{*i}) effects, though the rotation alone destabilizes the mode.
- Results of the stability analysis show not the measured vxB rotation of carbon but the vxB one averaged with carbon and deuterium stabilizes effectively the kink/peeling mode.
- The averaged vxB rotation evaluated based on the neoclassical theory can give reasonable results in stability analysis in QH-mode plasmas. This makes us hopeful to predict QH-mode plasma condition in future reactors like ITER/DEMO.
- If the toroidal rotation direction is inverted, the stabilizing effect is affected. The impact is not unique; the effect becomes weaker in some cases, but stronger in other cases.

BACKGROUND AND OUR RECENT RESULTS

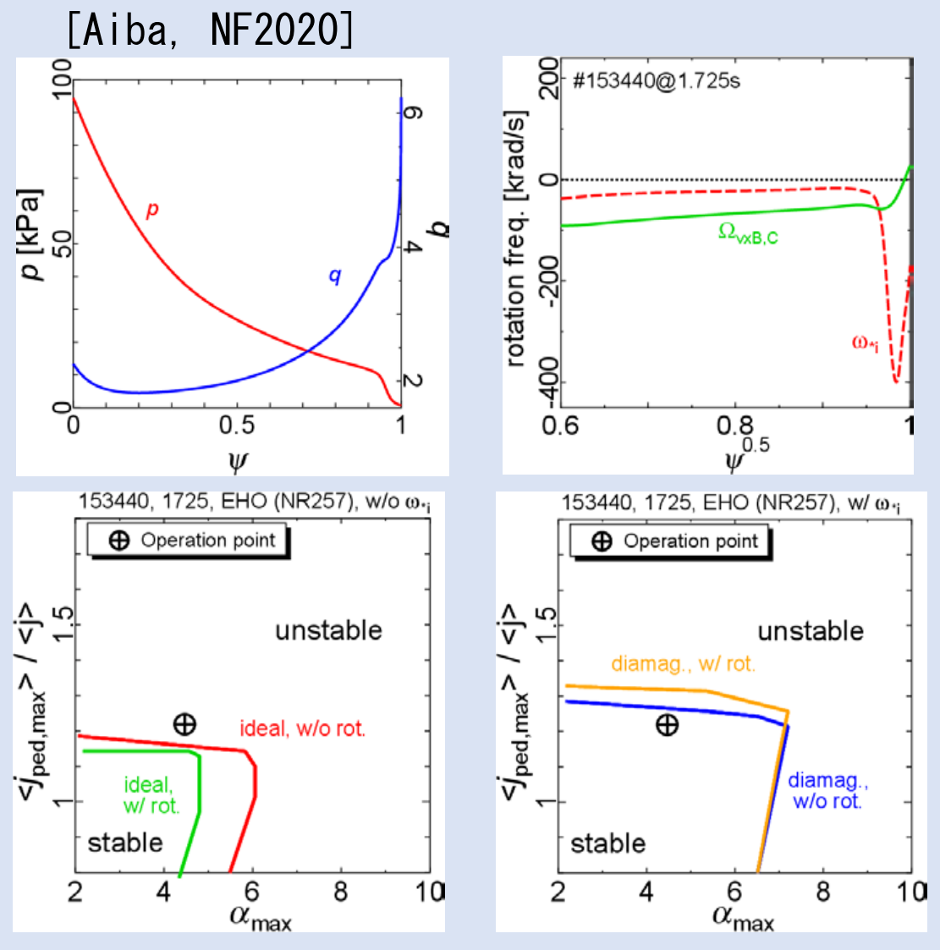
- QH-mode, found in 1999[Burrell Bull. APS1999], has EHO whose toroidal mode number is typically from 1 to <10.
- After the EHO appears, large ELMs disappear although pedestal performance does not change much.
- It is experimentally confirmed that plasma edge rotation (shear) is necessary, and the QH-modes in DIII-D and JT-60U favor B_t and I_p directions clockwise from the top view.



Waveform of QH-mode [Chen, NF2016]

- DIII-D team has explained that EHO is triggered by low-n MHD modes destabilized by rotation (shear) [Burrell PRL2009].
- Recently, we found that the low-n kink/peeling mode (K/PM) is stabilized by rotation in case the ion diamagnetic drift ω_{*i} is taken into account simultaneously.
- In this study, we investigate impact of the coupled rotation and ω_{*i} effects on MHD stability in several QH-mode plasmas in not DIII-D and JT-60U, and discuss the kind of rotation responsible for triggering EHO.

