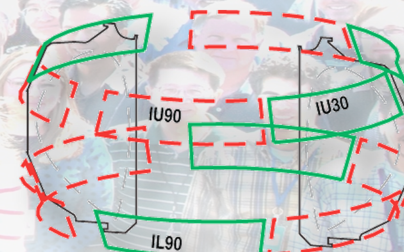
Towards prediction of ELM control by RMP in ITER based on linear and quasi-linear plasma response

Yueqiang Liu[1], Li Li[2], M. Becoulet[3], T.E. Evans[1], G.T.A. Huijsmans[3], A. Kirk[4], L.L. Lao[1], A. Loarte[5], C. Paz-Soldan[6], S.D. Pinches[5], A. Polevoi[5], A. Turnbull[1]

[1]General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
[2]College of Science, Donghua University, Shanghai 201620, People's Republic of China
[3]CEA, IRFM, 13108 Saint-Paul-Lez-Durance, France
[4]CCFE, Culham Science Centre, Oxon, OX14 3DB, UK Abingdon, UK
[5]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France
[6]Department of Applied Physics and Applied Mathematics, Columbia University New York, NY 10024, USA



28th IAEA Fusion Energy Conference

Outline

- **Introduction:** ELM control in ITER and modeling tools
- **Plasma response in present day devices**
  - Linear response
  - **Quasi-linear response**
- **Plasma response in ITER**
  - Linear response
  - **Quasi-linear response**
- **Summary**

Flexible magnetic coil system designed for controlling ELMs in ITER

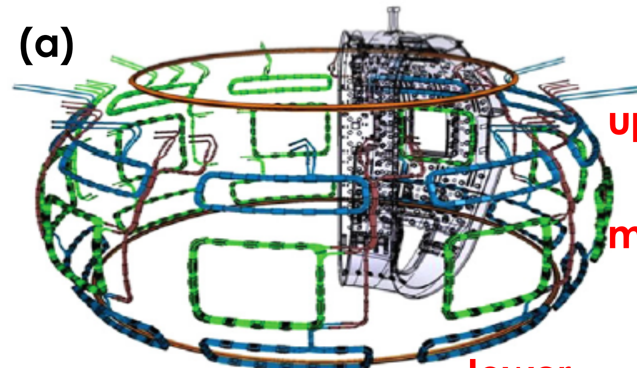
- **ELM control with RMP essential part of ITER operation, to reduce potential impact of large ELMs on materials**

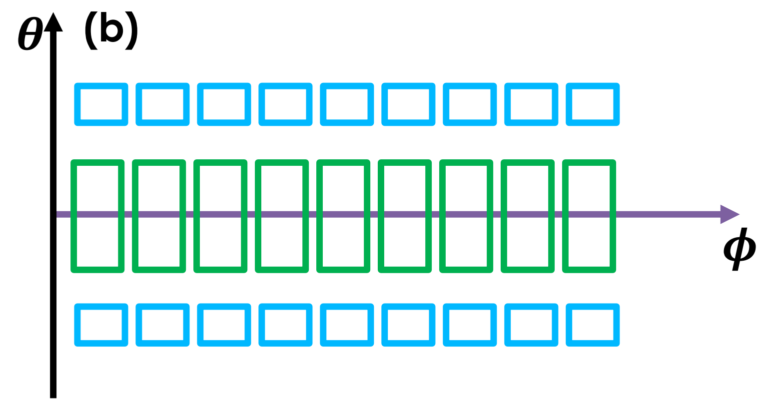
- **ITER has flexible RMP coil system:**
  - 3x9 coils
  - 27 independent power supplies

- **Is this system robust in controlling ELMs in all ITER scenarios?**

- **How to reliably predict ELM control in ITER?**

Evans NF 53 (2013) 093029





A range of plasma scenarios designed covering all stages of ITER operation

Shot	Scenario	Flow model (Pr, τ_ϕ/τ_E)
101007	5 MA/1.8 T	(0.3,0.65),(0.3,1,2#),(0.3,2)
131021	7.5 MA/2.65 T	(0.3,0.57),(0.3,1),(0.3,2)
131037	7.5 MA/4.5 T	(0.3,1),(0.3,2),(1,0.5),(1,1),(1,2)
131019	7.5 MA/5.3 T	(0.3,1),(0.3,2)
131036	10 MA/5.3 T	(0.3,1.2),(0.3,2)
131024	15 MA/5.3 T/Q=5	(0.3,0.73),(0.3,1),(0.3,2),(1,0.5),(1,1),(1,2)
131025	15 MA/5.3 T/Q=10	(0.3,0.72),(0.3,1),(0.3,2),(1,0.5),(1,1),(1,2)
131039	12.5 MA/5.3 T	(0.3,1),(0.3,2)

- **Scenarios cover PFPO and FPO phases (H-plasma ➔ D-T plasma)**
- **Examples: 15 MA baseline, 10 MA steady state, 12.5 MA hybrid**
- **Linear response computed by MARS-F, for each scenario, each row of RMP coils, each n=1-6, and each toroidal flow model**
- **Database generated and stored in IMAS**

[Li et al. NF 59, 096038(2019); NF 60, 016013(2020)]

MARS-Q solves perturbed resistive MHD equations coupled to n=0 momentum and density balance equations

Perturbed resistive MHD equations (MARS-F)

$$
\begin{aligned}
(\frac{\partial}{\partial t}+in\Omega)\xi &= \mathbf{v}+(\xi\cdot\nabla\Omega)R\hat{\phi}, \\
\rho(\frac{\partial}{\partial t}+in\Omega)\mathbf{v} &= -\nabla p+\mathbf{j}\times\mathbf{B}+\mathbf{J}\times\mathbf{b}-\rho\left[2\Omega\hat{\mathbf{Z}}\times\mathbf{v}+(\mathbf{v}\cdot\nabla\Omega)R\hat{\phi}\right] \\
&\quad -\rho\kappa_{\parallel}|k_{\parallel}v_{th,i}|\left[\mathbf{v}+(\xi\cdot\nabla)\mathbf{V}_0\right]_{\parallel}, \\
(\frac{\partial}{\partial t}+in\Omega)\mathbf{b} &= \nabla\times(\mathbf{v}\times\mathbf{B})+(\mathbf{b}\cdot\nabla\Omega)R\hat{\phi}-\nabla\times(\eta\mathbf{j}), \\
\mathbf{j} &= \nabla\times\mathbf{b}, \text{(plasma)} \quad \nabla\times\mathbf{b}=\mathbf{j}_{\mathrm{RMP}} \text{ (coil)} \\
(\frac{\partial}{\partial t}+in\Omega)p &= -\mathbf{v}\cdot\nabla P-\Gamma P\nabla\cdot\mathbf{v},
\end{aligned}
$$

source term for RMP

n=0 density eq.

