Aspects and Applications of Non-Axisymmetric Coils on KSTAR

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On behalf of

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16th Workshop on MHD Stability Control

1. Overview of 3D Field Coils in KSTAR

2. Applications

    2-1. Axisymmetric Applications

    2-2. 3D (Non-axisymmetric) Applications

        - ELM suppression by n=1 RMP

3. Summary

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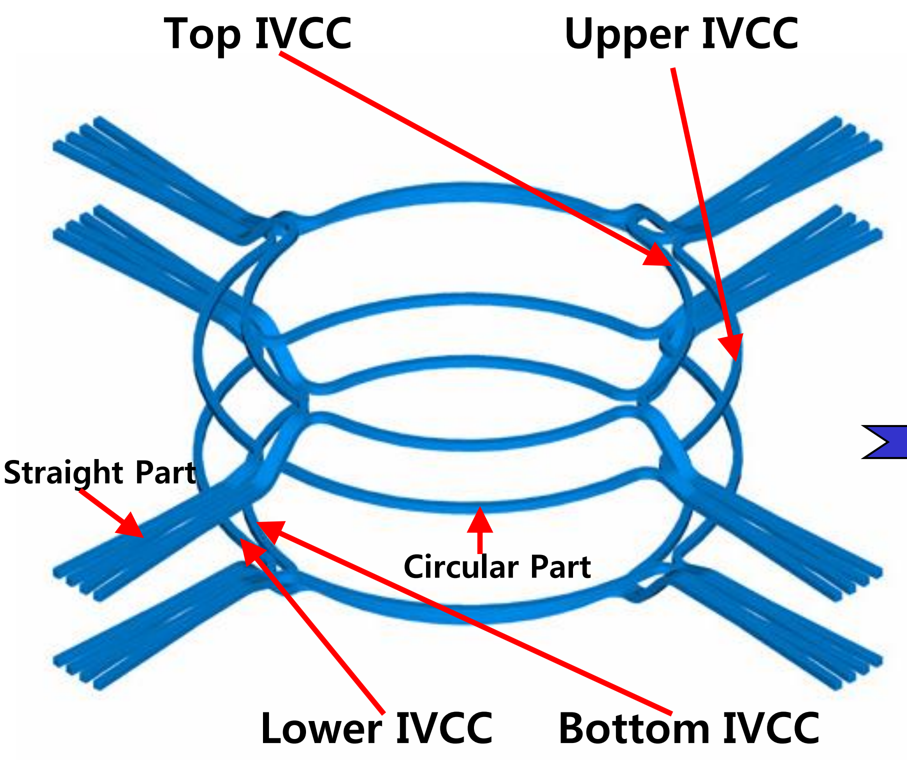
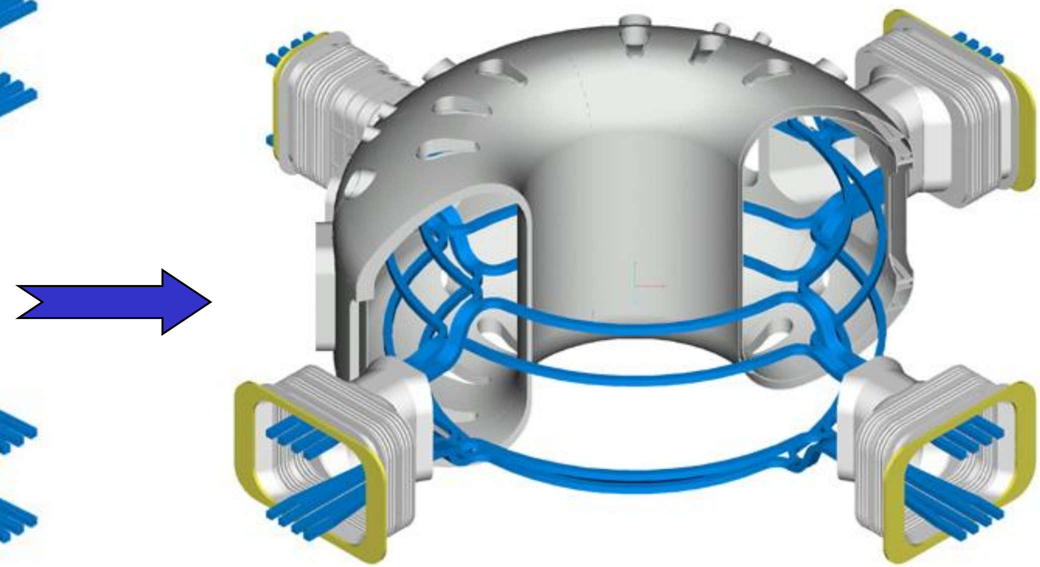
3. Summary

KSTAR Has A Versatile In-Vessel Control Coil (IVCC) System Inside Vacuum Vessel

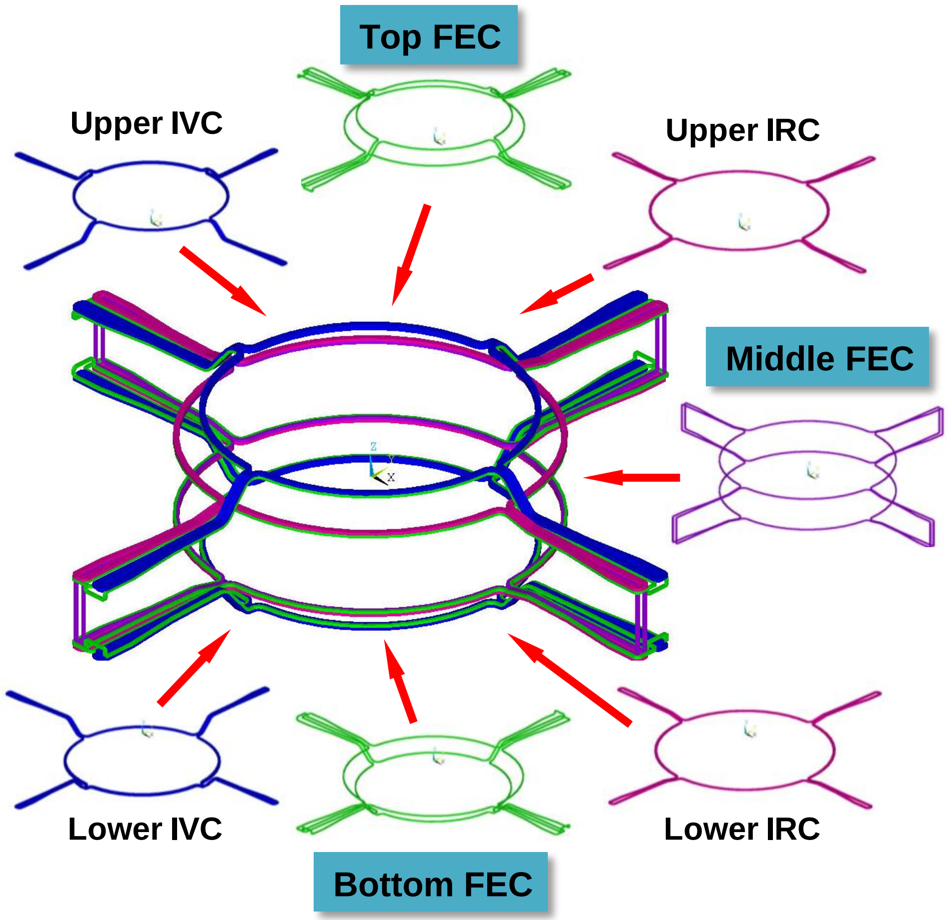
* H.K. Kim, H.L. Yang, et al., Fus. Eng. Design 84 (2009)

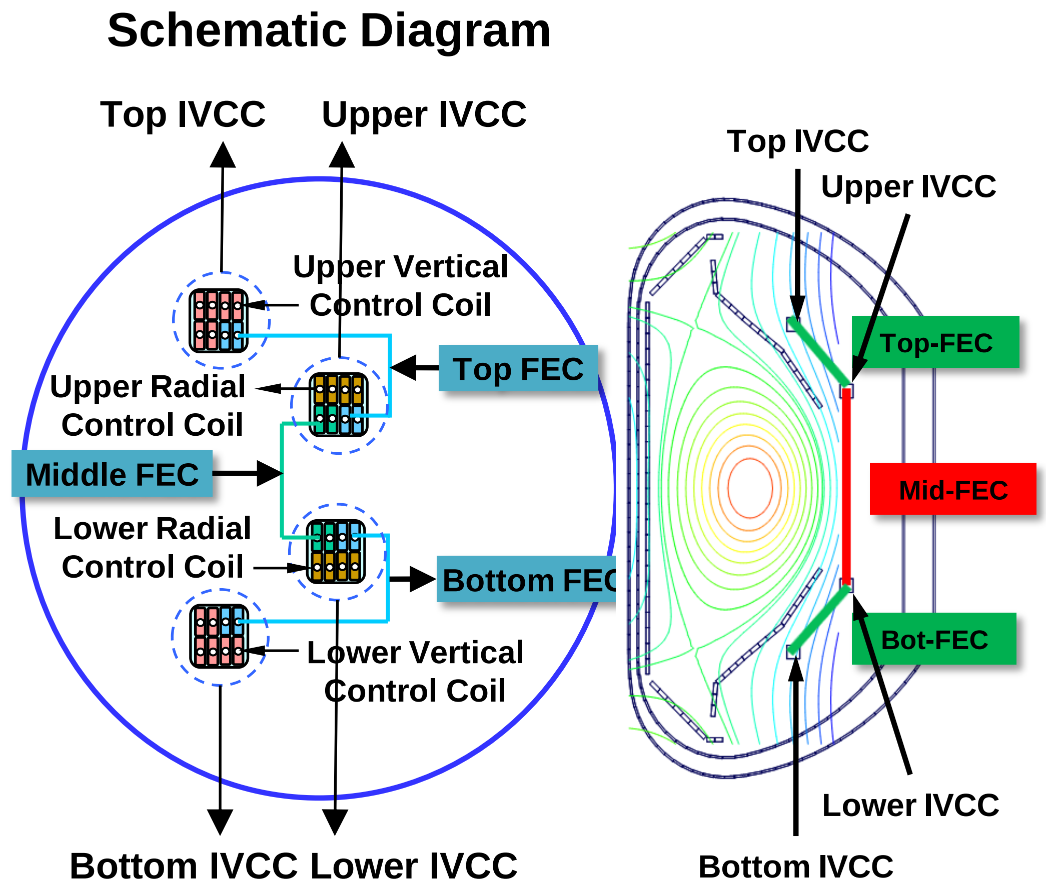




- **Toroidally segmented 3D shaped coil system**
  - **(1) Combining axisymmetric and non-axisymmetric field coils**
  - **(2) Easier installation and maintenance**

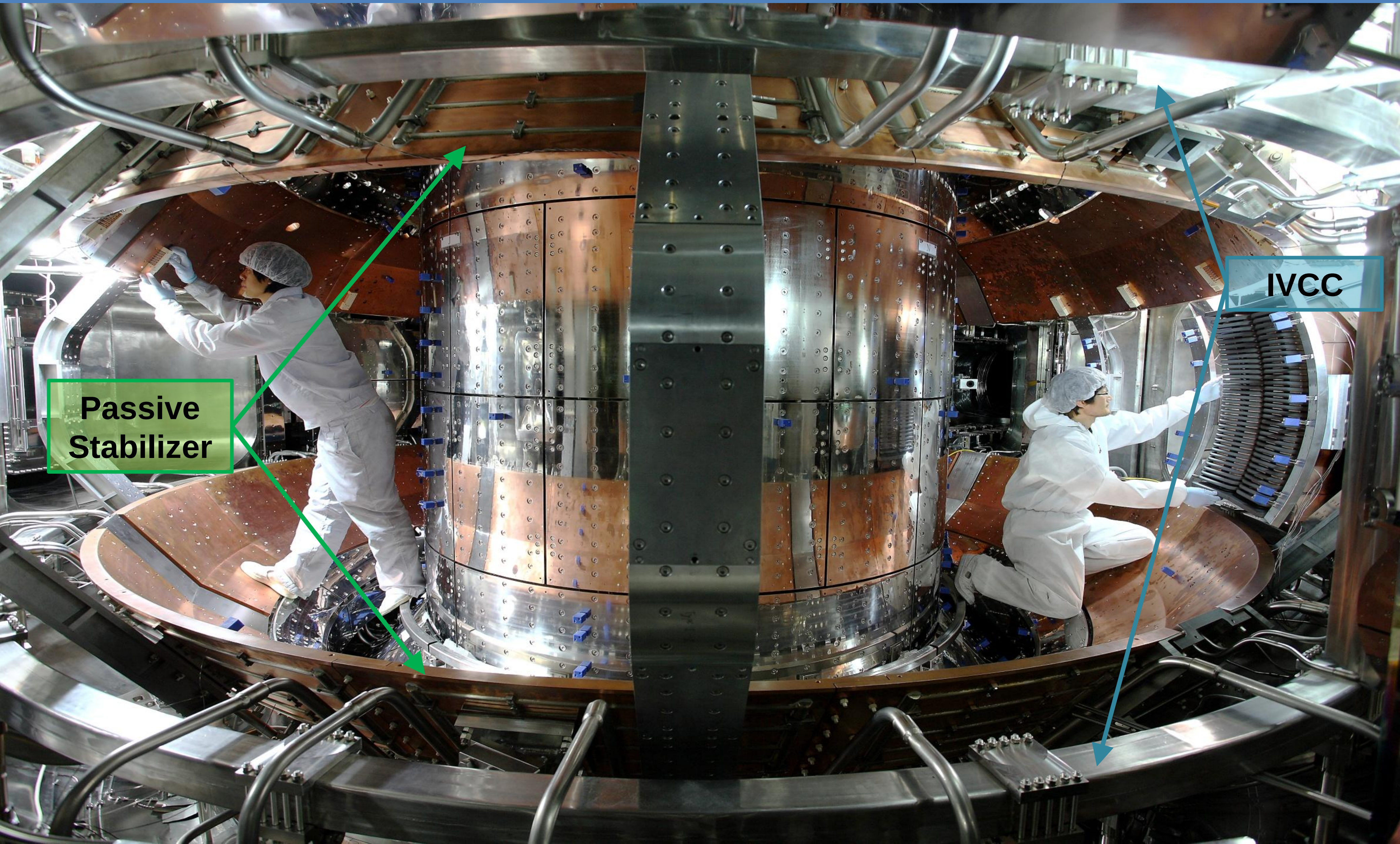
Applicable to Axisymmetric and Non-Axisymmetric Magnetic Applications





- **Axisymmetric applications**
  - **-Vertical stability control (IVC), fast radial control (IRC)**
- **Non-axisymmetric (3D) applications**
  - **-Field error corrections (FEC), RWM, RMP etc**