Impact of rotation on K/PM stability [Aiba, NF2020]



BASIC EQUATION AND ROTATION CONSIDERED HERE

Basic equation for linear stability analysis

- Frieman-Rotenberg (F-R) equation [Frieman RMP1960] can be the basic equation when analyzing linear MHD stability including rotation effect.
- For including the ω_{*i} effect simultaneously, the following extended F-R equation can be employed as the basic equation solved numerically with MINERVA-DI [Aiba PPCF2016].

$$\rho_0\frac{\partial^2\xi}{\partial t^2}+2\rho_0\left(\boldsymbol{V}_{0,MHD}\cdot\nabla\right)\frac{\partial\xi}{\partial t}+\rho_0\left(\boldsymbol{V}_{0,*i}\cdot\nabla\right)\frac{\partial\xi_\perp}{\partial t}=\boldsymbol{F}_{MHD}+\boldsymbol{F}_{*i},$$
$$\boldsymbol{F}_{MHD}=\boldsymbol{F}_s+\boldsymbol{F}_d,$$
$$\boldsymbol{F}_s=\boldsymbol{J}_0\times\boldsymbol{B}_1+(\nabla\times\boldsymbol{B}_1)\times\boldsymbol{B}_0-\nabla P_1,$$
$$\boldsymbol{F}_d=\nabla\otimes\left[\rho_0\boldsymbol{\xi}\otimes(\boldsymbol{V}_0\cdot\nabla)\boldsymbol{V}_{0,MHD}-\rho_0\boldsymbol{V}_0\otimes\left(\boldsymbol{V}_{0,MHD}\cdot\nabla\right)\boldsymbol{\xi}\right],$$
$$\boldsymbol{F}_{*i}=\frac{\rho_0}{2eN_eB_0^2}\{(\nabla\cdot(\boldsymbol{\xi}\times\nabla P_0)\boldsymbol{B}_0-(\boldsymbol{B}_0\cdot\nabla \mathrm{P}_0)\nabla\times\boldsymbol{\xi})\cdot\nabla\}\boldsymbol{V}_{0,MHD,\perp}$$
$$+\nabla\otimes\left[\rho_0\boldsymbol{\xi}\otimes\left(\boldsymbol{V}_{0,*i}\cdot\nabla\right)\boldsymbol{V}_{0,MHD}-\rho_0\boldsymbol{V}_{0,*i}\otimes\left(\boldsymbol{V}_{0,MHD}\cdot\nabla\right)\boldsymbol{\xi}\right],$$

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

Plasma (fluid) rotation considering in MINERVA-DI

- Experimentally, toroidal (and sometimes poloidal) rotation of carbon 'C' ($\Omega_{\phi,C},\ \Omega_{\theta,C}$) is measured in DIII-D. In JT-60U, only $\Omega_{\phi,C}$ could be measured.
- At present, the DIII-D team pays attention to $\Omega_{\phi,C}$, $\Omega_{\theta,C}$, and the $E\times B$ rotation defined as

$$\omega_{E\times B}=\frac{E_r}{RB_p}=\omega_{*C}+s_I\omega_{\phi,C}+\omega_{\theta,C}=\omega_{*c}+s_I\Omega_{v\times B,C},$$

  where s_I is the sign of I_p direction with respect to B_t one.
- We regard $\omega_{E\times B}$ as a good parameter for EHO trigger condition[Garofalo NF2011].
- Note that MINERVA-DI assumes as $\boldsymbol{V}=\boldsymbol{V}_{v\times B}+\boldsymbol{V}_\parallel+\boldsymbol{V}_{*i}=\boldsymbol{V}_{MHD}+\boldsymbol{V}_{*i}$, hence, using $R\Omega_{v\times B}$ as $\boldsymbol{V}_{v\times B}$ corresponds to $\omega_{E\times B}$.