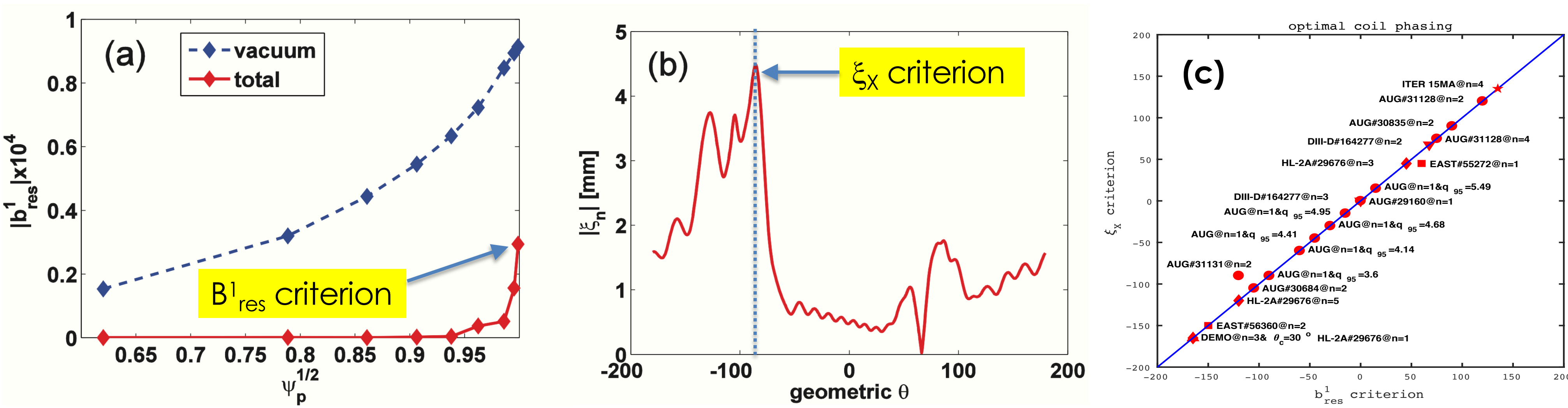
$$\frac{\partial(\Delta\rho)}{\partial t}+\nabla\cdot(\tilde{\rho}\tilde{\boldsymbol{v}})+\nabla\cdot(m\Gamma_{NTV})=\nabla\cdot D_{\perp}\nabla(\Delta\rho)$$

n=0 momentum eq.

$$\frac{\partial L}{\partial t}=D(L)+T_{\mathrm{source}}+T_{\mathrm{NTV}}+T_{j\times b}+T_{\mathrm{REY}}$$

$$L=\rho<R^2>\Omega$$

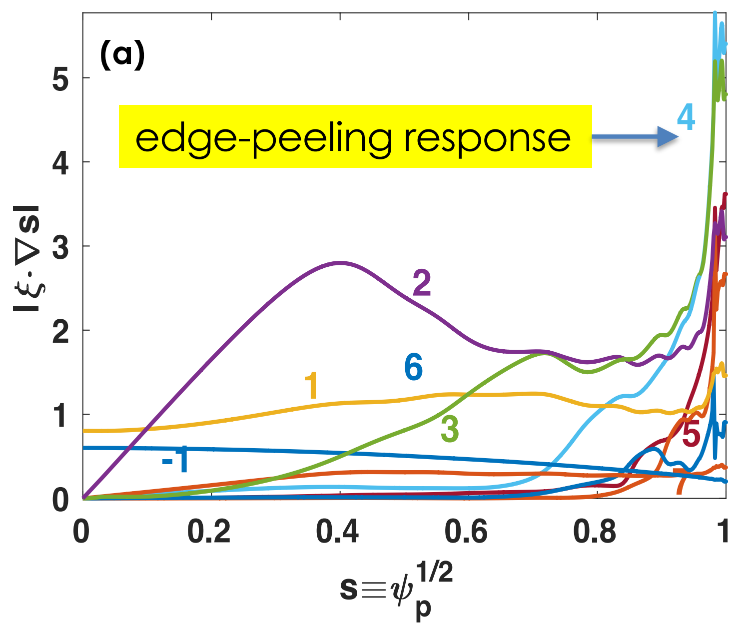
Linear resistive plasma response modeling by MARS-F for present days experiments identified two criteria for ELM control

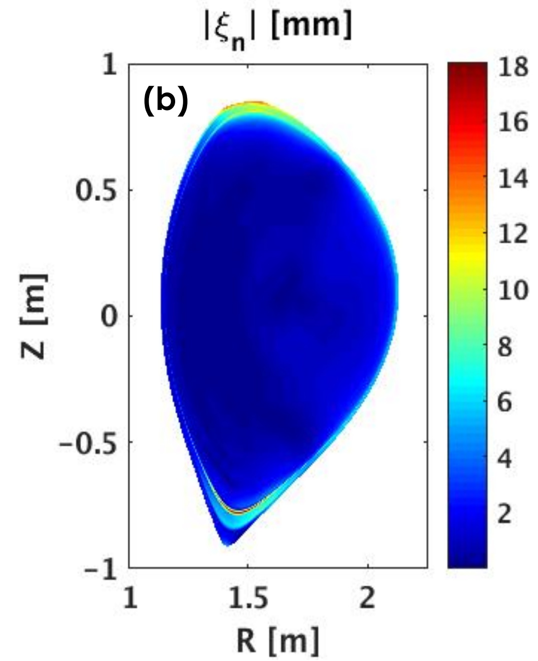


- **Linear resistive plasma response computed by MARS-F for ELM control experiments in DIII-D, MAST, ASDEX Upgrade, EAST, HL-2A as well as for future devices (ITER, EU DEMO)**
- **Identified two criteria based on plasma response, that can help to choose optimal ELM control coil current configuration**
- **Both criteria related to edge-peeling response and yields similar optimal coil phasing**

Example: linear plasma response for ASDEX Upgrade shows strong edge-peeling response with n=2 RMP at 90° coil phasing

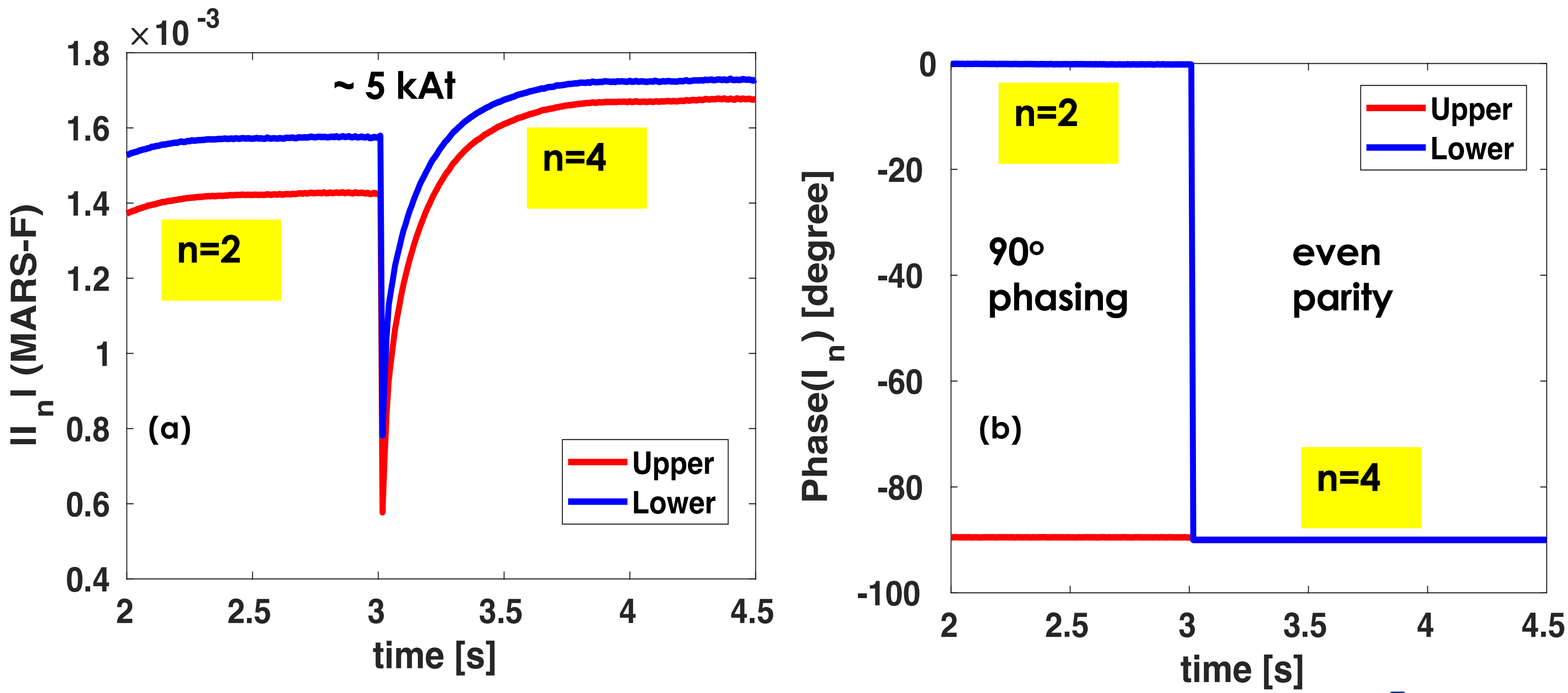
- ASDEX Upgrade discharge 33353: n=2 RMP, 90° coil phasing, 5 kAt
- Strong edge-peeling response shown by radial displacement of plasma
- Large plasma displacement near top and bottom of plasma