Full IVCC System Installed in 2010



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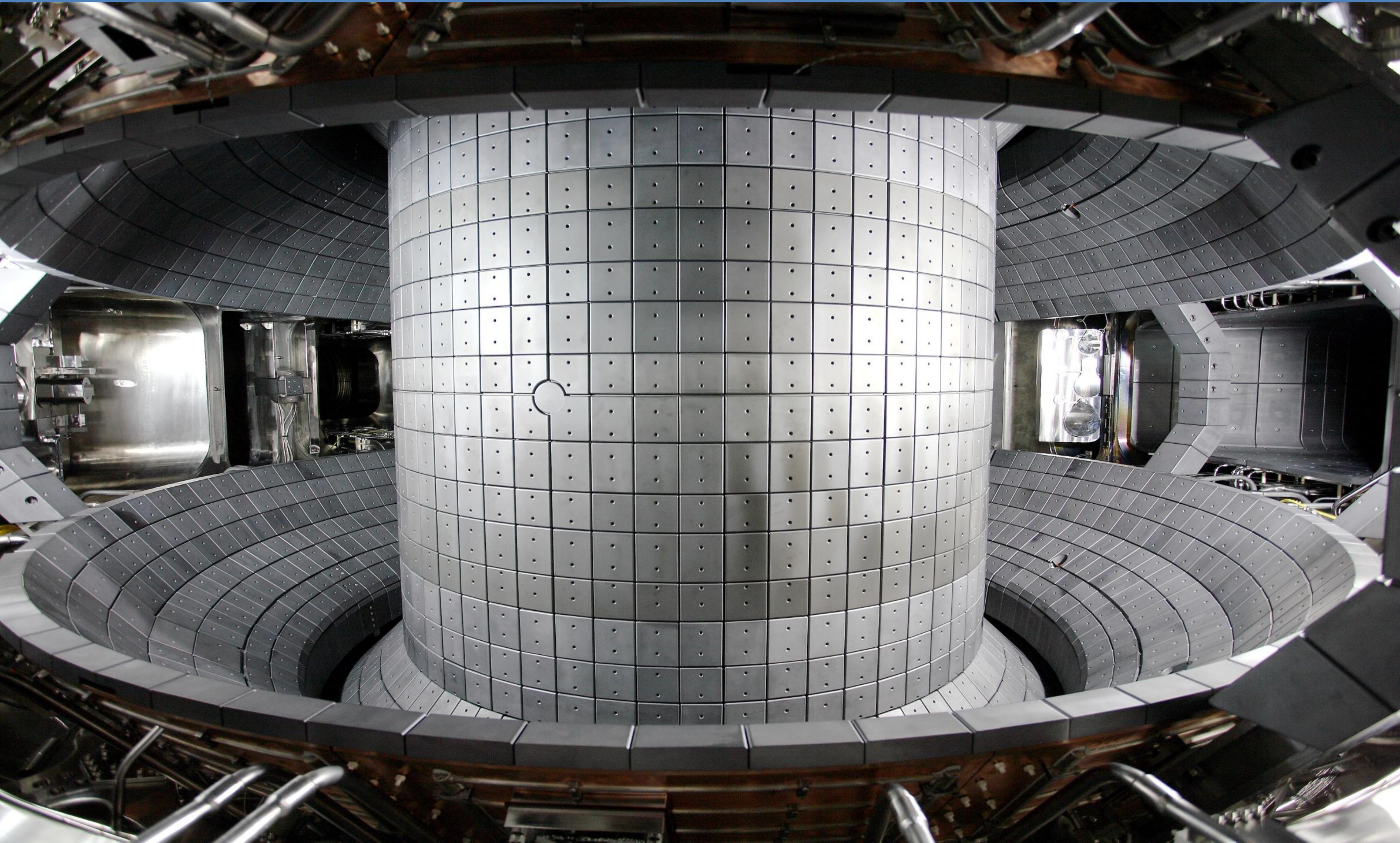

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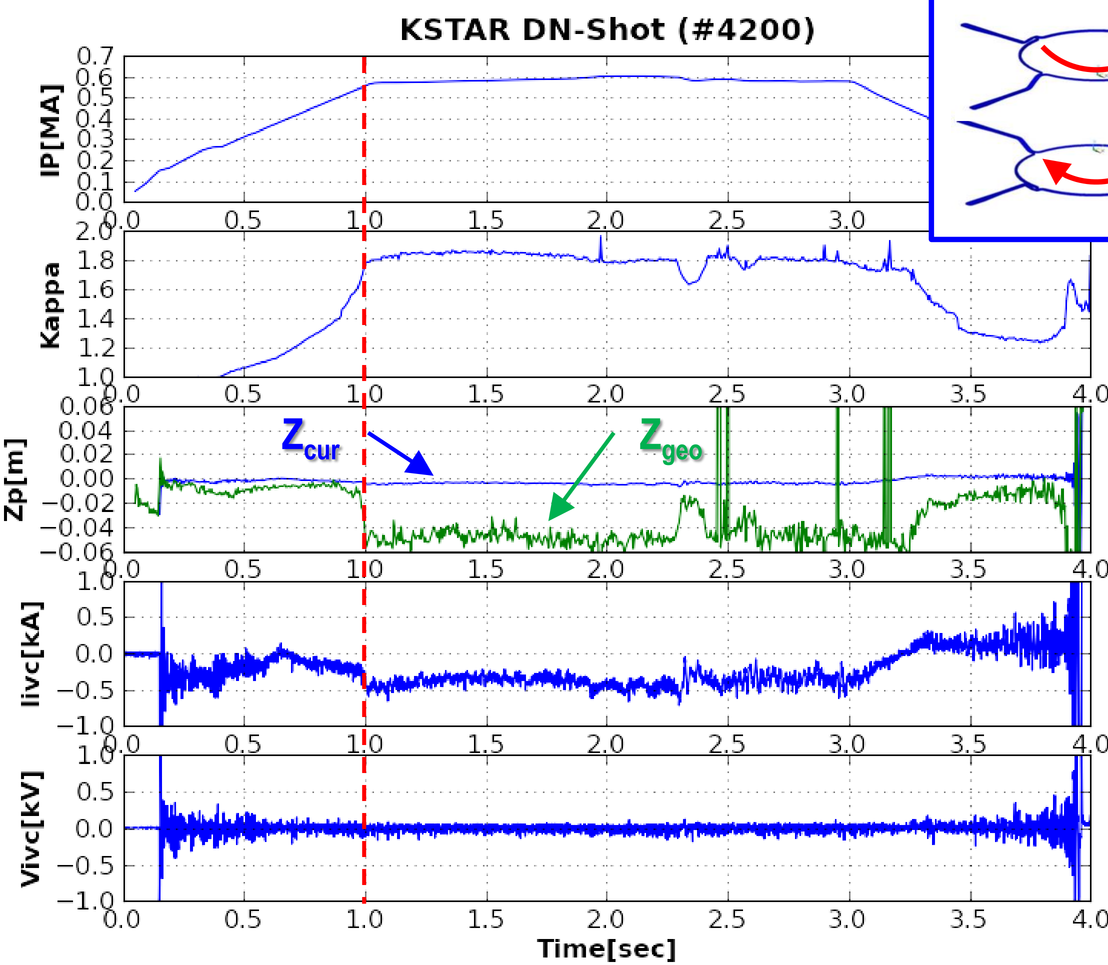
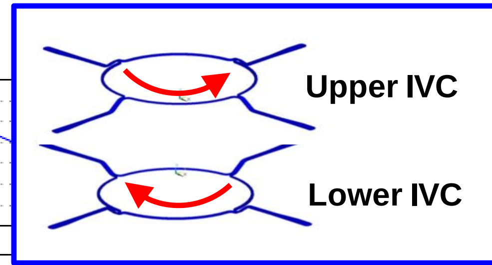
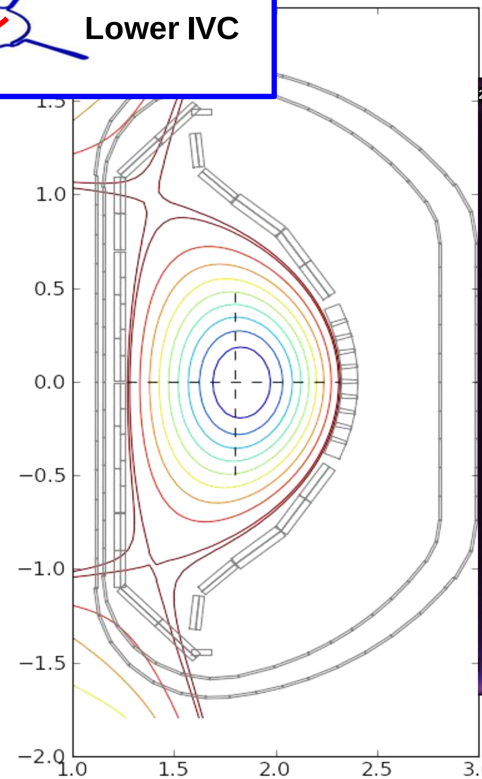
      - ELM suppression by n=1 RMP

3. Summary

Successful Vertical Stabilizations of Highly Shaped Plasmas by IVC (κ~1.85 and δ~1.0)







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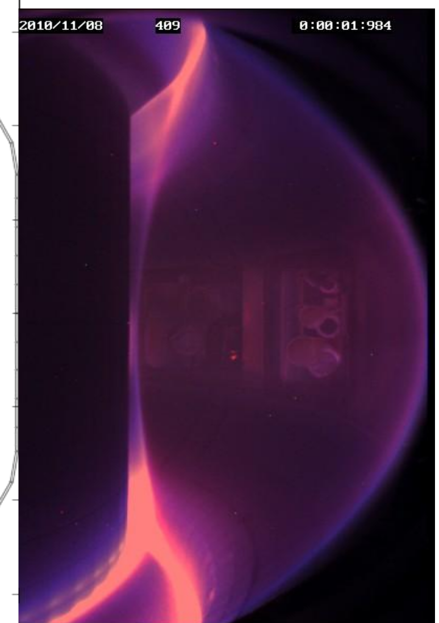
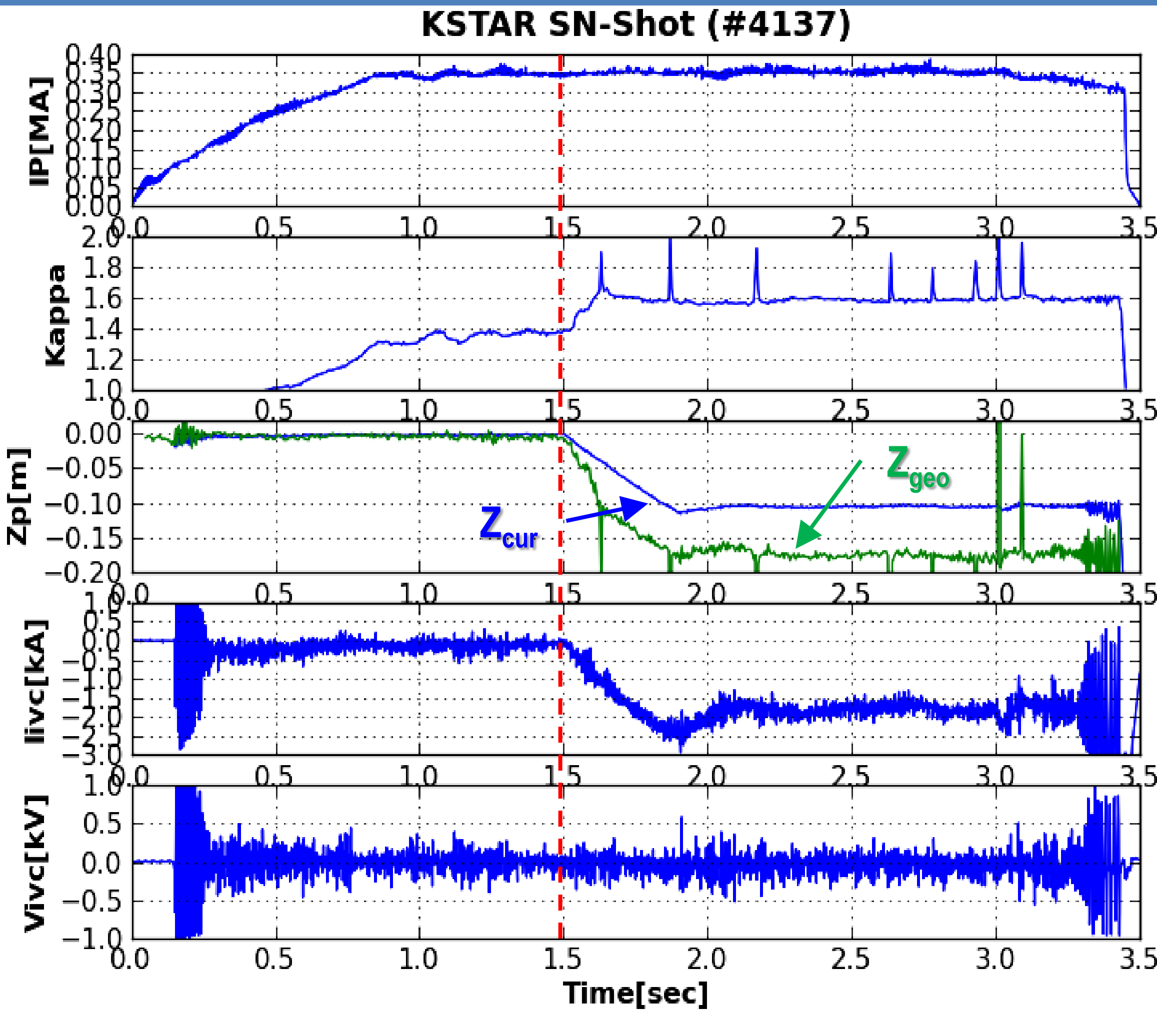
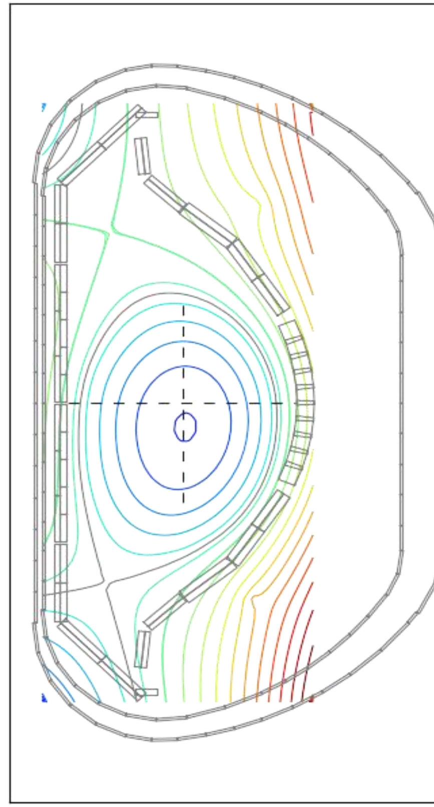


- κ~1.85 & δ~1.0 achieved successfully
- Led to early achievement of first H-mode (2010)