Candidates of rotation responsible for triggering EHO

- The mass density is composed of deuterium and carbon, hence, there are at least two candidates of $\omega_{v\times B}$ to be included in the analysis.
  1. $\Omega_{v\times B}=\Omega_{v\times B,C}$: the rotation of 'D' is assumed as the same as that of carbon (measured)
  2. $\Omega_{v\times B}=(\rho_D\Omega_{v\times B,D}+\rho_C\Omega_{v\times B,C})/(\rho_D+\rho_C)=\Omega_{v\times B,CD}$; $s_I\Omega_{v\times B,D}=\omega_{E\times B}-\omega_{*,D}$
- In [Aiba et al., NF2020], the impact of $\Omega_{v\times B,C}$ on MHD stability in DIII-D #153440 QH-mode plasma was investigated, but that of $\Omega_{v\times B,CD}$ has not been analyzed. Hence, in this study, we analyze the MHD stability in several QH-mode plasmas in DIII-D and JT-60U by considering $\Omega_{v\times B,C}$ or $\Omega_{v\times B,CD}$, and discuss which is responsible for triggering EHOs.
- In addition, E_r can be determined through radial force balance equation in neoclassical theory (NC) if $\Omega_{\phi,C}, n_C, T_C$ are measured. Hence, the stability in QH-mode plasmas is also investigated by considering $\Omega_{v\times B,CD}$, which is estimated based on NC with CHARROT code [Aiba, Honda, NF2017].

ACKNOWLEDGEMENTS

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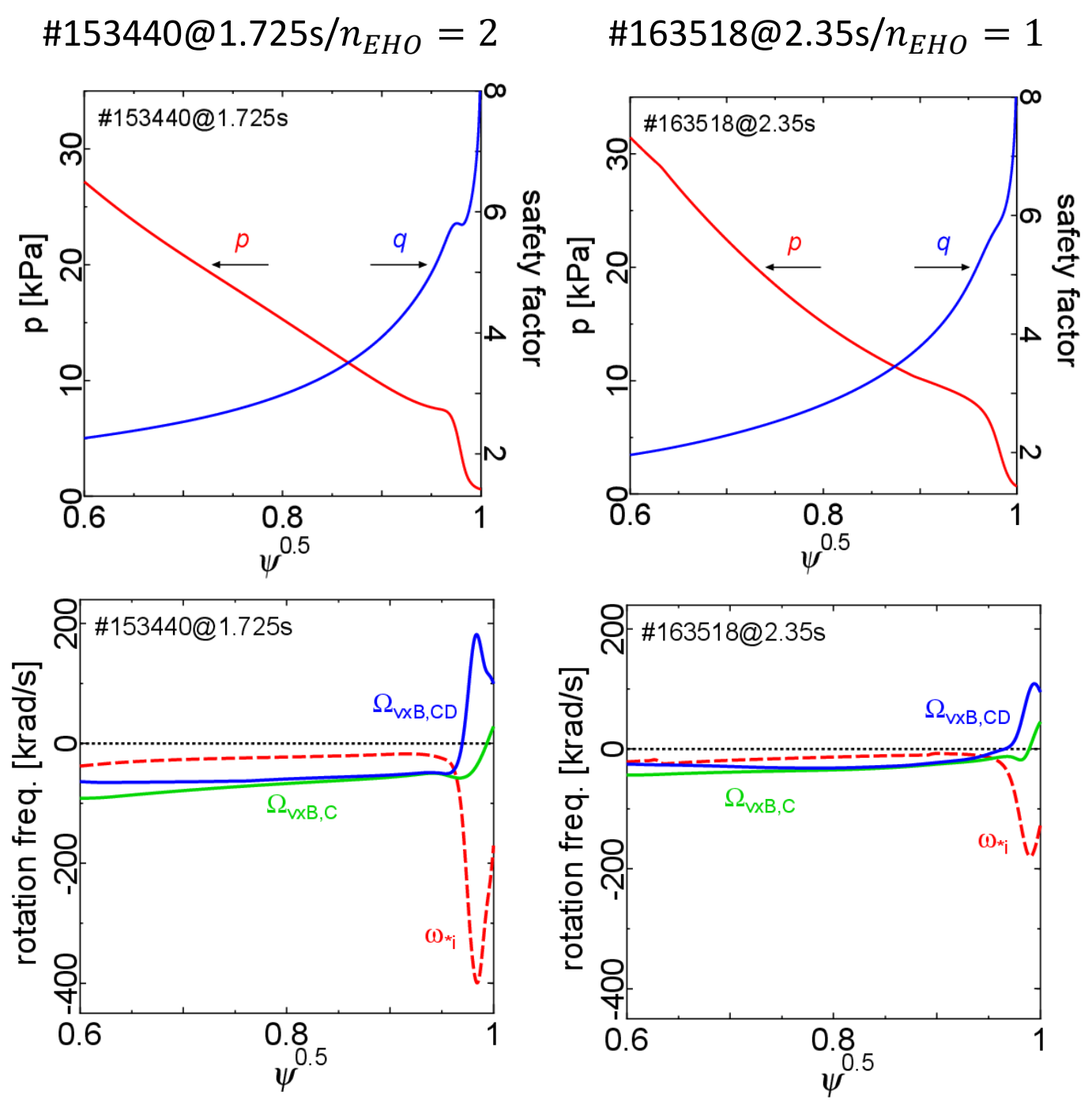
Results in DIII-D