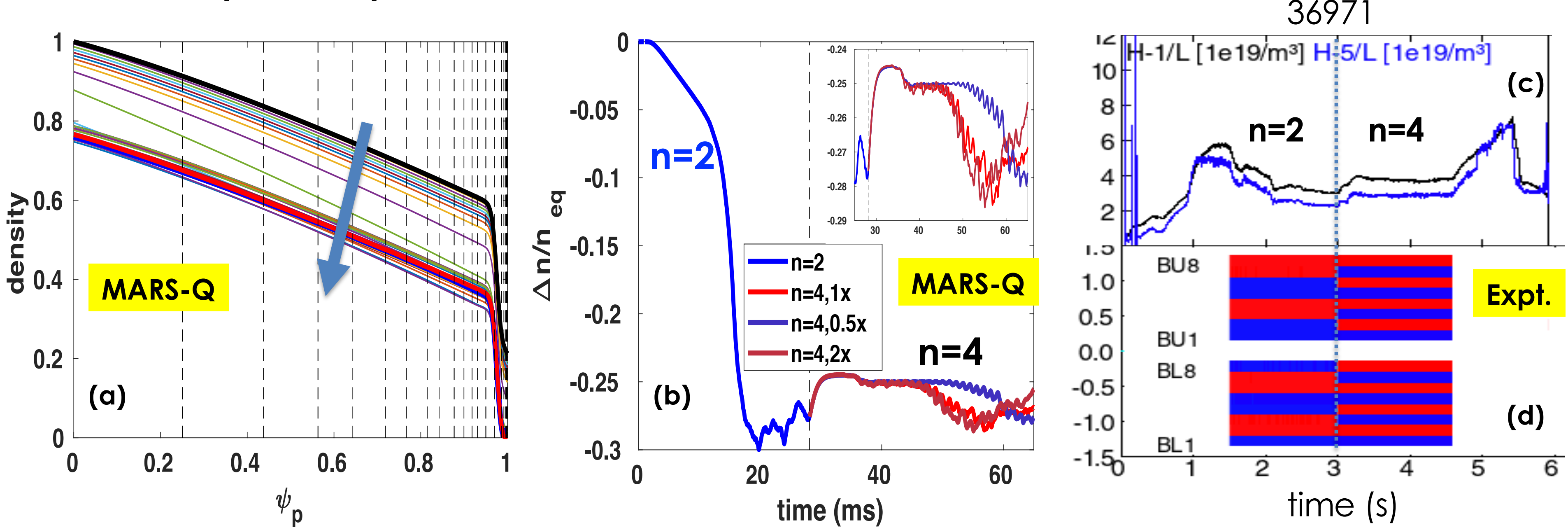
ELM control experiments with changing toroidal spectra of RMP carried out in ASDEX Upgrade and modeled by MARS-Q

- ASDEX Upgrade utilizes two rows of ELM control coils: upper and lower B-coils to control ELM
- n=2 RMP configuration at 90° coil phasing ➔ n=4 even parity configuration
- Goal of MARS-Q quasi-linear modeling: density behavior during transition from n=2 to n=4



MARS-Q modeling for ASDEX Upgrade finds strong density pumpout by n=2 RMP followed by slight recovering of density with n=4 RMP

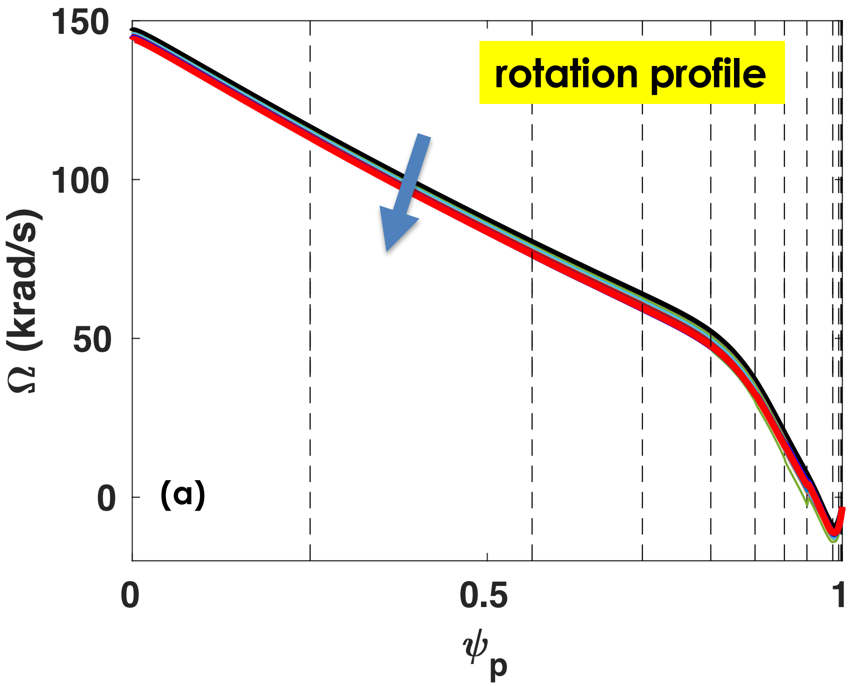
- Reference equilibrium from AUG discharge 33353
- Assume same RMP configuration as in experiments: n=2 at 90° coil phasing ➔ n=4 even parity
- MARS-Q: ~30% pumpout by n=2 followed by ~5% pumpin with n=4: weaker effect than experiments
- Better density recovery at lower n=4 current but effect not dramatic