Even LSN Plasmas Enforced by IVC Were Well Controlled





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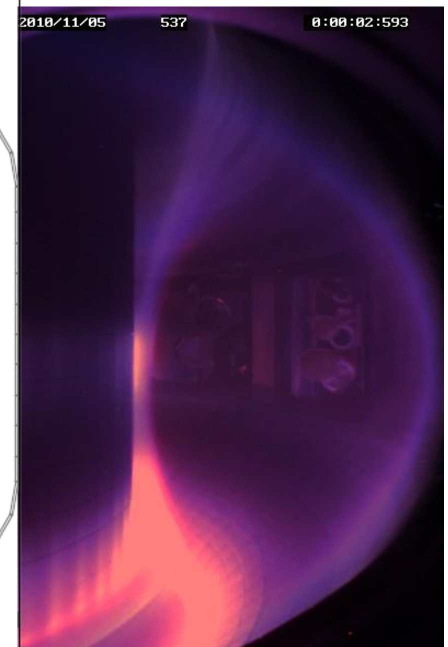
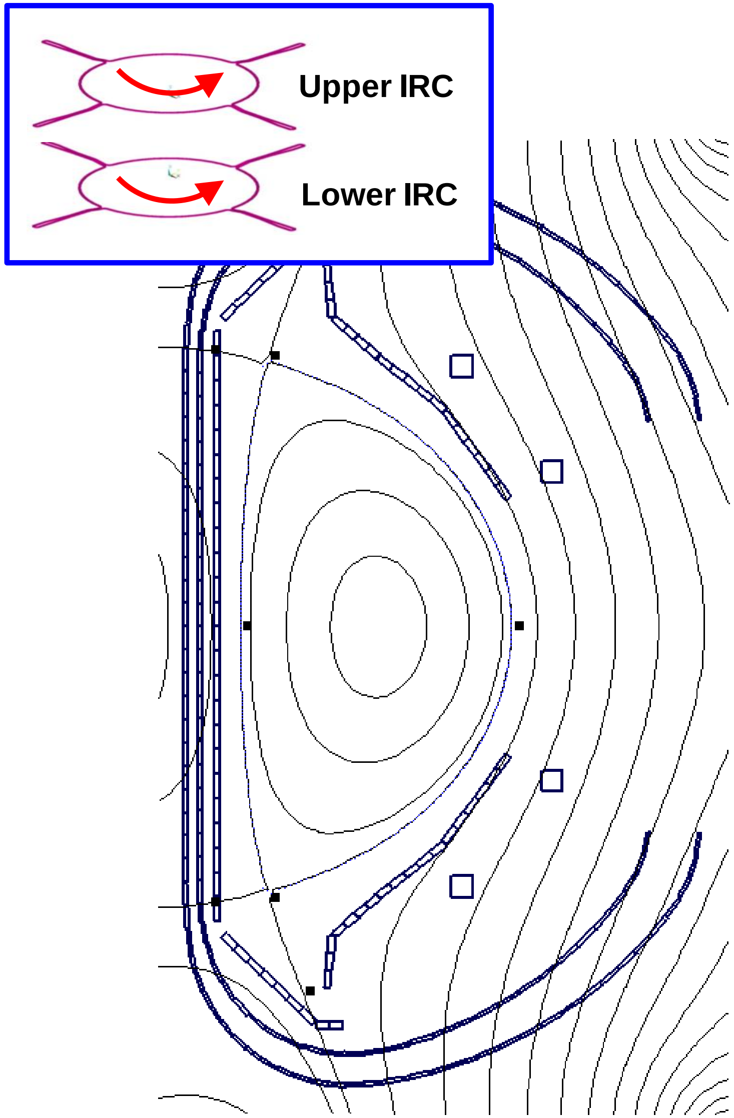
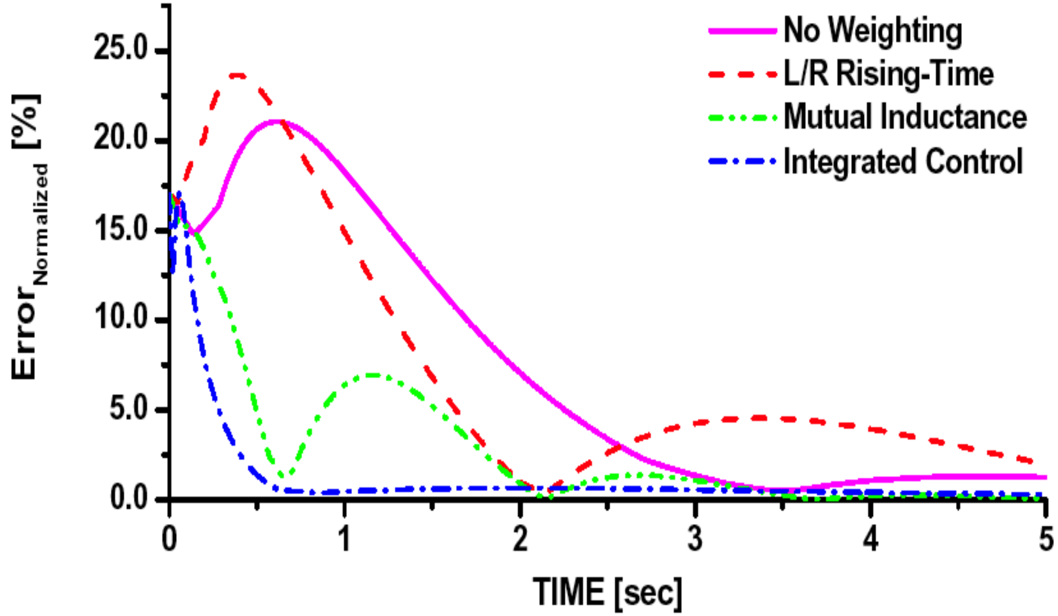


- **For LSN shaping, plasma pushed down by ~10cm using IVC**
  - **- I_{IVC}~2.0kA/t applied to hold it**
- **Well controlled even though its worse field curvature**

Integrated Shape Control Combined with IRC Can Enhance Control Performance Significantly





- **IRC is not essential component, but …**
- **Can enhance shape control performance significantly**
- **Improved shape control=**
  "Fast R_p control by IRC"
  + "isoflux control with M_{ij}-decoupling"
- **Example: All volume shifted by ΔR=+2cm**

➔ IRC is on preparation for use in 2012

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- ELM suppression by n=1 RMP

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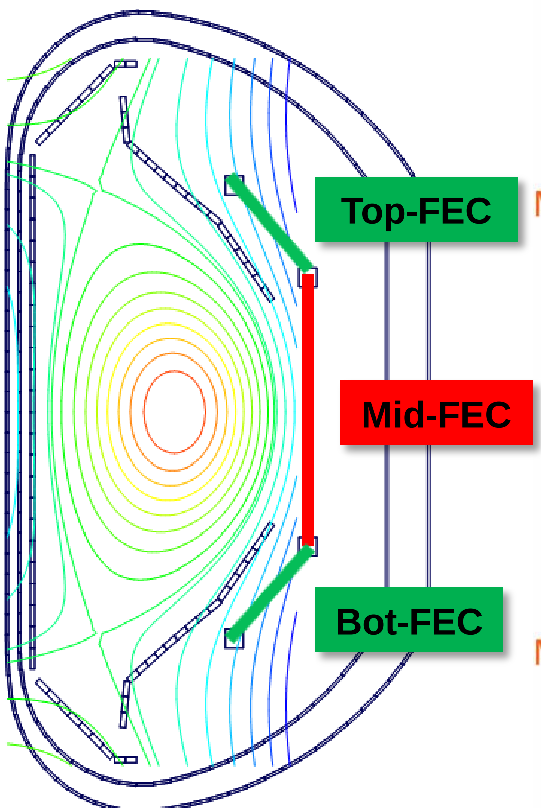
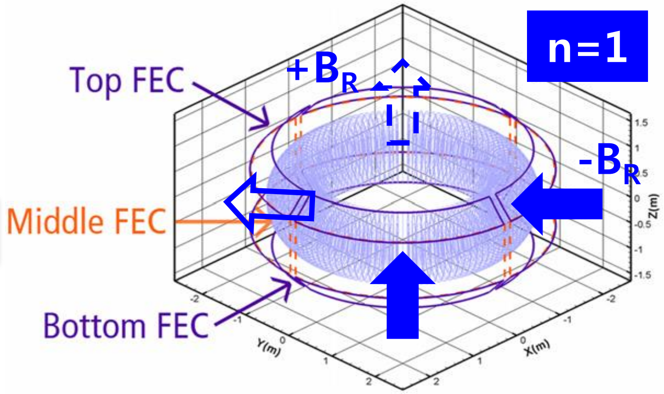
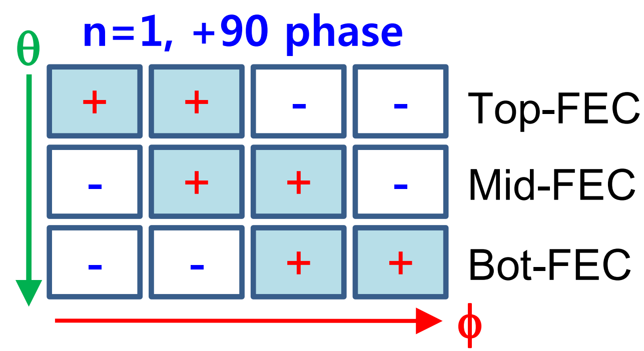
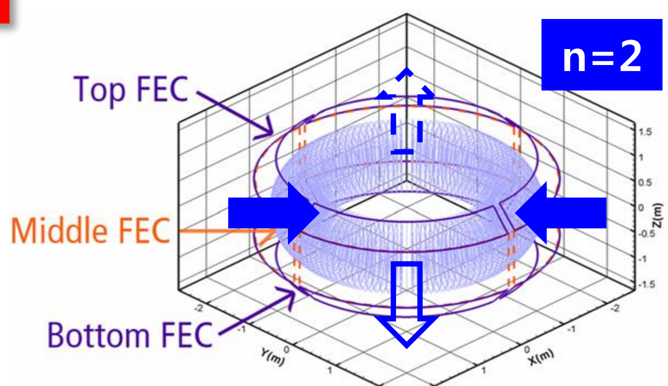
KSTAR Can Provide Wide Spectra of 3D Magnetic Perturbations

- **3-by-4 3D field coils available having 2 turns for each**
  - all internal and segmented with saddle loop configurations
  - n=1 and 2 applicable
- **Wide spectra of magnetic perturbations are possible**
  - Poloidal helicity change for n=1
  - Even/odd parity change for n=2







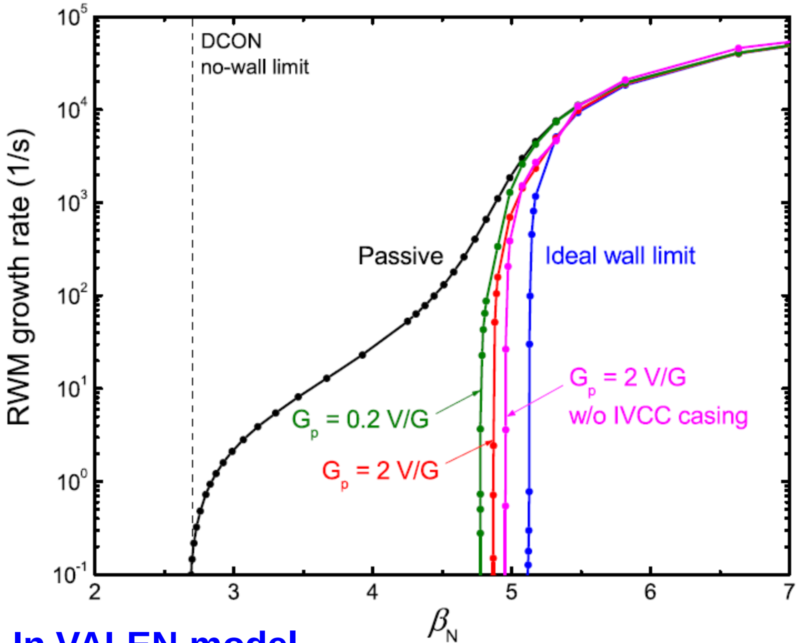


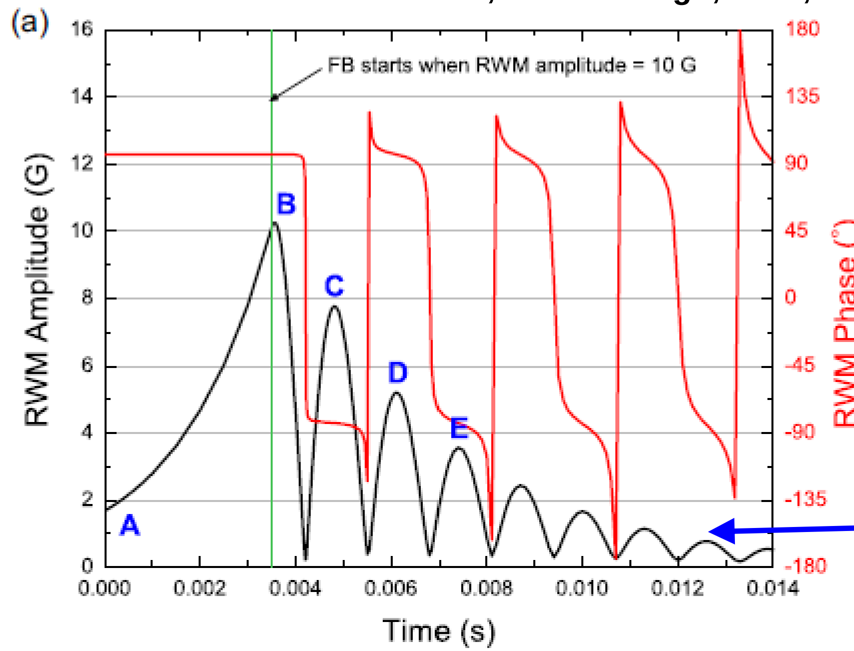
Main applications of 3D fields

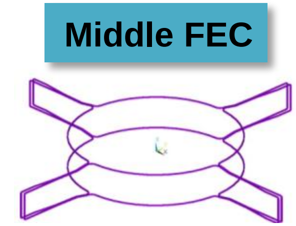
1. **Resistive Wall Mode Control**
2. **Error Field Correction**
3. **RMP/NRMP Physics Study**

RWM Controls Are Under Design and Study
: Cu-Passive Stabilizer + RWM coils → $\beta_{N,Wall}$(~5.0)

* Y.S. Park, S.A. Sabbagh, et al., Nucl. Fusion 51 (2011)