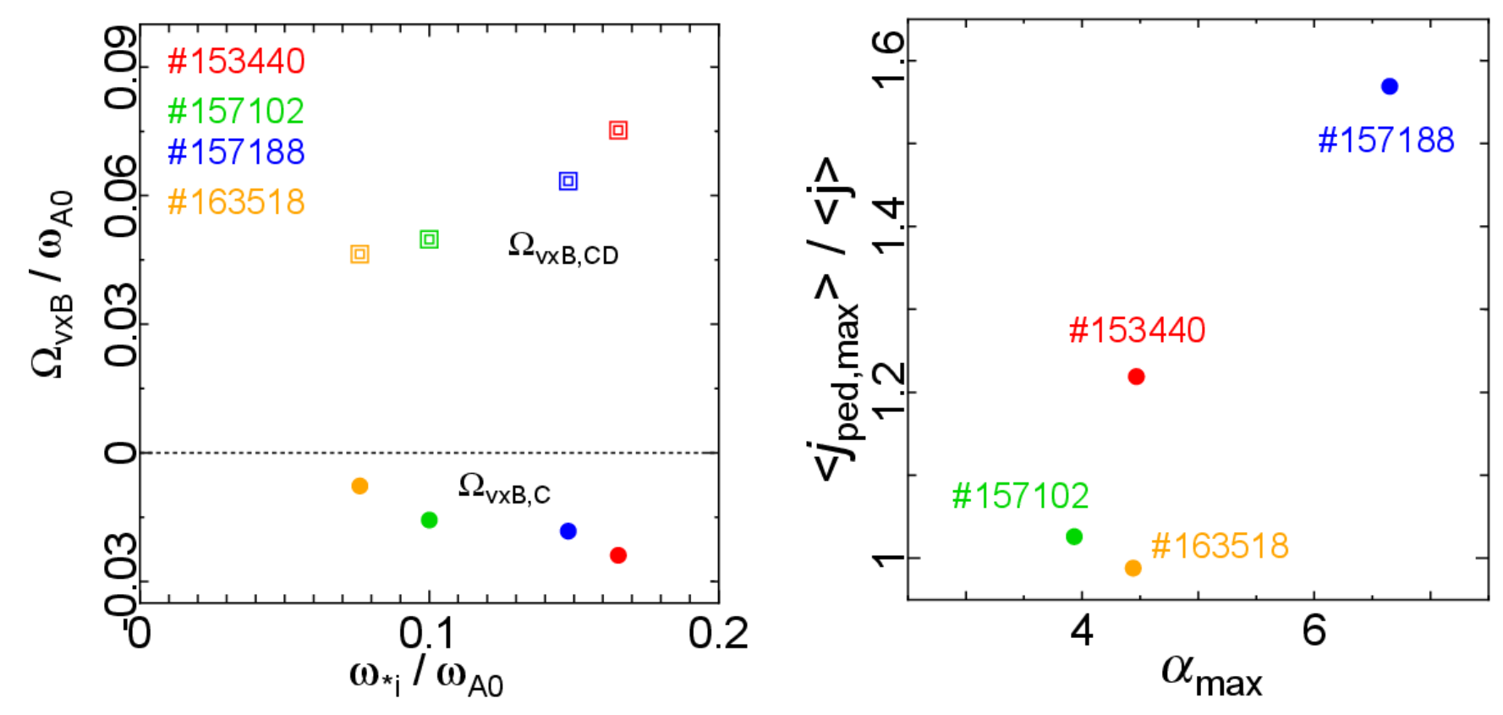
QH-mode plasmas in DIII-D; #153440@1.725s/$n_{EHO}=2$, #157102@2.42s/$n_{EHO}=1$, #157188@2.06s/$n_{EHO}=1,2$, #163518@2.35s/$n_{EHO}=1$