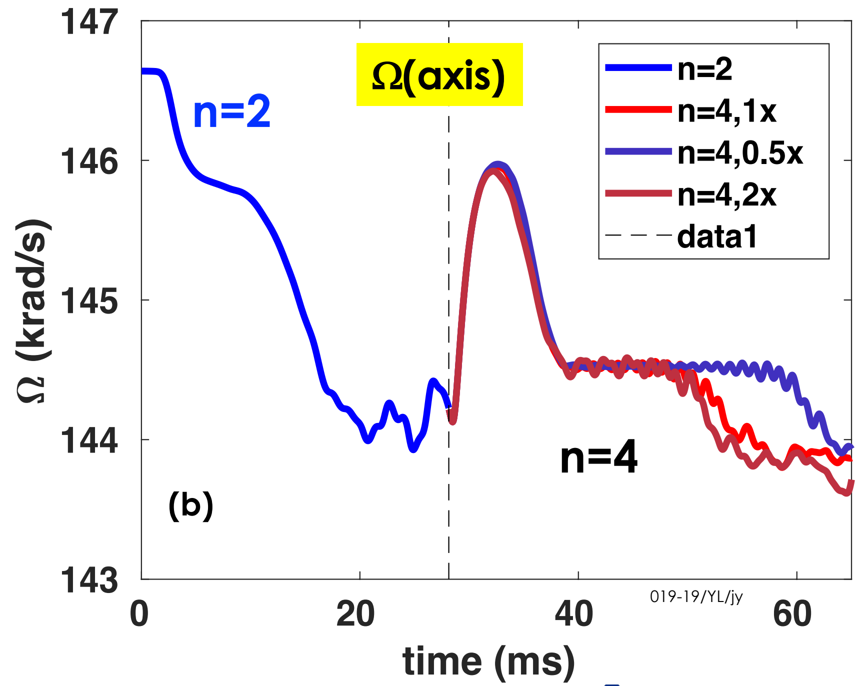


GENERAL ATOMICS

MARS-Q quasi-linear modeling for ADEX Upgrade finds weak effects of n=2 and n=4 RMP on plasma toroidal rotation

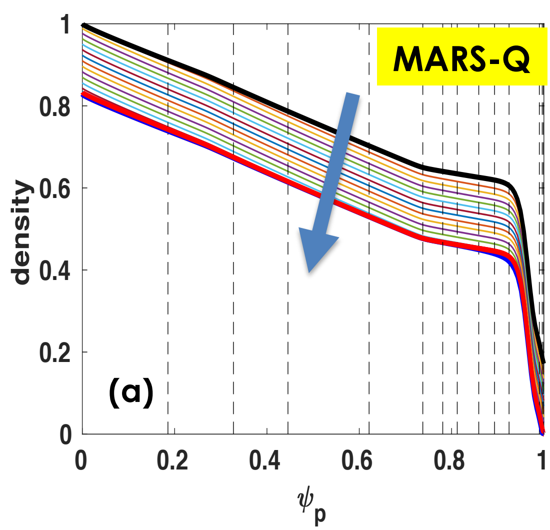
- Reference equilibrium from AUG discharge 33353
- Assume same RMP configuration as in experiments: n=2 at 90° coil phasing ➔ n=4 even parity
- MARS-Q: weak toroidal flow damping by both n=2 and n=4 RMPs

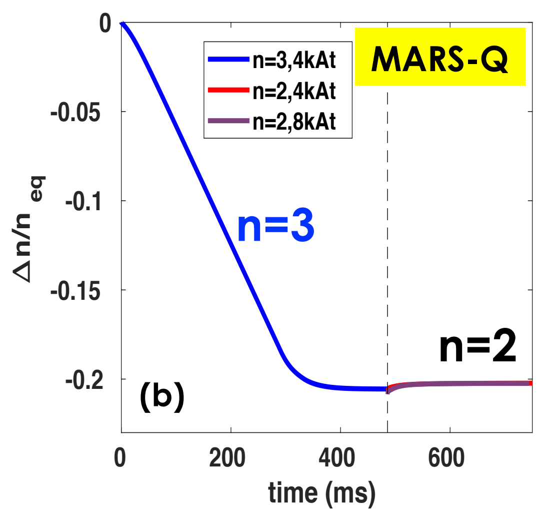




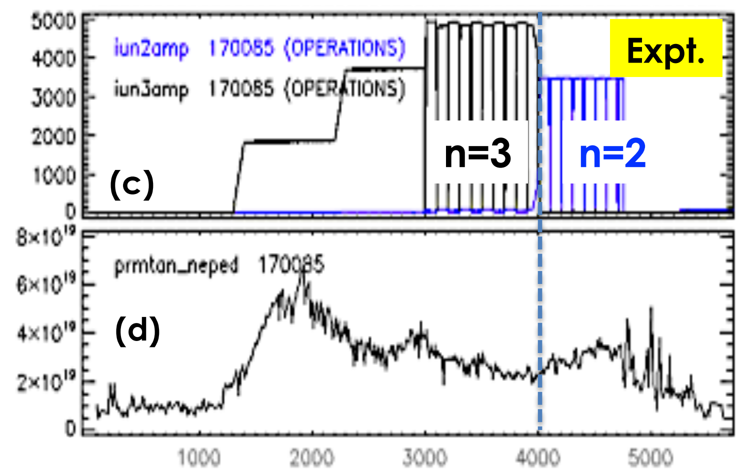
MARS-Q modeling for DIII-D finds weaker density pumpout (with n=3) and density recovering (with n=2) compared to experiments

- Reference equilibrium from DIII-D discharge 157376
- MARS-Q: 4 n=3 RMP in even parity (I-coils) at 4 kAt ➔ n=2 RMP in even parity (I-coils) at 4&8 kAt
- MARS-Q: ~20% density pumpout by n=2 RMP, followed by very weak density recovery with n=4
- Modeled effects on density weaker than experiments (slightly lower I-coil current, hysteresis?)