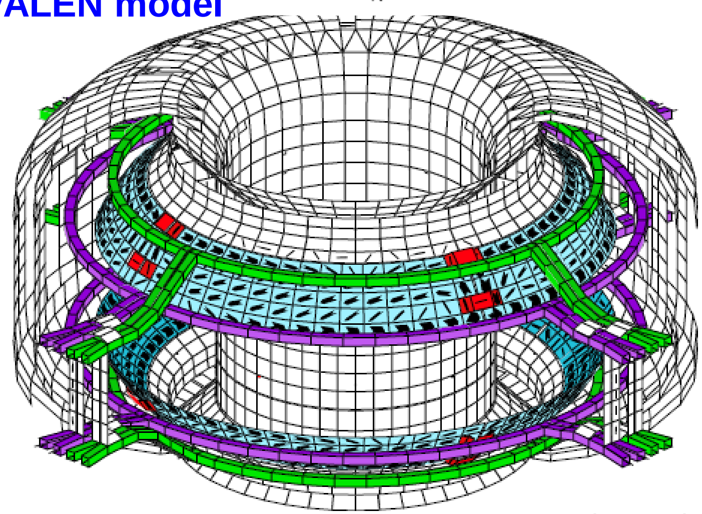


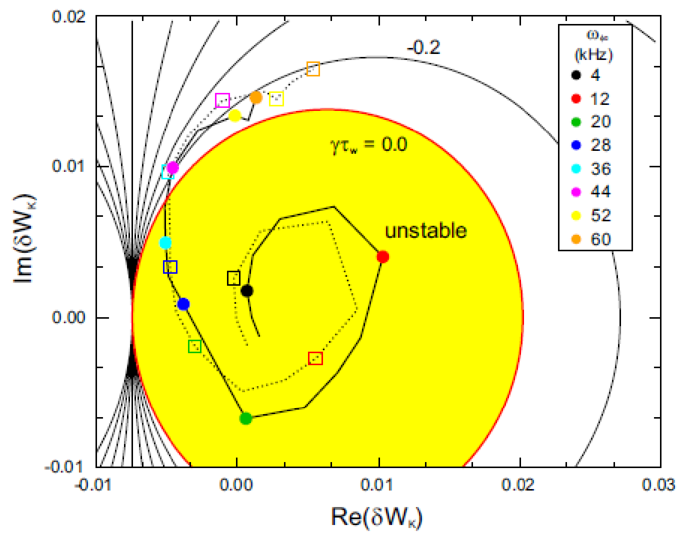




Controlled within ~8ms

In VALEN model





MISK predicts relatively large rotations are required for RWM stability

Applicable Spectra of n=1 and n=2 MP

n=1, -90 phase

-	-	+	+	top
-	+	+	-	mid
+	+	-	-	bot

n=1, 0 phase

+	+	-	-	top
+	+	-	-	mid
+	+	-	-	bot

n=1, +90 phase

+	+	-	-	top
-	+	+	-	mid
-	-	+	+	bot

θ ϕ B_T

n=1, 180 phase

+	+	-	-	top
-	-	+	+	mid
+	+	-	-	bot

n=1, mid-FEC alone

				top
+	+	-	-	mid
				bot

n=2, even parity

+	-	+	-	top
-	+	-	+	mid
+	-	+	-	bot

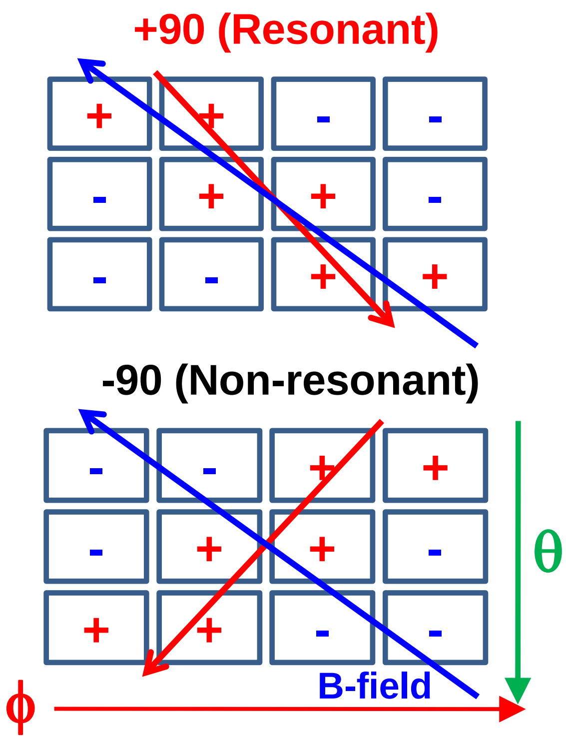
n=2, odd parity

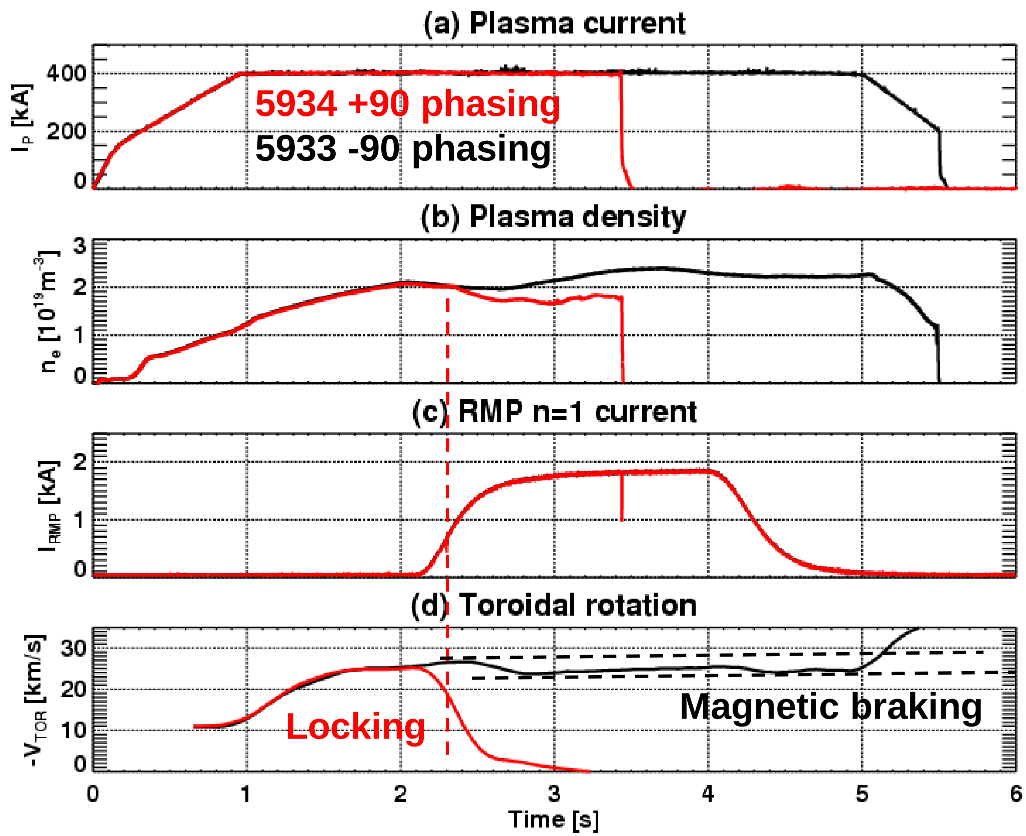
+	-	+	-	top
				mid
-	+	-	+	bot

Non-Axisymmetric Plasma Responses Were Investigated Using Two Different Phasings

* J.-K. Park, Y.M. Jeon, et al., in preparation for publication

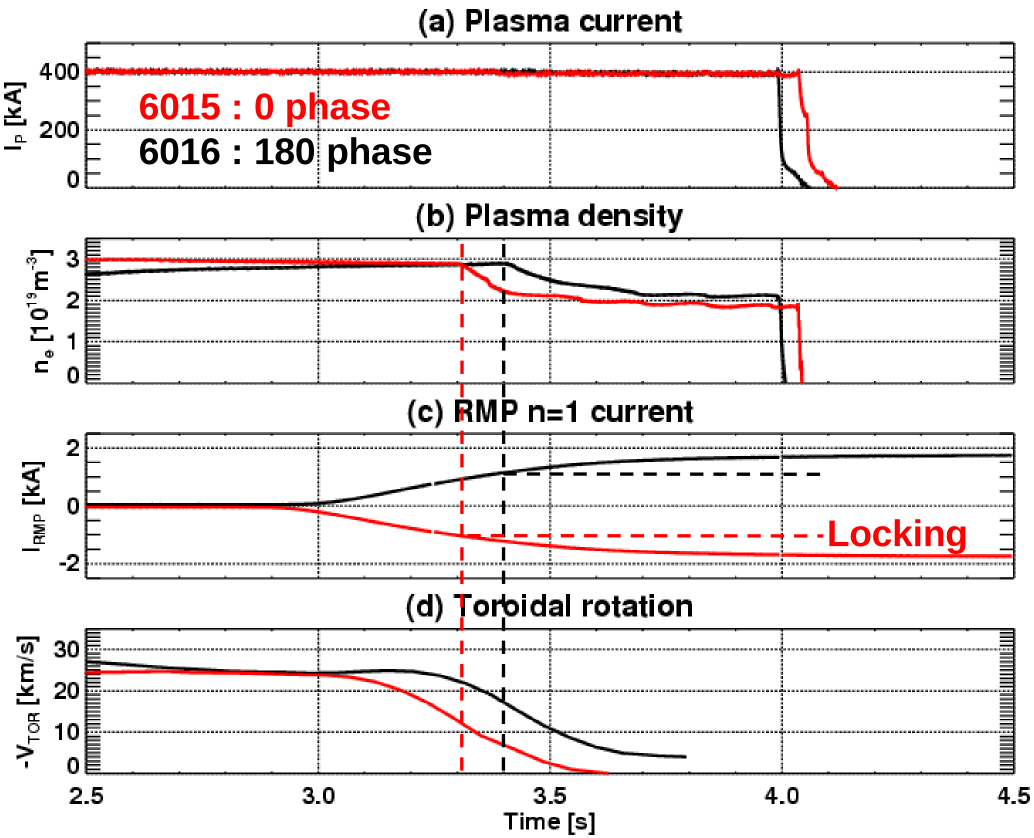
- Two different phasings (+90 and -90) of the n=1 fields were applied to Ohmic discharges (I_P=400kA, BT=2.0T)
  - The +90 phasing induced a locking and disruption with I_{FEC}~600A/turn
  - The -90 phasing caused only a slight braking of rotation

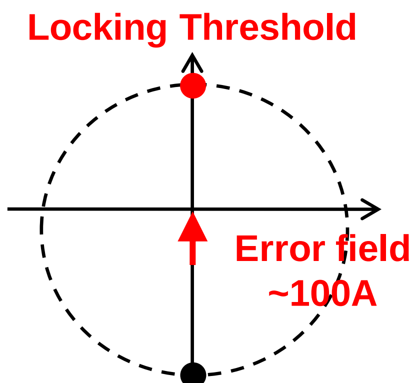


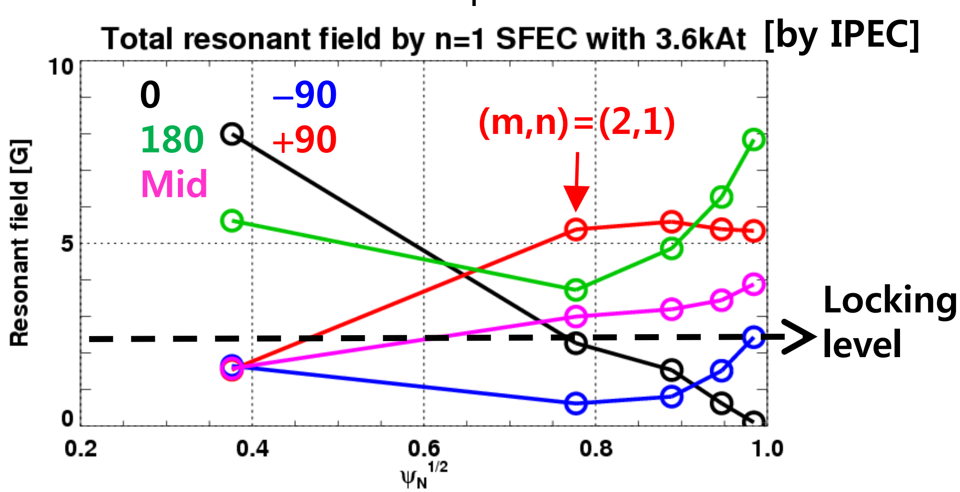


Non-Axisymmetric Plasma Responses Were Found In +90 Phasing By Locking

- A small non-axisymmetry was found in +90 phasing, by applying two different toroidal phases
  - Locking threshold I_{FEC}~1kA/turn for 0 phase, I_{FEC}~1.2kA/turn for 180 phase







➔ A small intrinsic error-field (~100A) found in KSTAR

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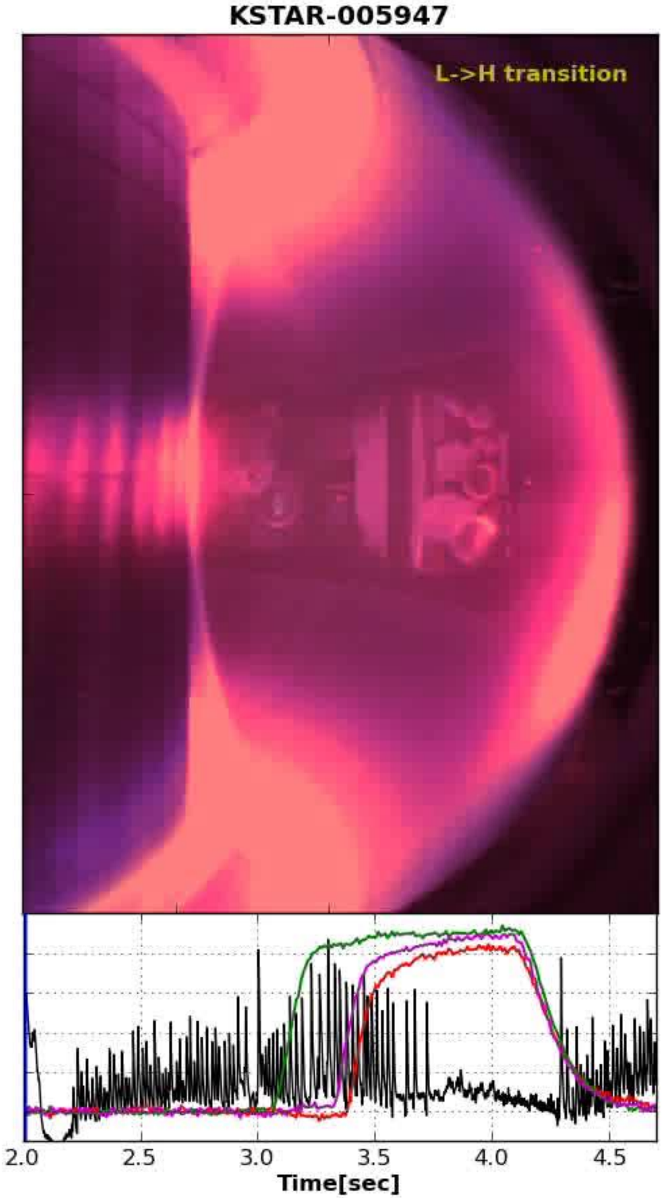
ELMs Suppressed by n=1 MPs in KSTAR 2011

• COMPASS-D	(n=1)	triggered (2001)
• DIII-D	(n=3)	suppressed (2004)
• JET	(n=1, 2)	mitigated (2007)
• NSTX	(n=3)	triggered (2010)
• MAST	(n=3)	mitigated (2011)
• ASDEX-U	(n=2)	mitigated (2011)