Pressure, Safety factor

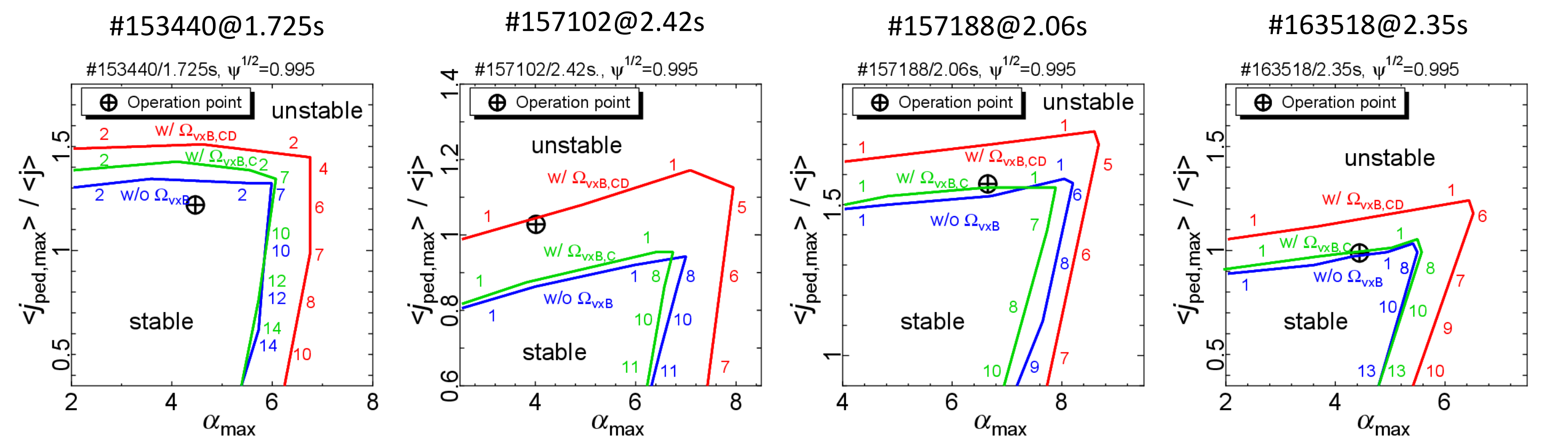
Rotation freq., Ion diamag. freq.



Range of plasma parameters
(left: $\Omega_{v\times B},\omega_{*i}$, right: j_{max},α_{max})