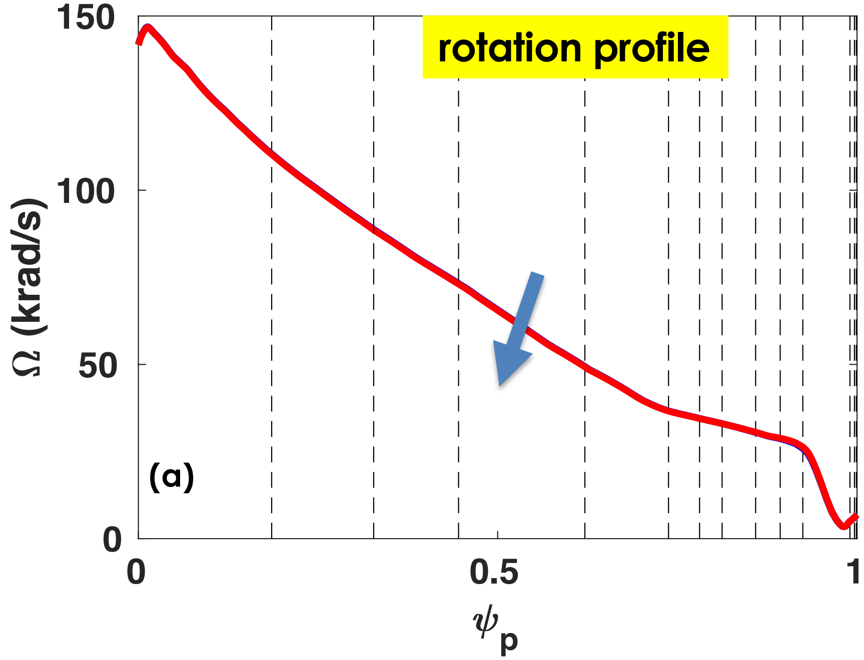
170085

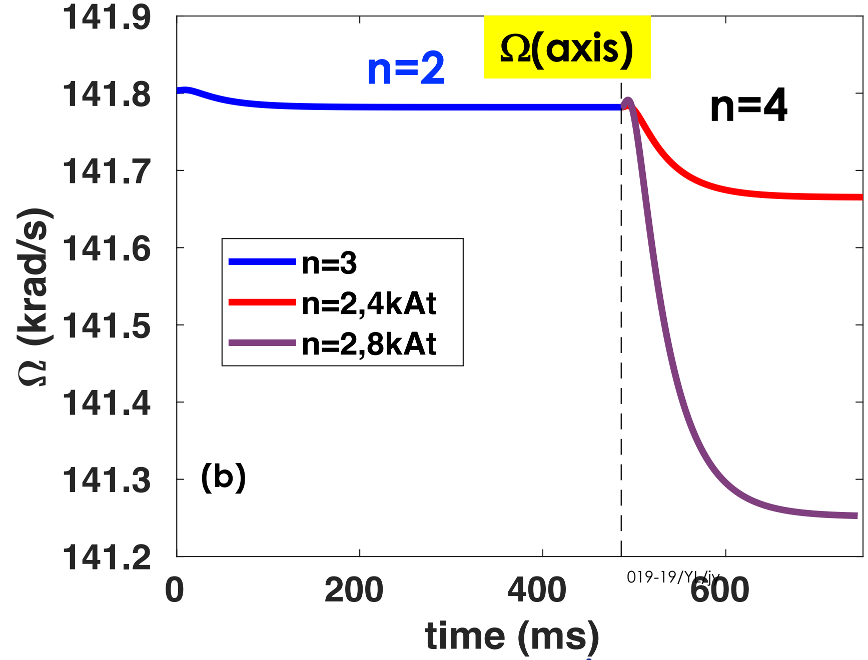


time (ms)

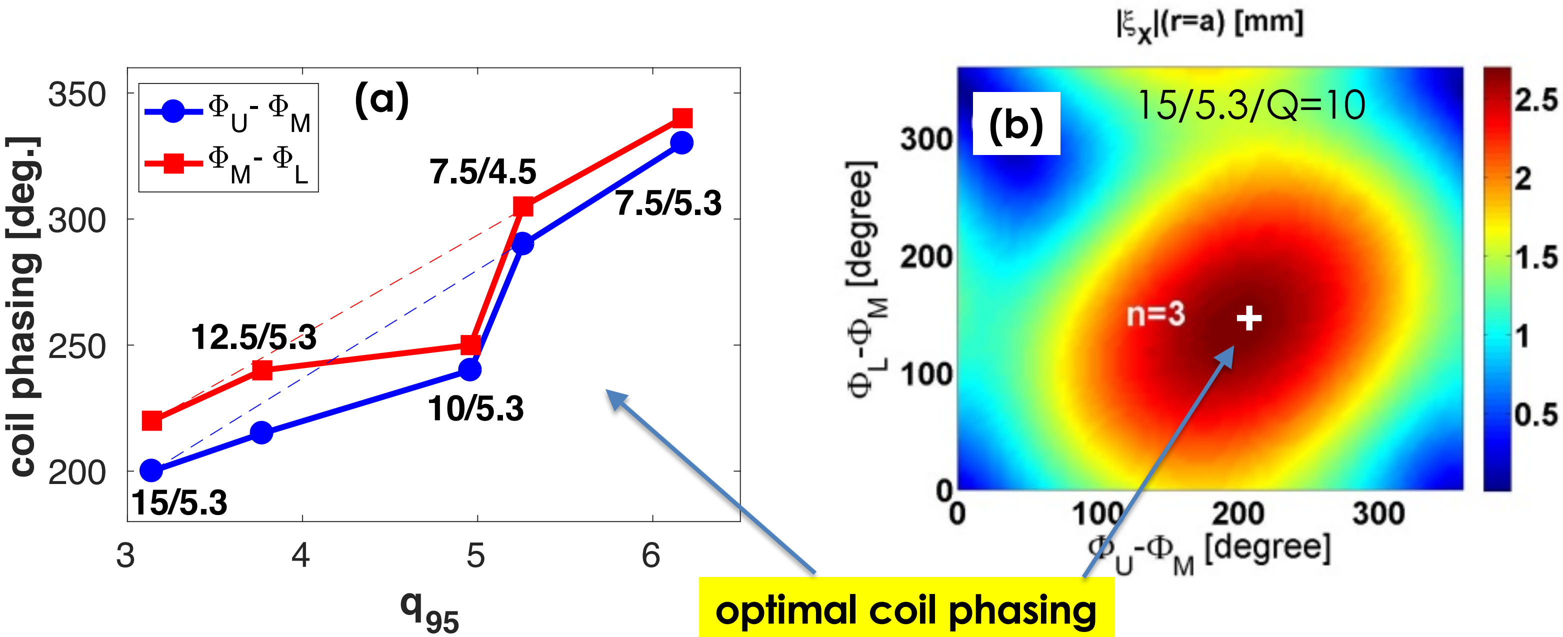
MARS-Q modeling for DIII-D finds negligible effect of RMP on plasma toroidal flow

- Reference equilibrium from DIII-D discharge 157376
- MARS-Q: 4 n=3 RMP in even parity (I-coils) at 4 kAt ➔ n=2 RMP in even parity (I-coils) at 4&8 kAt
- MARS-Q: negligible effect on plasma toroidal flow with both n=3 and n=2 RMPs





MARS-F linear response modeling for ITER finds that optimal coil phasing scales linearly with q_{95} but with an outlier for 10 MA scenario



- **Assume all 3 rows of ELM control coils with same current amplitude in n=3 configuration**
- **Vary relative coil phase between upper-middle rows and between middle-lower rows**
- **Pecularity of 10 MA scenario: steady state with plasma pressure near no-wall Troyon limit**

MARS-Q quasi-linear response modeling carried out for all 8 ITER scenarios assuming various RMP configurations

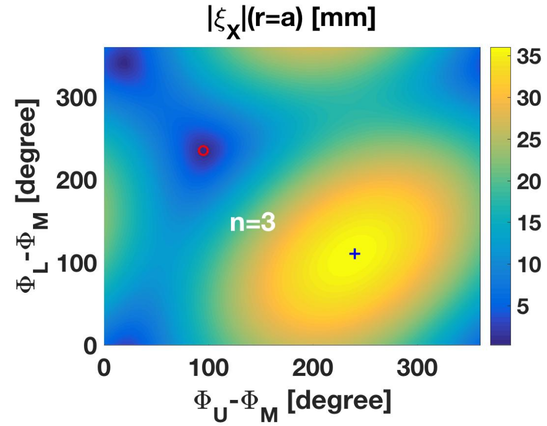
Example: 10 MA/5.3 T steady state scenario with n=3 RMP

Assume 5 different RMP configurations:

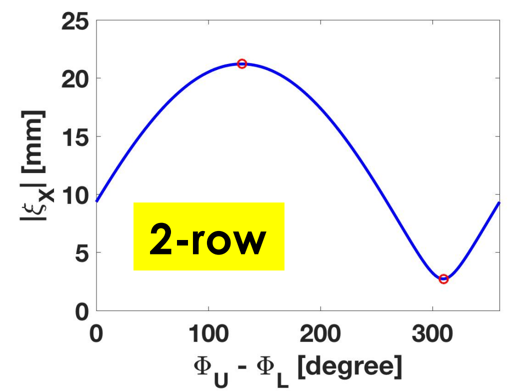
- **Setup-A**: 3-row(U+M+L), 60 kAt/row, $\Delta\Phi_{UM}$=240°, $\Delta\Phi_{LM}$=110°
  ➔ best ELM control
- **Setup-B**: 3-row, 60 kAt/row, $\Delta\Phi_{UM}$=95°, $\Delta\Phi_{LM}$=235°
  ➔ worst ELM control
- **Setup-C**: 2-row(U+L), 60 kAt/row, $\Delta\Phi_{UL}$=130°
  ➔ best ELM control
- **Setup-D**: 2-row(U+L), 60 kAt/row, $\Delta\Phi_{UL}$=310°
  ➔ worst ELM control
- **Setup-E**: 1-row(M), 60 kAt