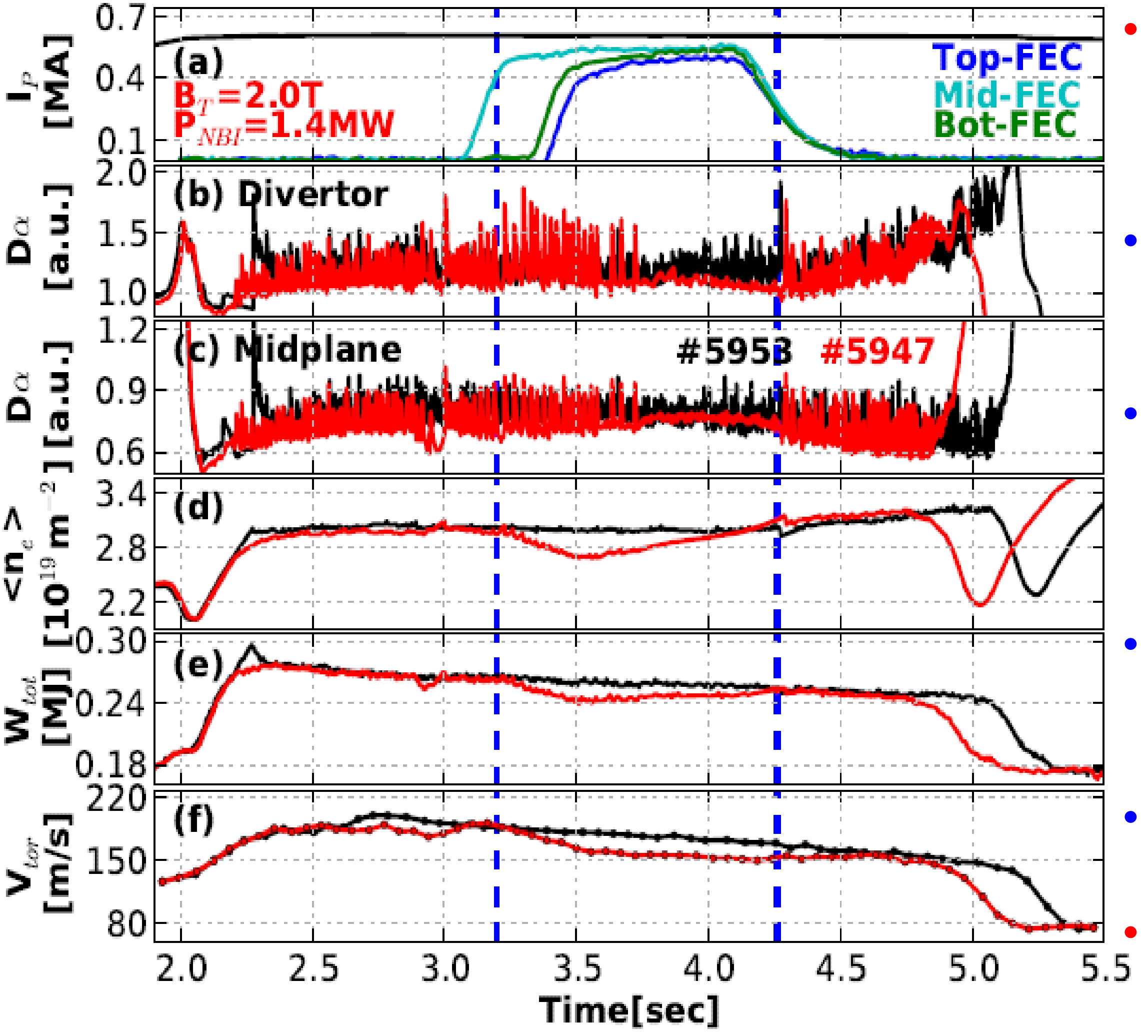
We are adding …

• KSTAR	(n=1)	Suppressed (2011)

* Y.M. Jeon, J.-K. Park, et al., submitted to PRL (Nov 05, 2011)

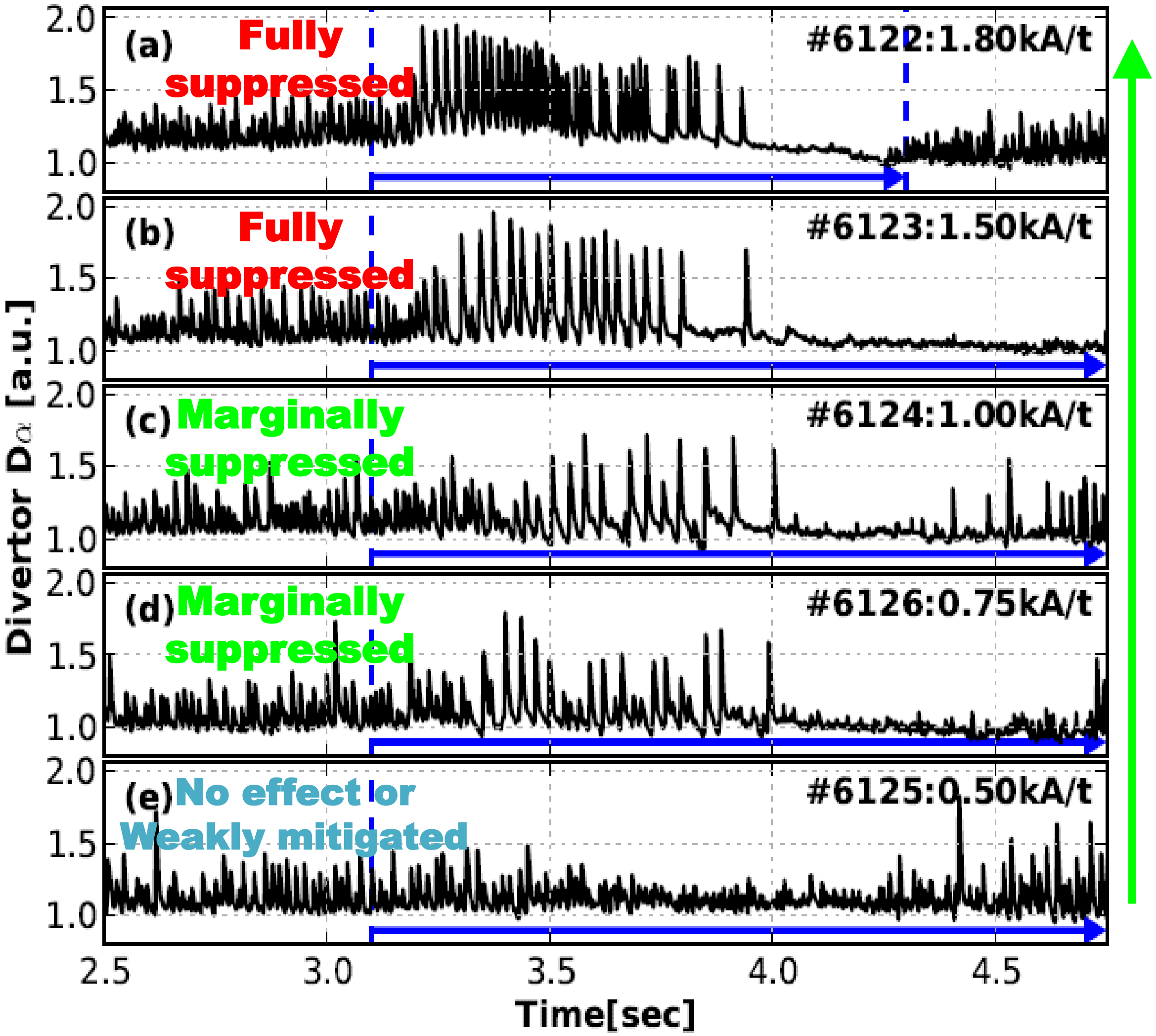


ELMs Suppressed For the First Time by n=1 MP (+90)



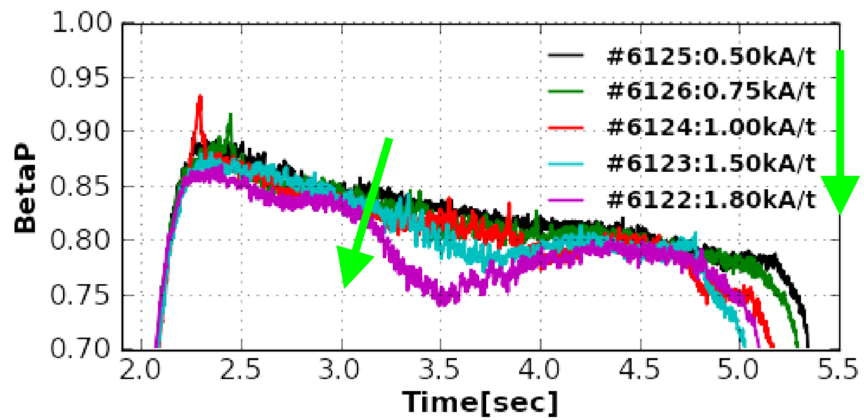
- **+90 phased n=1 MP suppressed ELMs**
  - In JET, ELM mitigated by n=1 (Y.Liang, PRL, 2007)
- **Density** (~10%) pumping out initially. Then, increased when ELM suppressed
- **Stored energy** drop by ~8% initially. Then slightly increased or sustained when ELM suppressed
- **Rotation** decreased (~10%) initially. Then sustained when ELM suppressed
- **Te/Ti** changes were relatively small
- **Two distinctive phases** observed
  - **(1)ELM excitation phase**
  - **(2)ELM suppression phase**

Threshold FEC Current for ELM Suppression



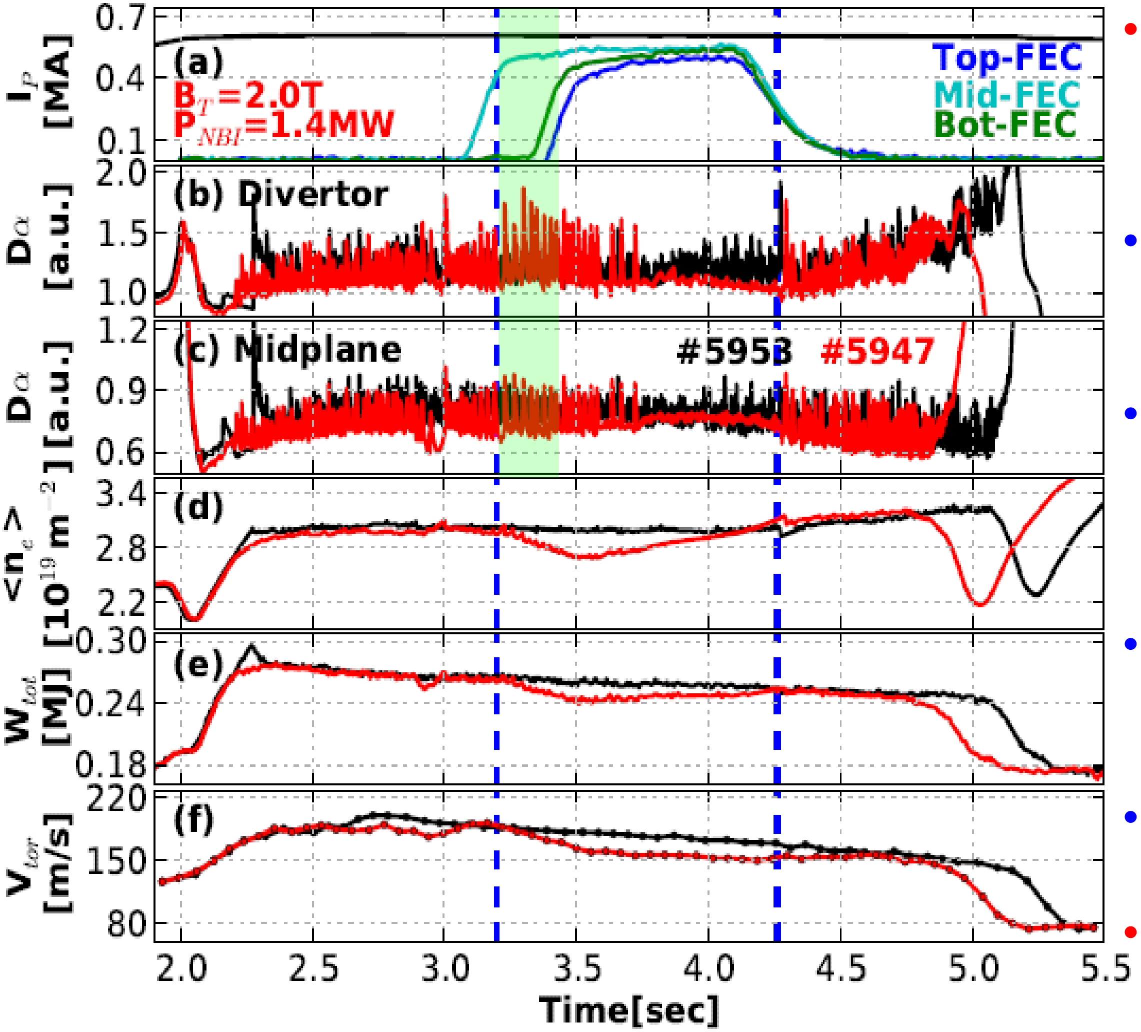
- $I_{FEC,threshold}$
  $\geq$ 0.75 kA/t : marginal suppression
  > 1.00 kA/t : full suppression
  (vacuum analysis predicted $\geq$ 1.00 kA/t)

- $\Delta\beta_p$ is dependent on I_{FEC}
  (similar Δn_e, ΔW_{tot}, ΔV_ϕ, …)



- Note that there was no clear change of ELM size on transition (excitation → suppression), while the ELM frequency decreased dramatically

ELMs Suppressed For the First Time by n=1 MP (+90)