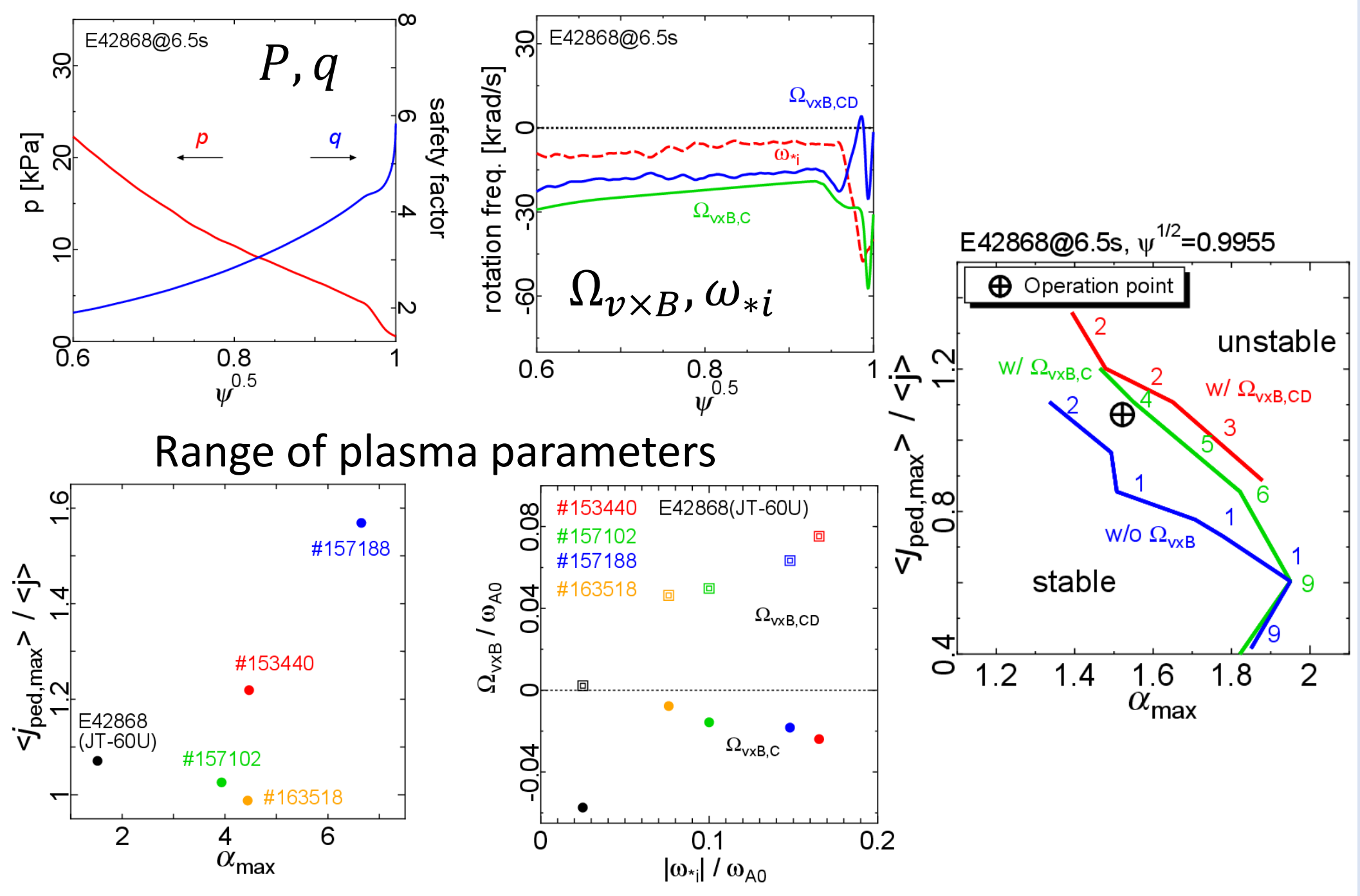
Results of stability analysis with rotation measured in experiment



- In all the discharges, the $\Omega_{v\times B,CD}$ rotation stabilizes clearly the kink/peeling modes by coupling with the ω_{*i} effect, though the $\Omega_{v\times B,C}$ one can stabilize them only in #153440.
- The toroidal mode number of K/PM is consistent with that of dominant EHO, n_{EHO}.
- Since plasma rotation has been confirmed as a main player for triggering EHOs but $\Omega_{v\times B,C}$ changes little the kink/peeling mode stability, $\Omega_{v\times B,CD}$, the one-fluid rotation averaged between C and D, could be a strong candidate of the rotation responsible for triggering EHO.