- **Flow model:** $P_r = 0.3, \tau_\phi/\tau_E = 2$

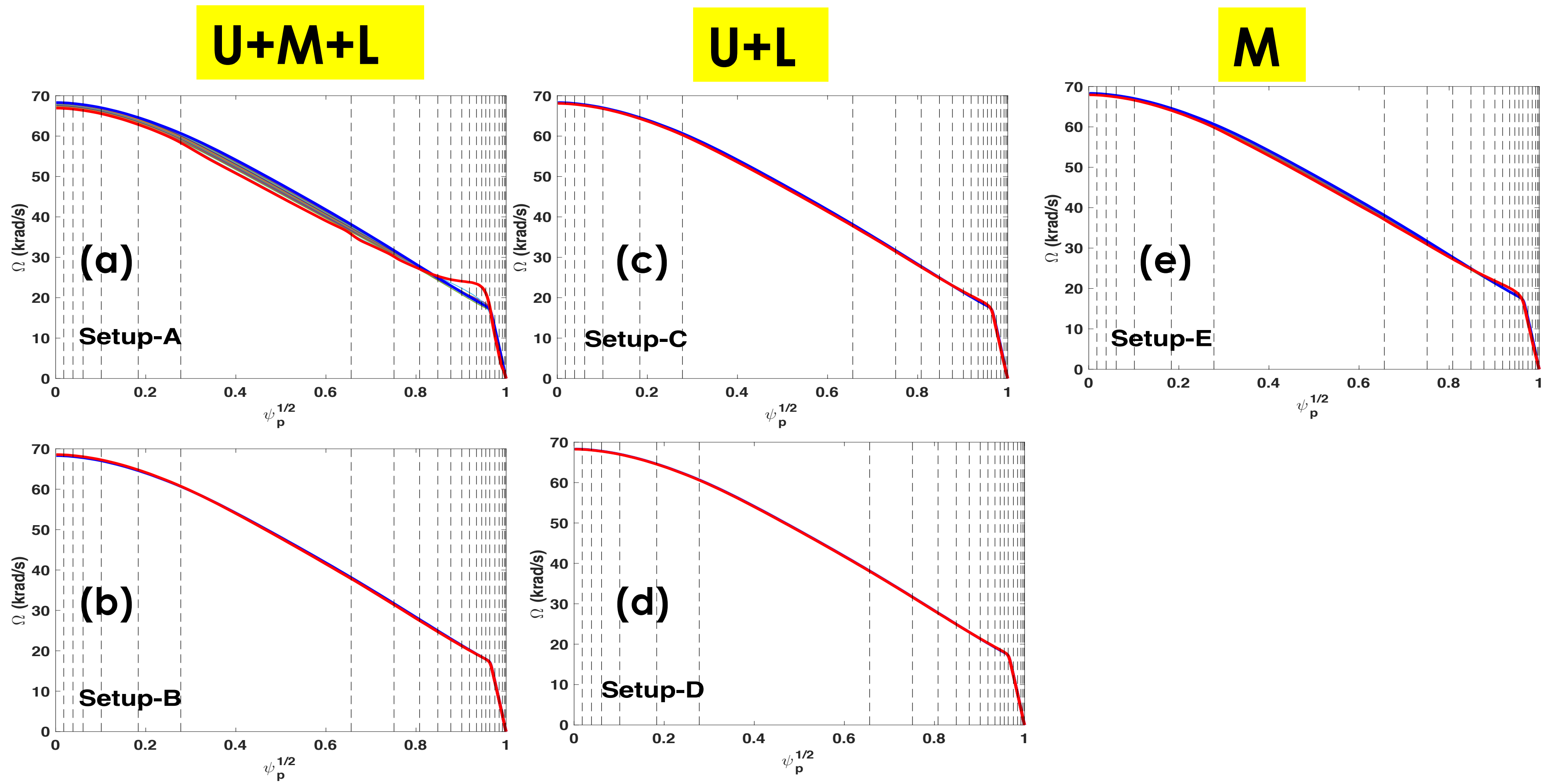
3-row



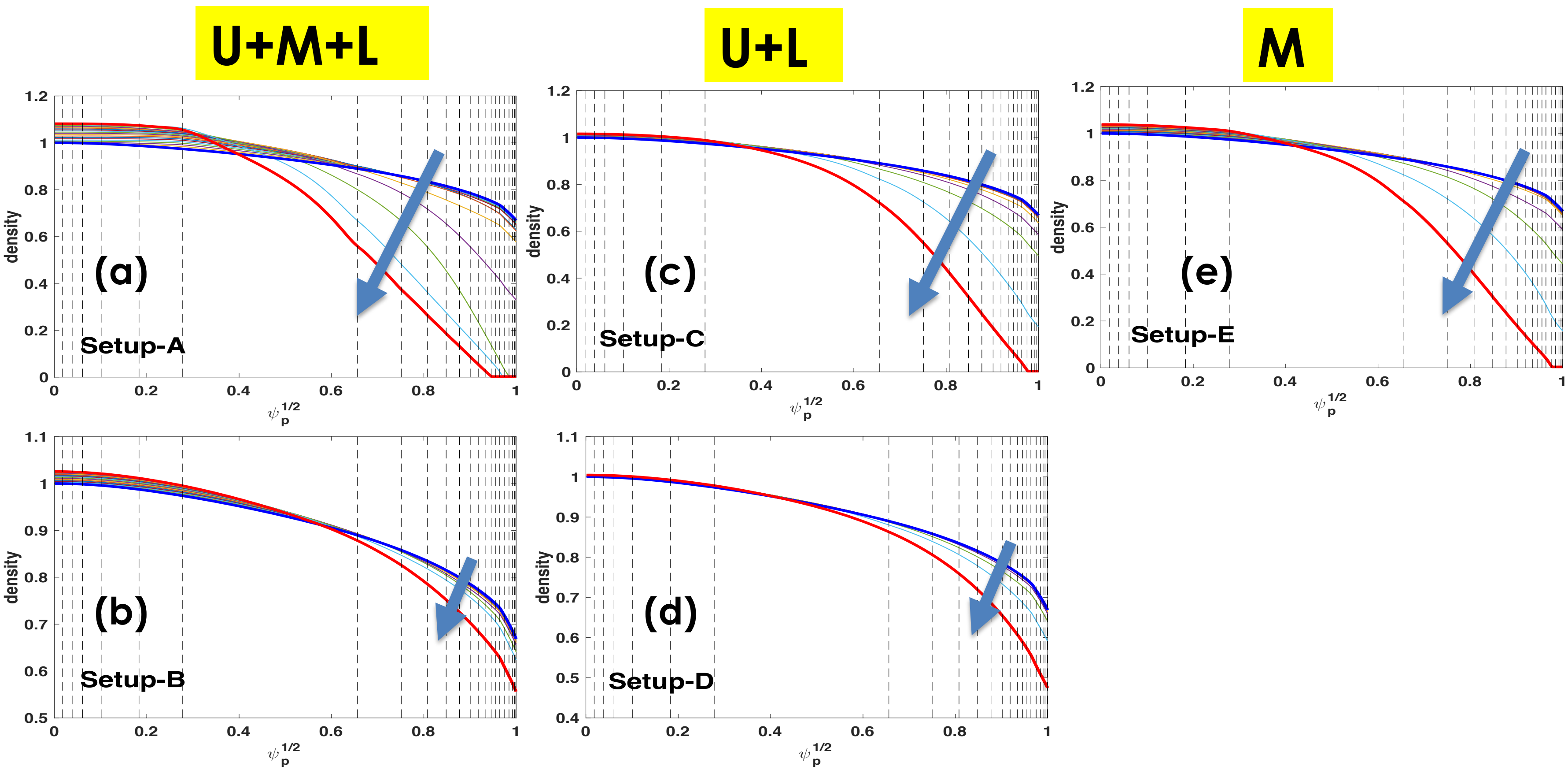
2-row



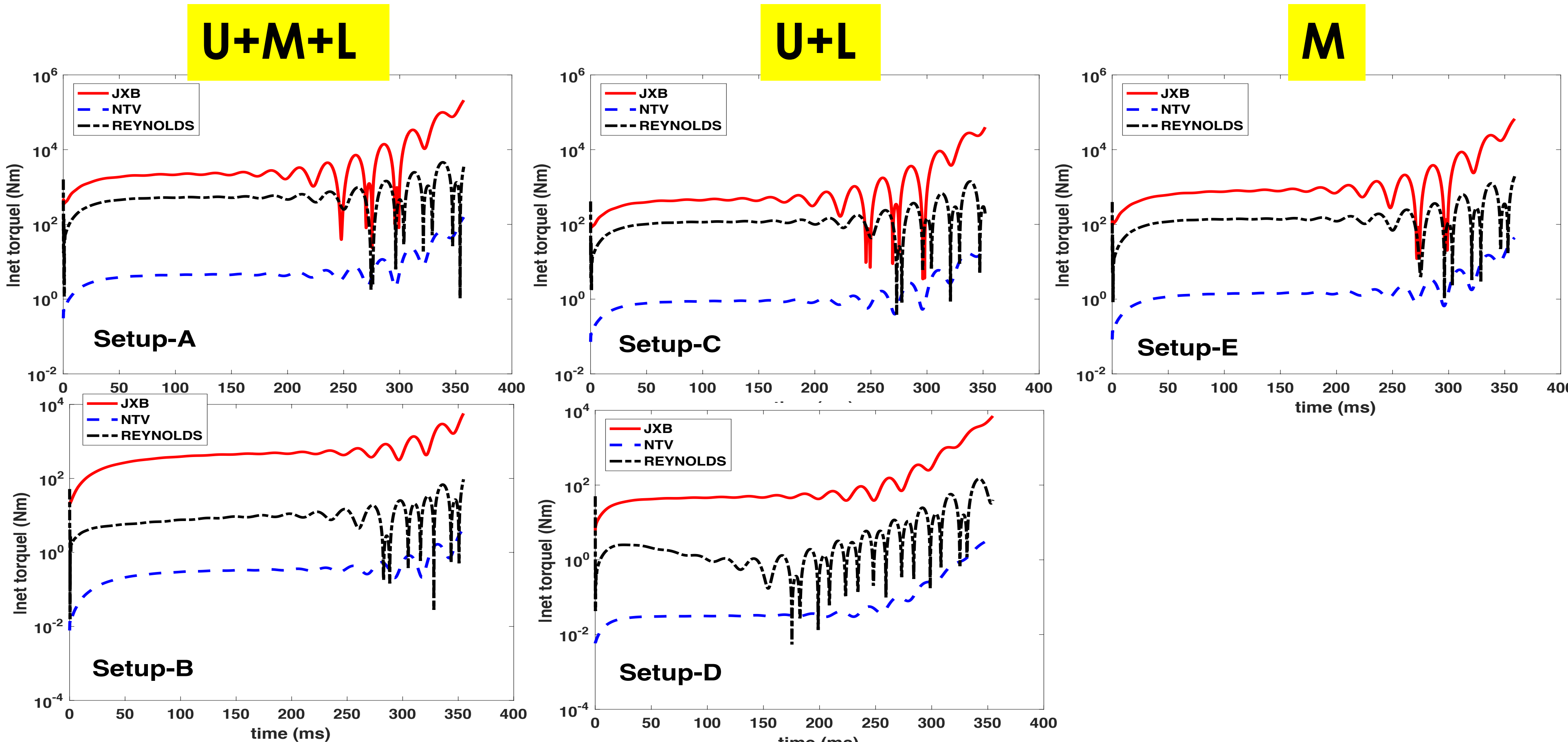
MARS-Q simulations find minor effects on toroidal flow with all 5 RMP coil configurations in ITER 10 MA/5.3 T steady state scenario