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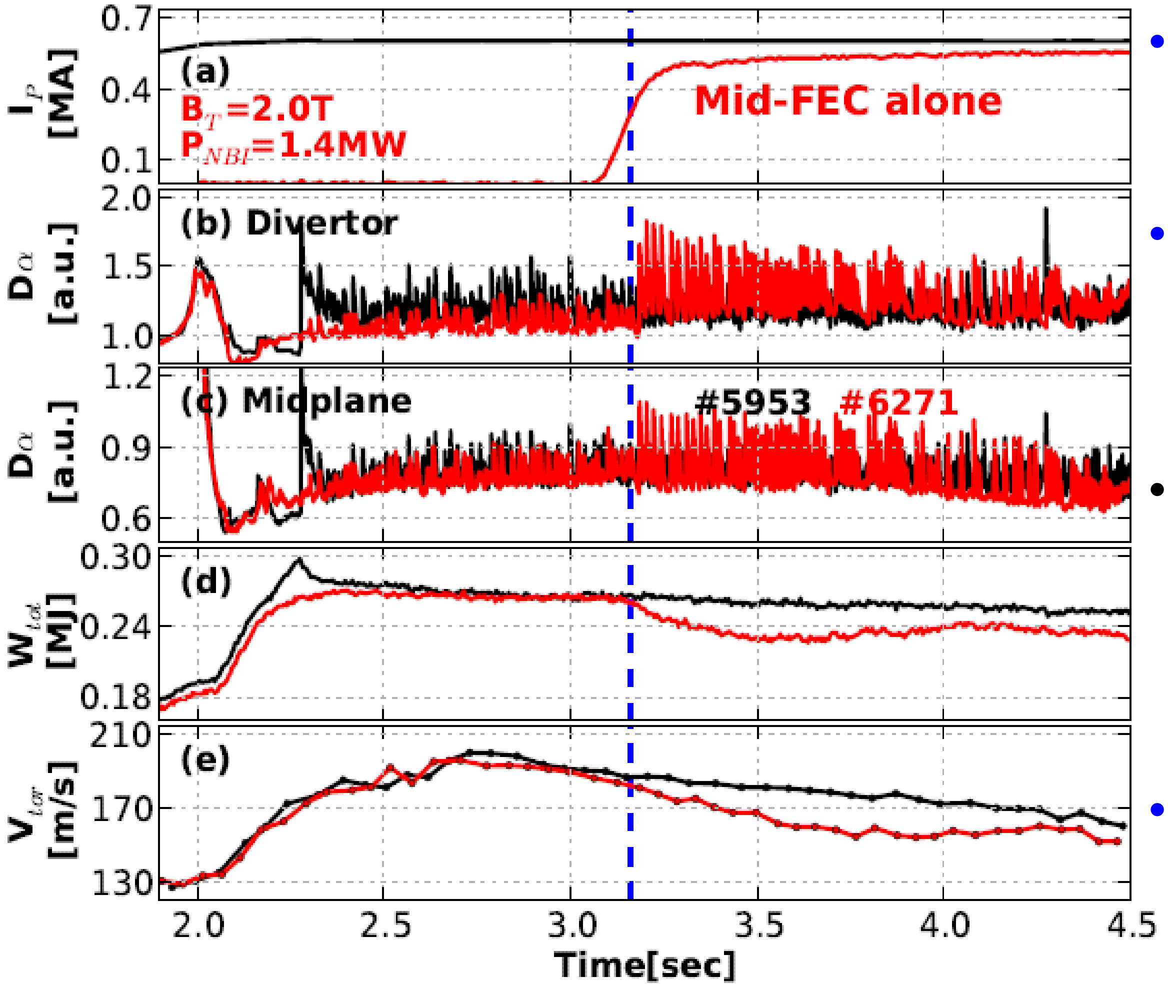
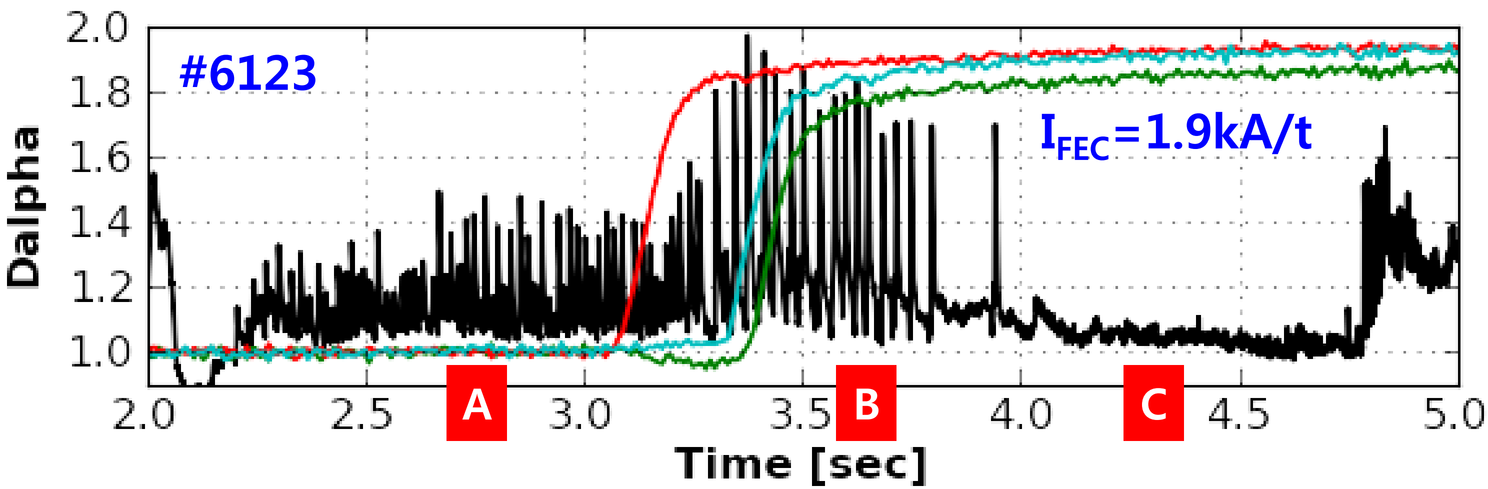
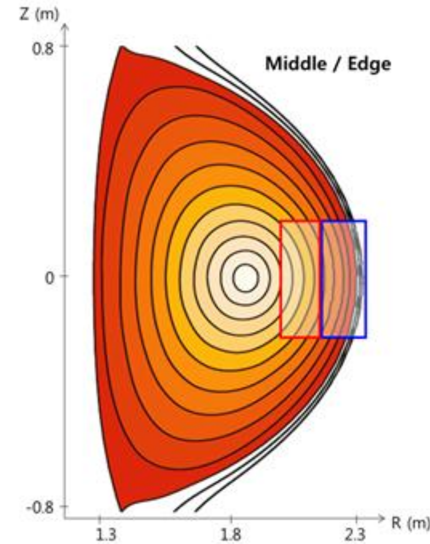
Mid-FEC May Responsible for ELM-Excitation

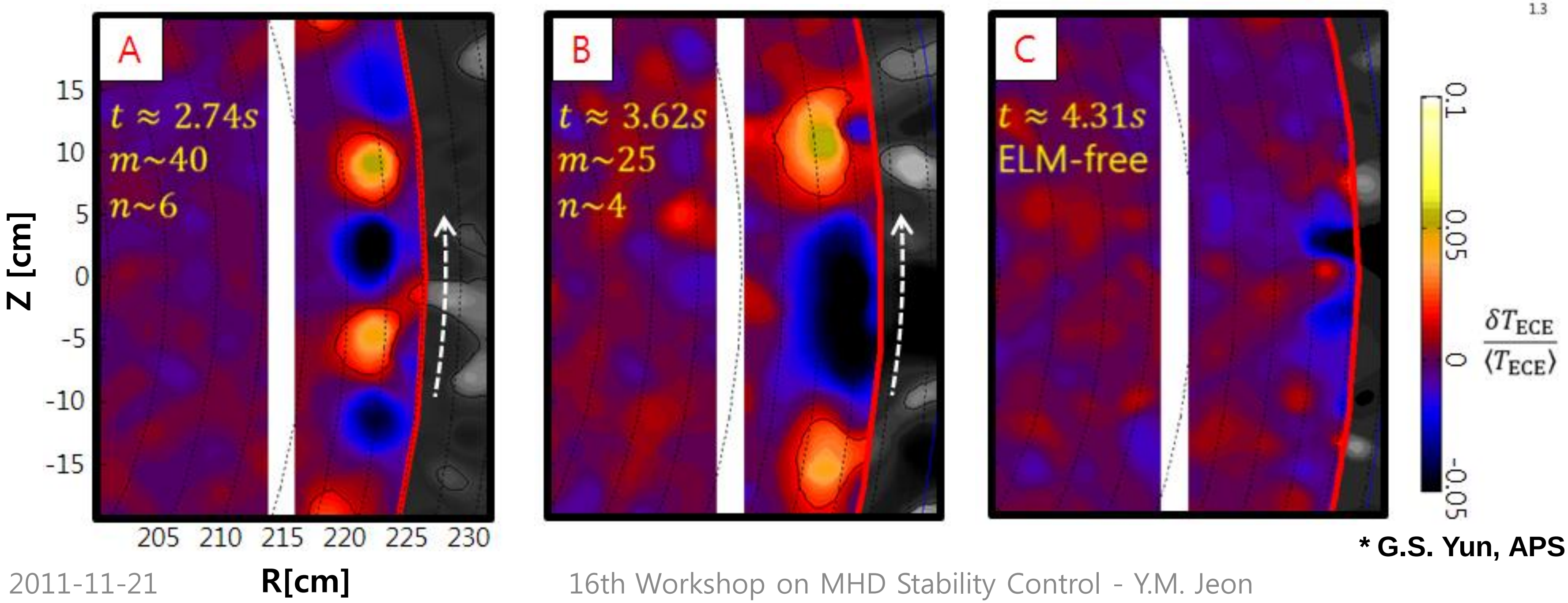


- **ELMs excitation observed as expected**
- **Similar evolutions of global parameters with those on the initial ELM-excited phase**
- **Note that ELM-excitation should be distinguished from ELM-triggering**
- **Therefore, mixed MPs made two phases ELMs i.e. 'mid-FEC alone' + 'n=1, +90'**

ELMs Were Suppressed Rather Than Mitigated

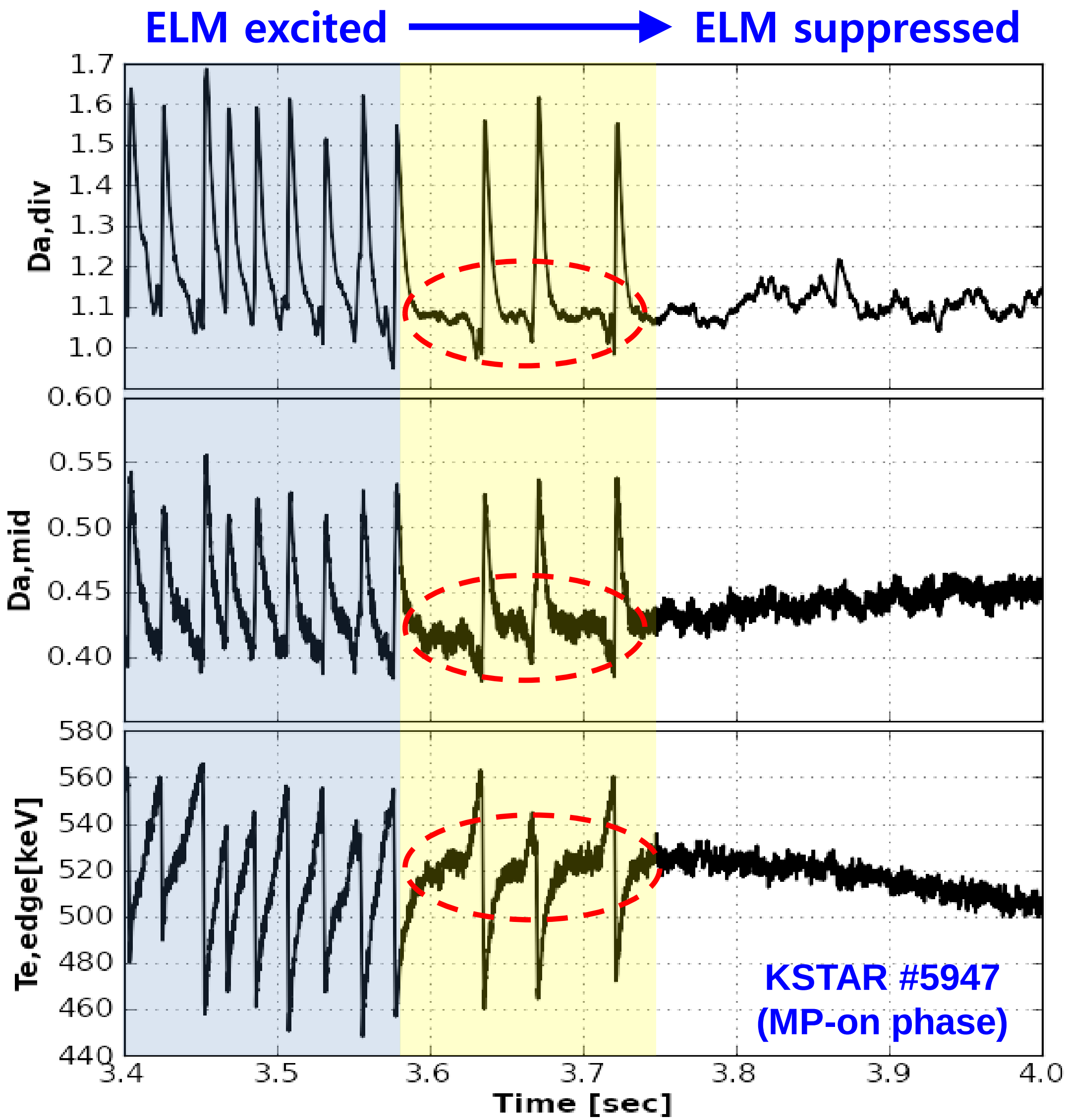






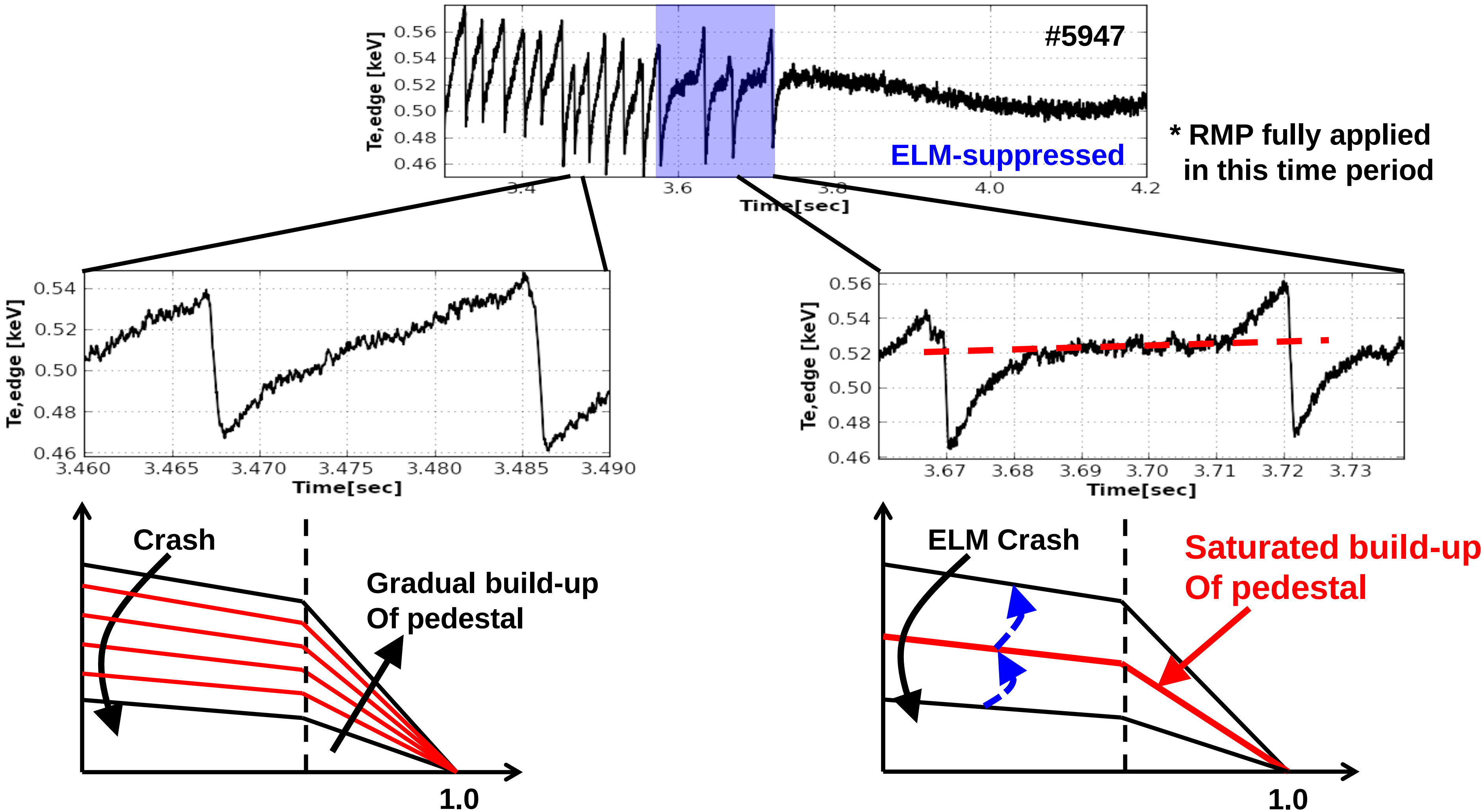
* G.S. Yun, APS invited, YI2 (2011)