Results in JT-60U

QH-mode plasma in JT-60U;
E42868@6.5s/$n_{EHO}=1,2$



Range of plasma parameters

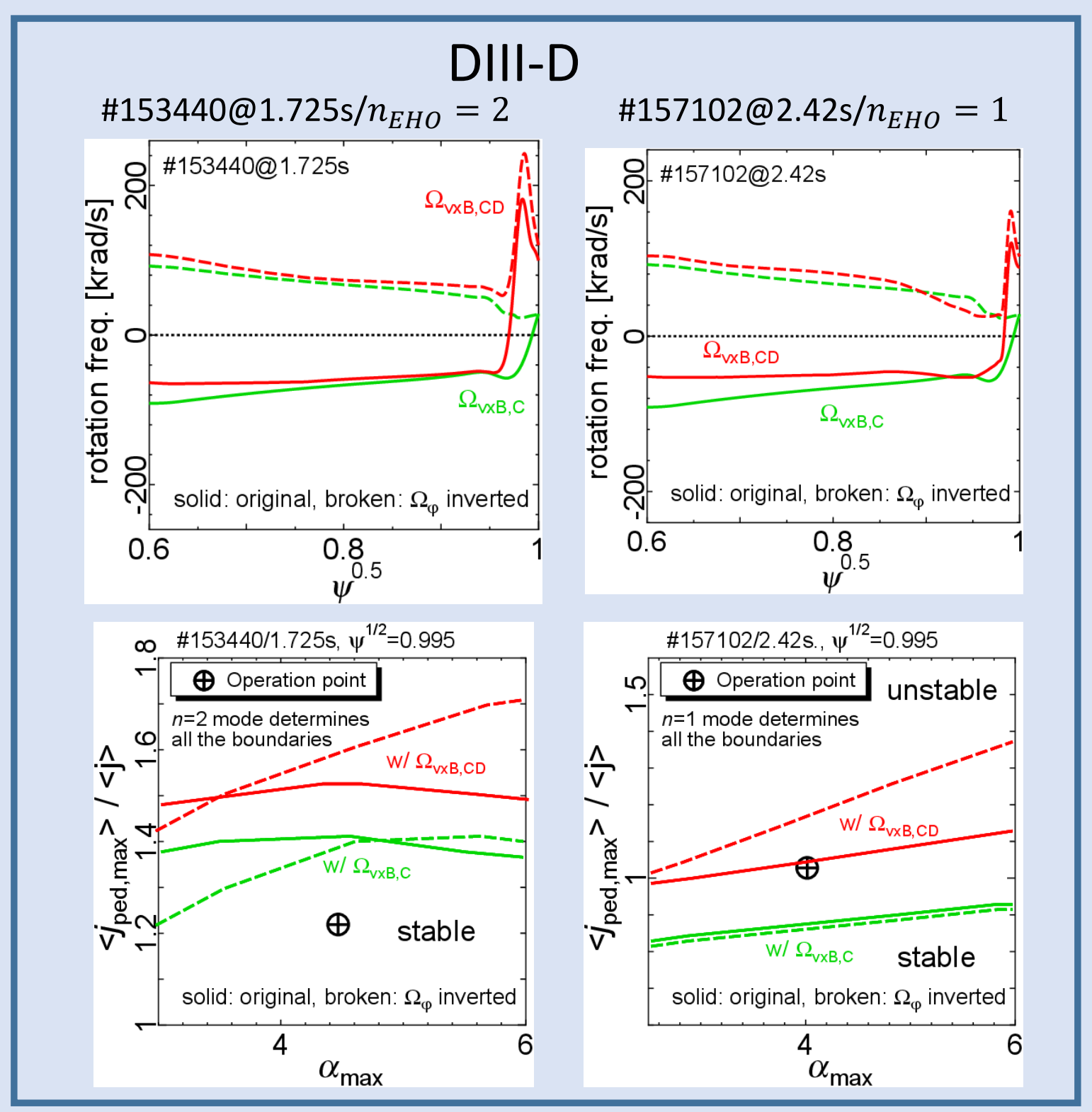
- As in the DIII-D case, plasma rotation stabilizes the K/PM when considering the ω_{*i} effect, though both ($\Omega_{v\times B},\omega_{*i}$) and ($j_{max},\alpha_{max}$) are much different from those in DIII-D plasmas.
- Both $\Omega_{v\times B,C}$ and $\Omega_{v\times B,CD}$ stabilizes the mode, but the n number to be unstable near the operational point is different (4 with $\Omega_{v\times B,C}$, 2 with $\Omega_{v\times B,CD}$).

$\Omega_{v\times B,CD}$ could be better, because the n number is consistent with n_{EHO}=1,2.

Impact of toroidal rotation direction on stability

- Pedestal stability in case inverting the toroidal rotation direction has also been investigated using two DIII-D discharges.
- In both discharges, the stability boundary of K/PM moves (slightly) downward on the diagram by considering $\Omega_{v\times B,C}$, but moves upward when using $\Omega_{v\times B,CD}$.
- If assuming the stabilizing effect on K/PM is important to obtain EHO, destabilization of K/PM when inverting the rotation direction could be consistent why QH-modes in DIII-D and JT-60U favor the rotation direction.
- Further study, such as using measured data for deuterium, is necessary to clarify why QH-mode favors ctr-I_p toroidal rotation.
- Analysis with inverted B_t direction is also on going.