MARS-Q simulations find moderate density pumpout with 3-row or 2-row coil configurations that offer best ELM control

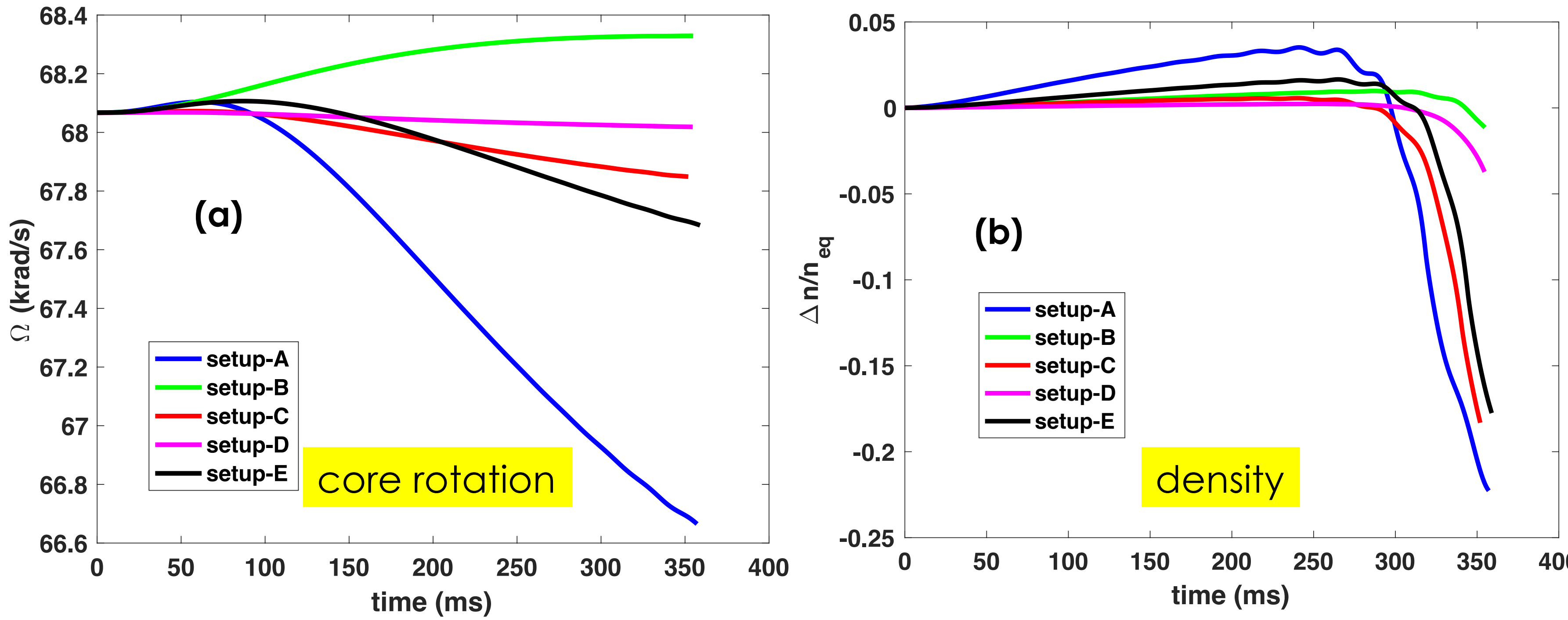


Resonant electromagnetic torque provides dominant contribution with all 5 RMP configurations in ITER 10 MA/5.3 T steady state scenario