Unusual Pedestal Evolutions Observed Suggesting Edge Transport Change by MP

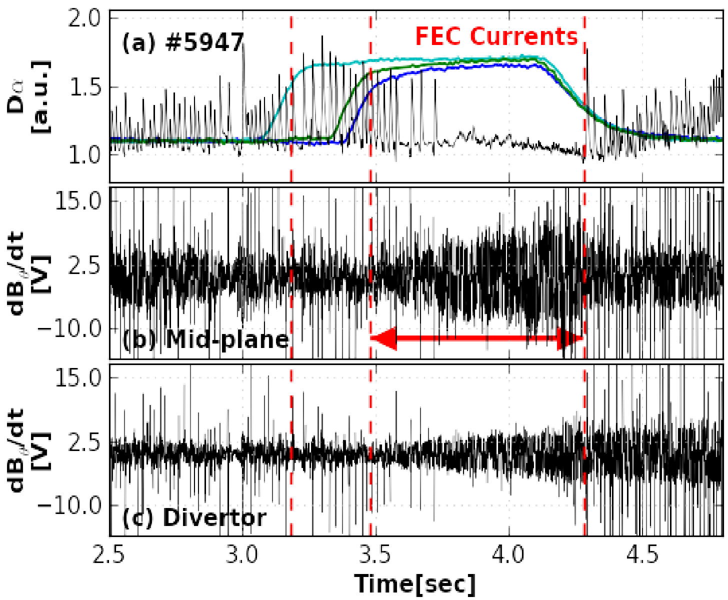


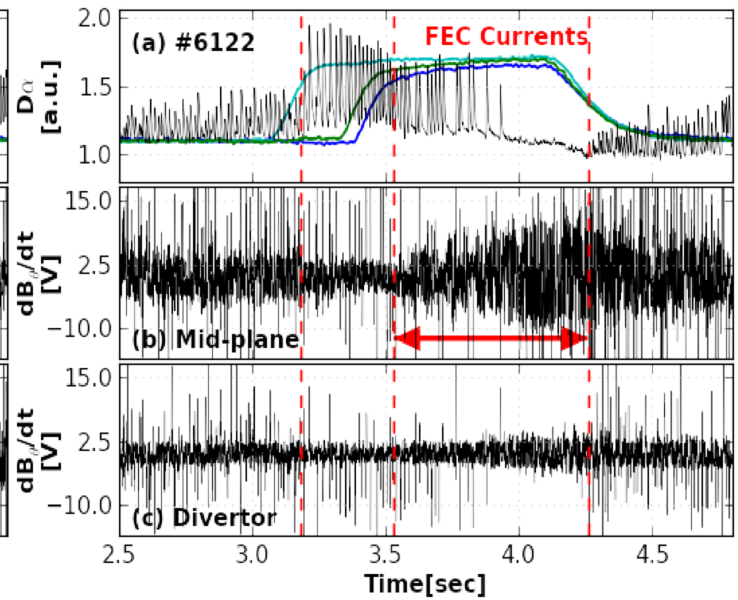
- **Observations are …**
  - Pedestal buildup saturated in the intermediate level
  - When destabilized, it resume pedestal build-up until the original threshold level.
  - After crash, it became back to the original crashed level
  - Edge stability seems to be not much changed

Experimental Evidence for Edge Transport Change by MPs → Saturation of Pedestal Evolution



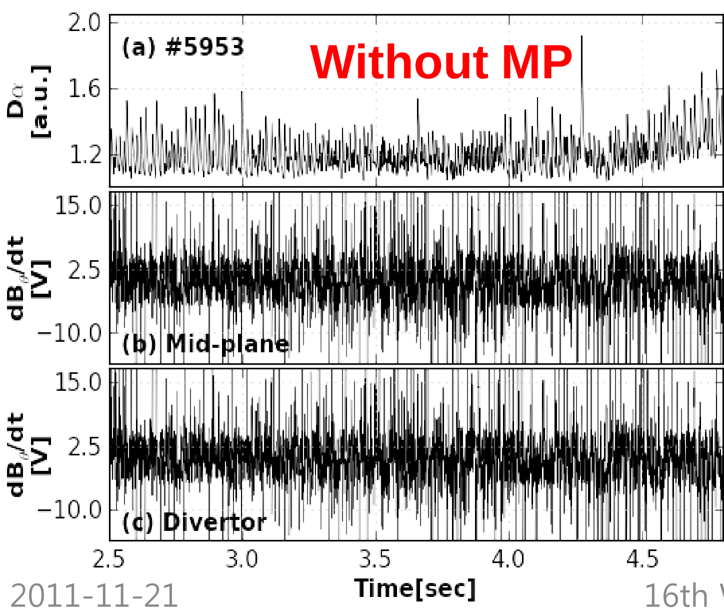
Specific Changes of Magnetic Fluctuation May Be A Clue Or Evidence for Edge Transport Change

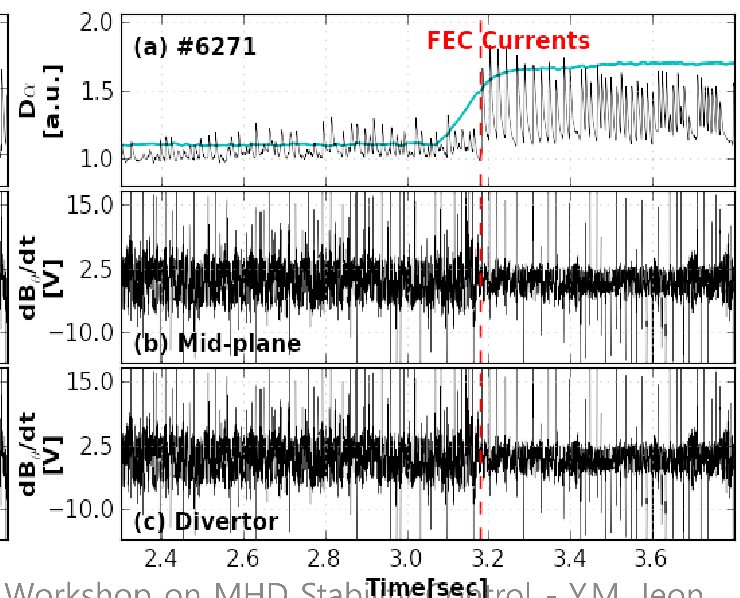




ELM-suppressed

- Fluctuation rising
- Mid-plane dominant
- Broad (not specific) spectrum

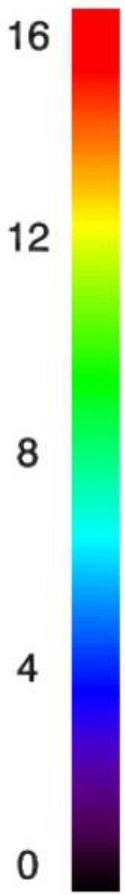




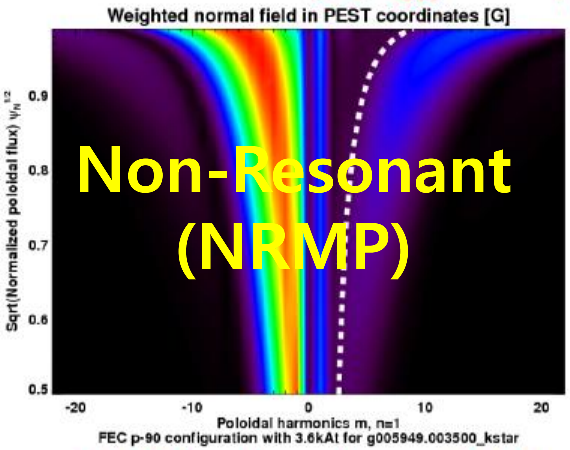
ELM-excited

- Fluctuation reduced
- both midplane and divertor

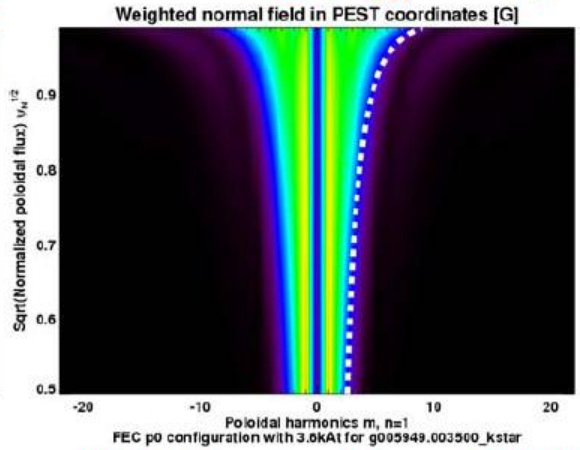
Vacuum Analysis for n=1 Magnetic Perturbations

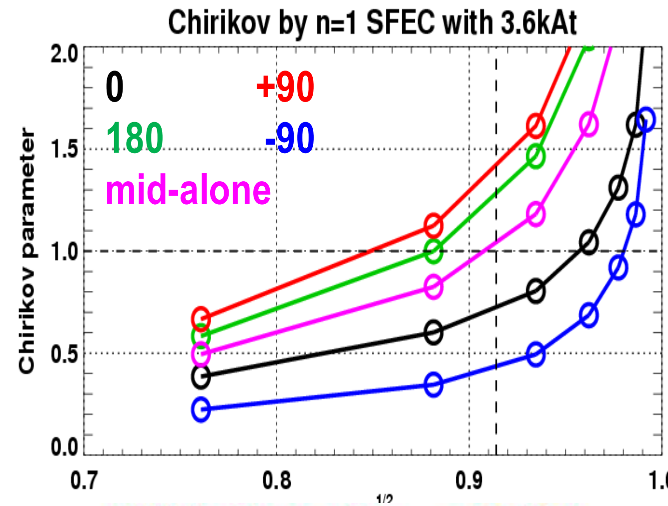


-90 Phasing (σ_{CH}~0.04)

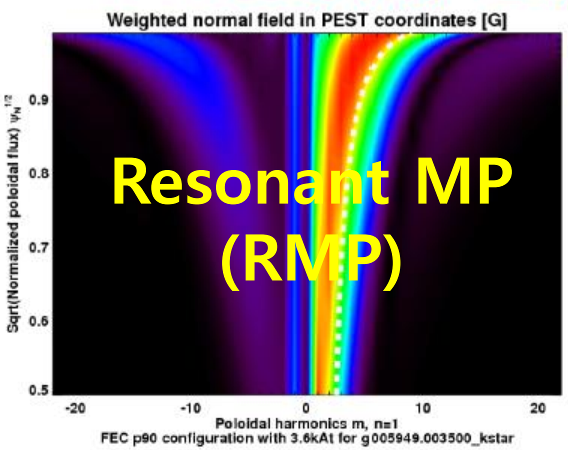


0 Phasing (σ_{CH}~0.08)

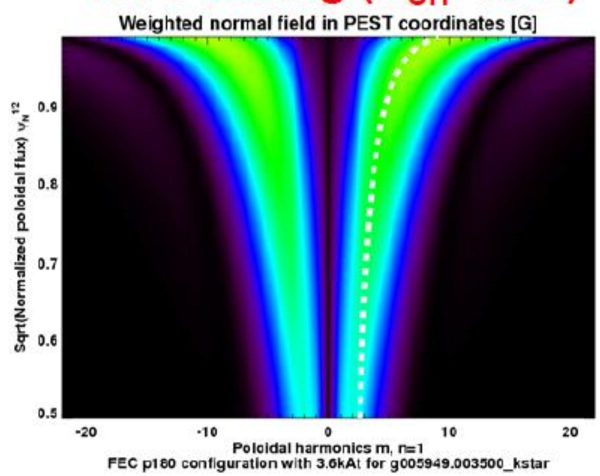




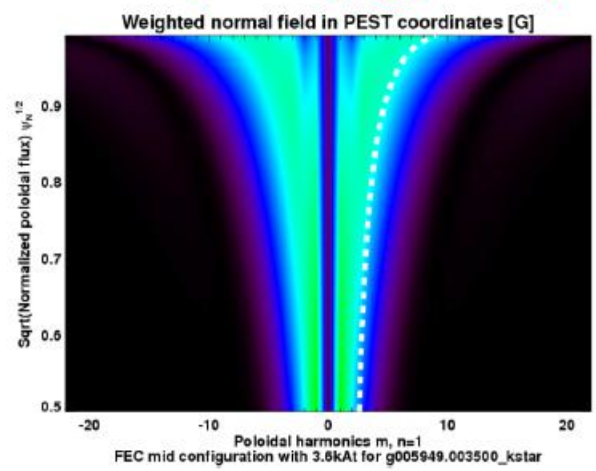
90 Phasing (σ_{CH}~0.27)



180 Phasing (σ_{CH}~0.22)

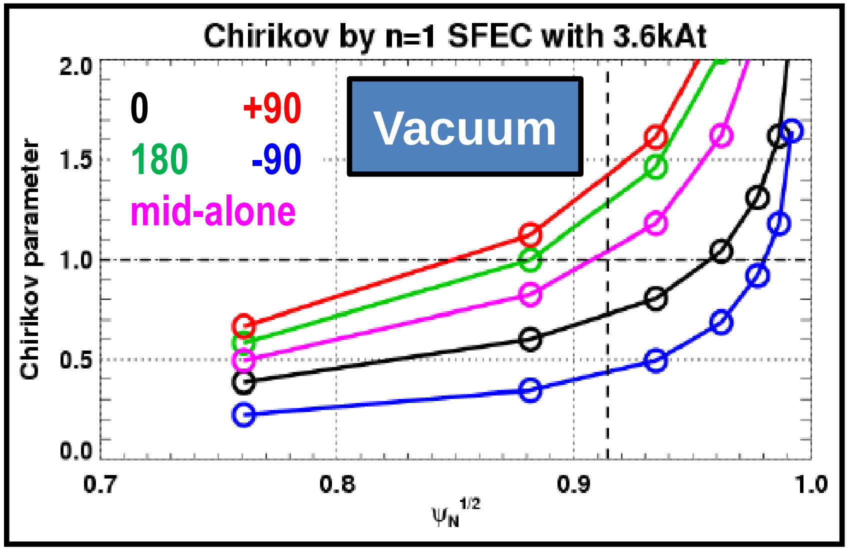


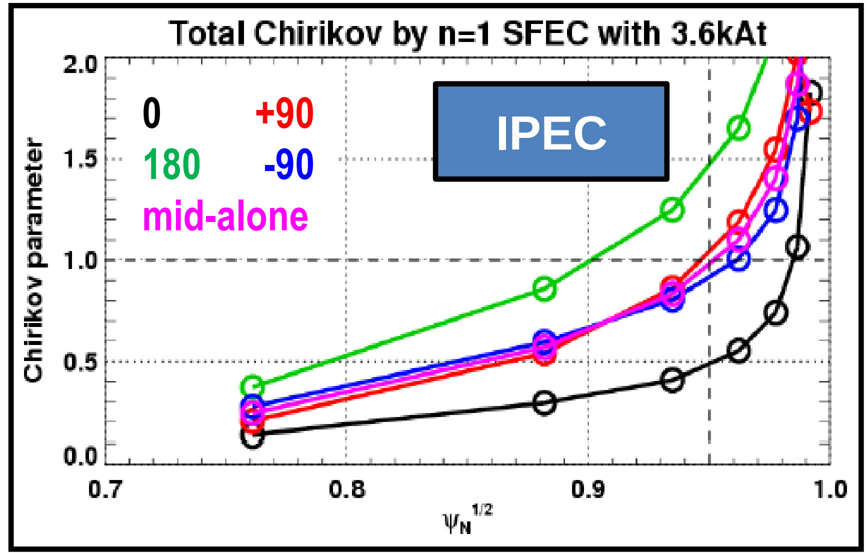
Midplane (σ_{CH}~0.17)