DIII-D

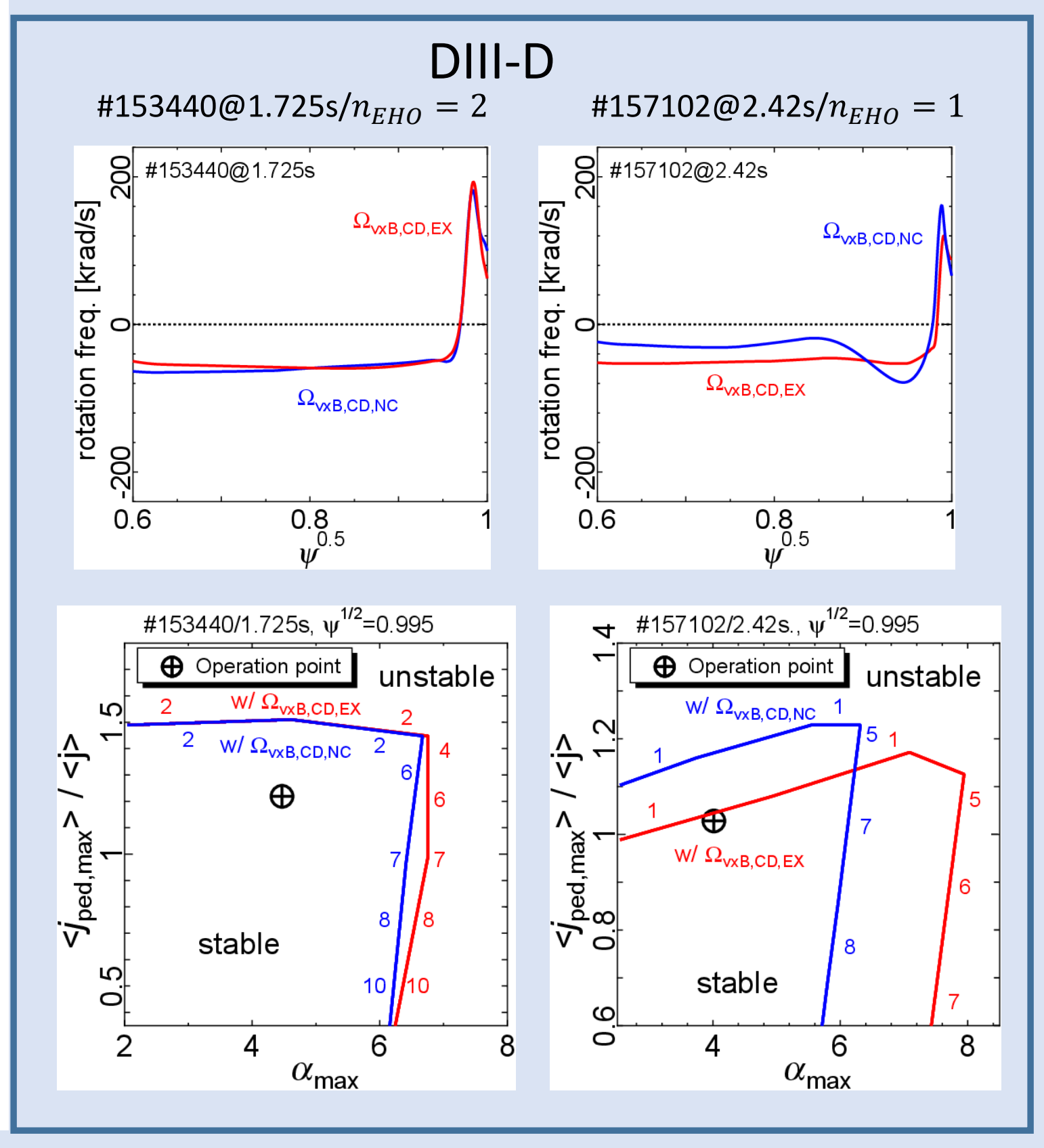


Results with rotation estimated with neoclassical theory in DIII-D and JT-60U

- $\Omega_{v\times B,CD}$ was estimated with neoclassical theory, $\Omega_{v\times B,CD,NC}$, in DIII-D and JT-60U.
- The $\Omega_{v\times B,CD,NC}$ profile in DIII-D reasonably agree with the $\Omega_{v\times B,CD}$ in experiment; those in #153440 are almost the same as each other.
- The difference between these profiles mainly affects the stability boundary in ballooning mode side.
- In JT-60U, the rotation profile near very edge region is clearly different, but the stability boundary is similar to each other.

Rotation estimated with neoclassical theory can give reasonable results of stability analysis in QH-mode plasmas.

DIII-D



JT-60U