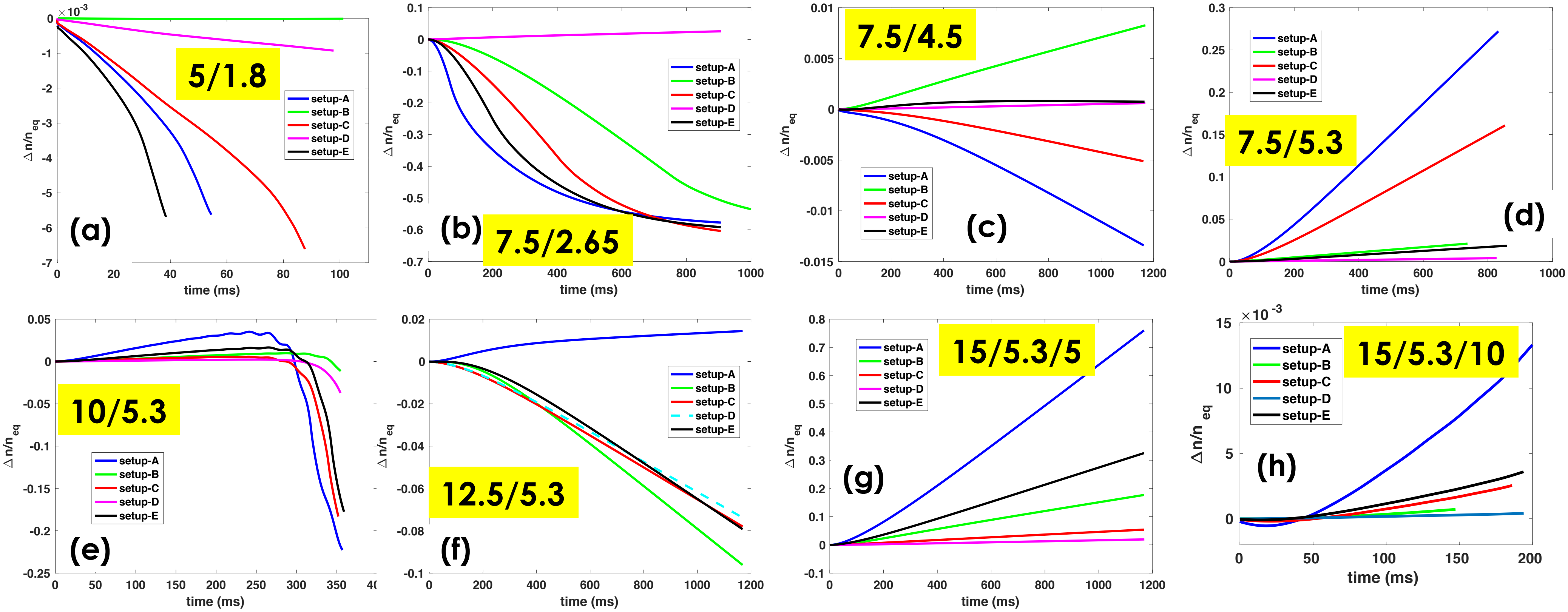
MARS-Q simulated time traces of core rotation and net density change show weak flow damping and moderate density pumpout

- **Setup-A (3-row with best ELM control) produces strongest (albeit still moderate) effects on plasma density and toroidal flow**



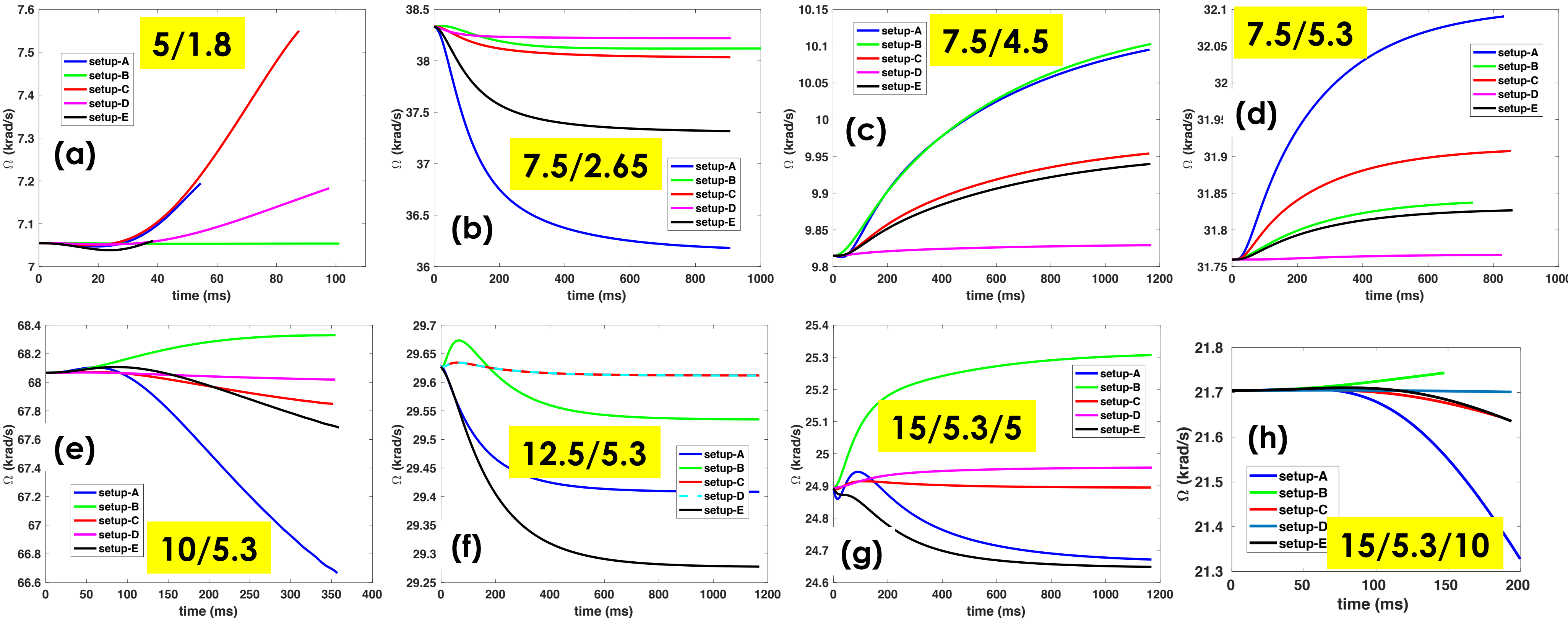
GENERAL ATOMICS

MARS-Q simulated density effect by RMP varies with plasma scenario and ELM control coil current configuration in ITER



GENERAL ATOMICS

MARS-Q finds weak effect on plasma core rotation by RMP in ITER independent of plasma scenarios and coil current configurations



GENERAL ATOMICS

Summary

- Two criteria established to guide optimal choice of ELM control coil current configurations, based on linear response modeling for various present day experiments
- Both criteria directly related to maximizing edge-peeling response and yield similar optimal coil phasing
- Quasi-linear modeling of ASDEX Upgrade and DIII-D, with varying toroidal spectra during RMP, finds same trend but weaker effects on plasma density than experiments
- Both linear and quasi-linear response modeling systematically carried out for 8 ITER scenarios covering both PFPO and FPO phases
- With 3 rows of ELM control coils in ITER, linear response modeling finds optimal coil phasing that scales linearly with q95 with an outlier for 10 MA steady state scenario
- Quasi-linear response modeling finds weak core flow damping in all ITER scenarios, but effect on density varies depending on plasma scenario and coil current configuration