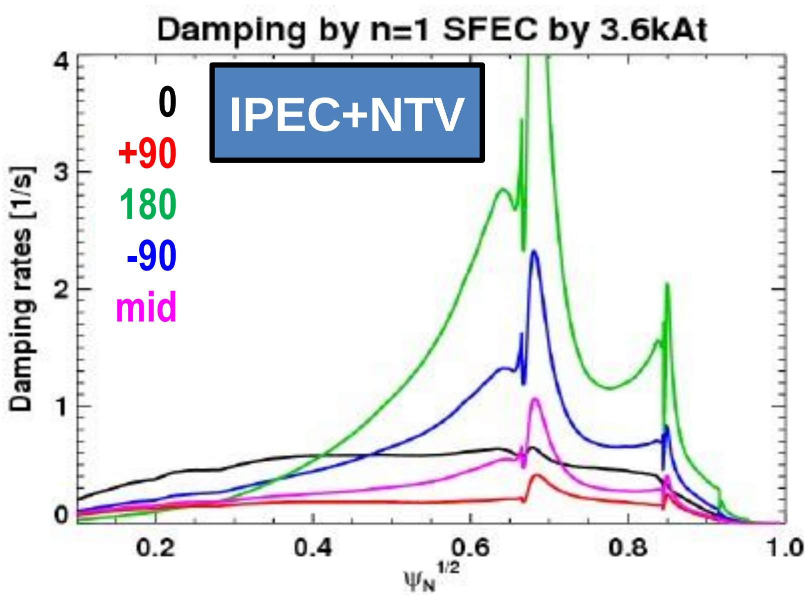


* σ_{CH}=stochastic layer width in the edge

IPEC With Plasma Responses Predicts Somewhat Differently

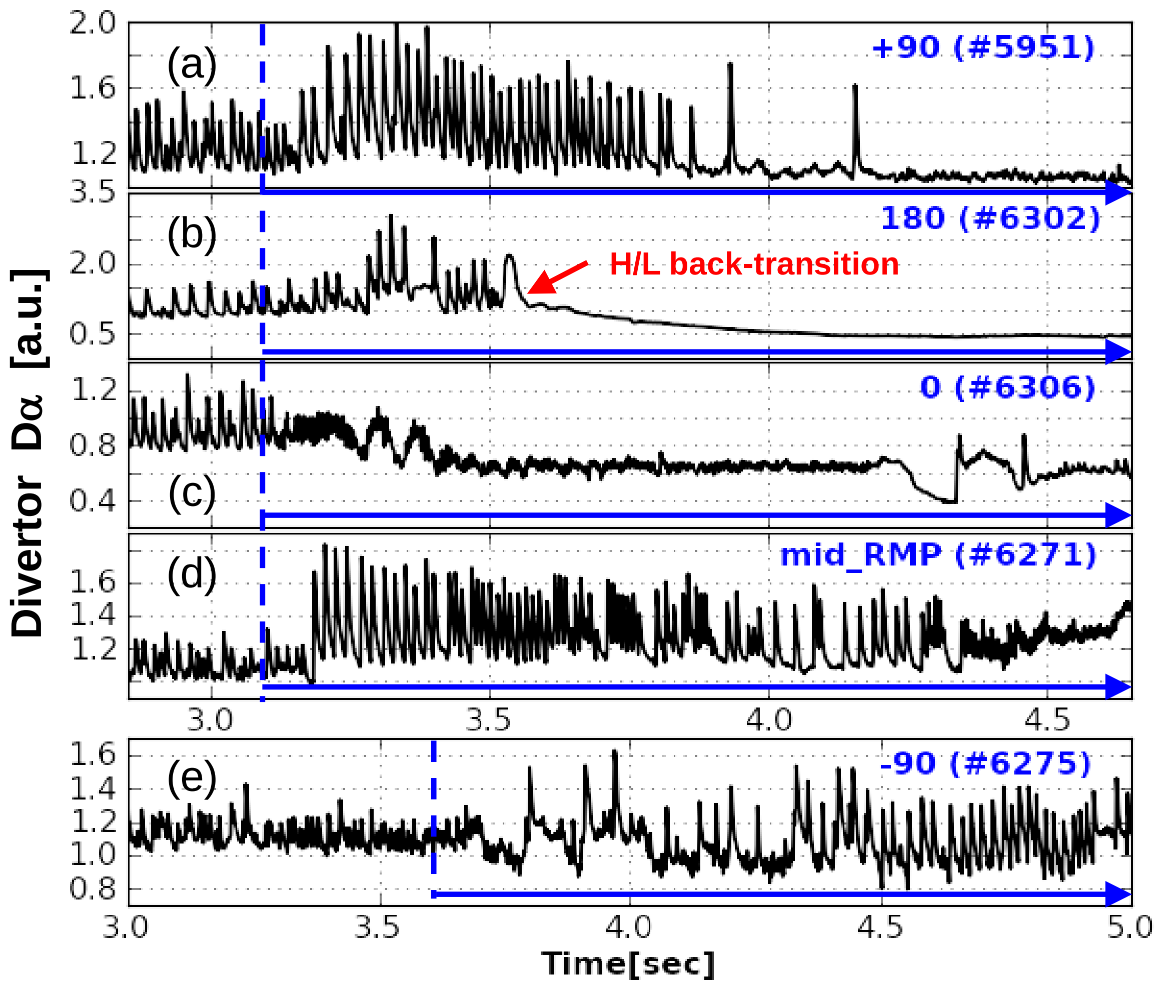






- **180 phase** is the best for Chirikov
- 180 phase may have **strongest rotation damping**

Experimental Observations for Wide MP Spectra



➔ ELM Suppression

➔ H/L Back-transition / Locking

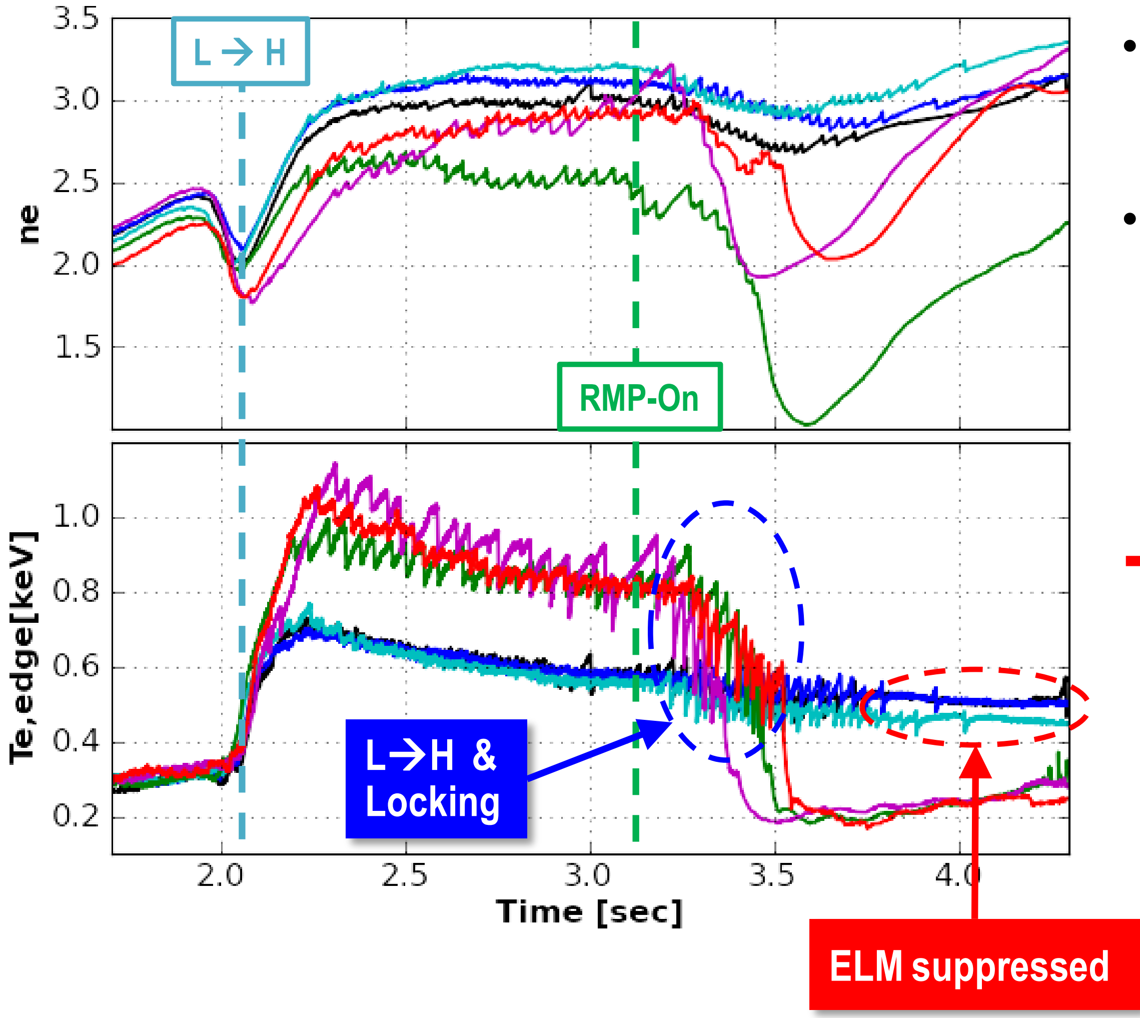
➔ ELM (strong) mitigation ~ JET n=1

➔ ELM Excitation

➔ ELM Excitation

- **Variety of ELM responses to different MP spectra**
- **Various ELM controllability of MPs**

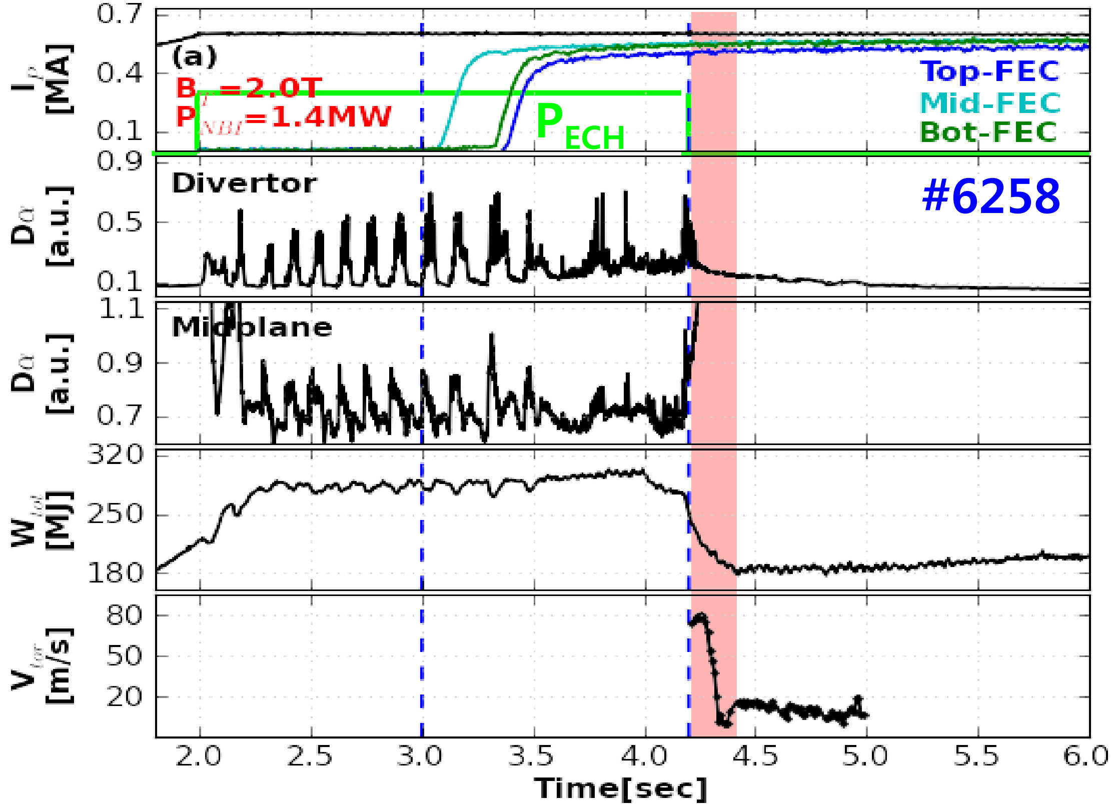
Occasionally, H→L Transition and Locking Observed Instead of ELM-Suppression, Responding to n=1 MPs

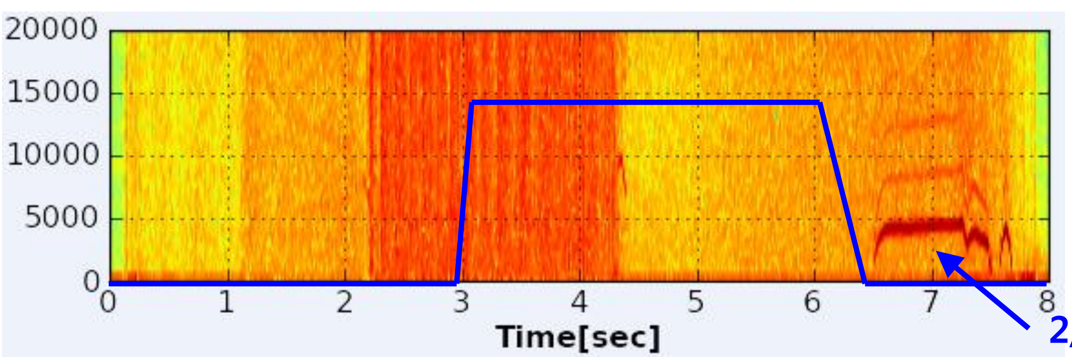


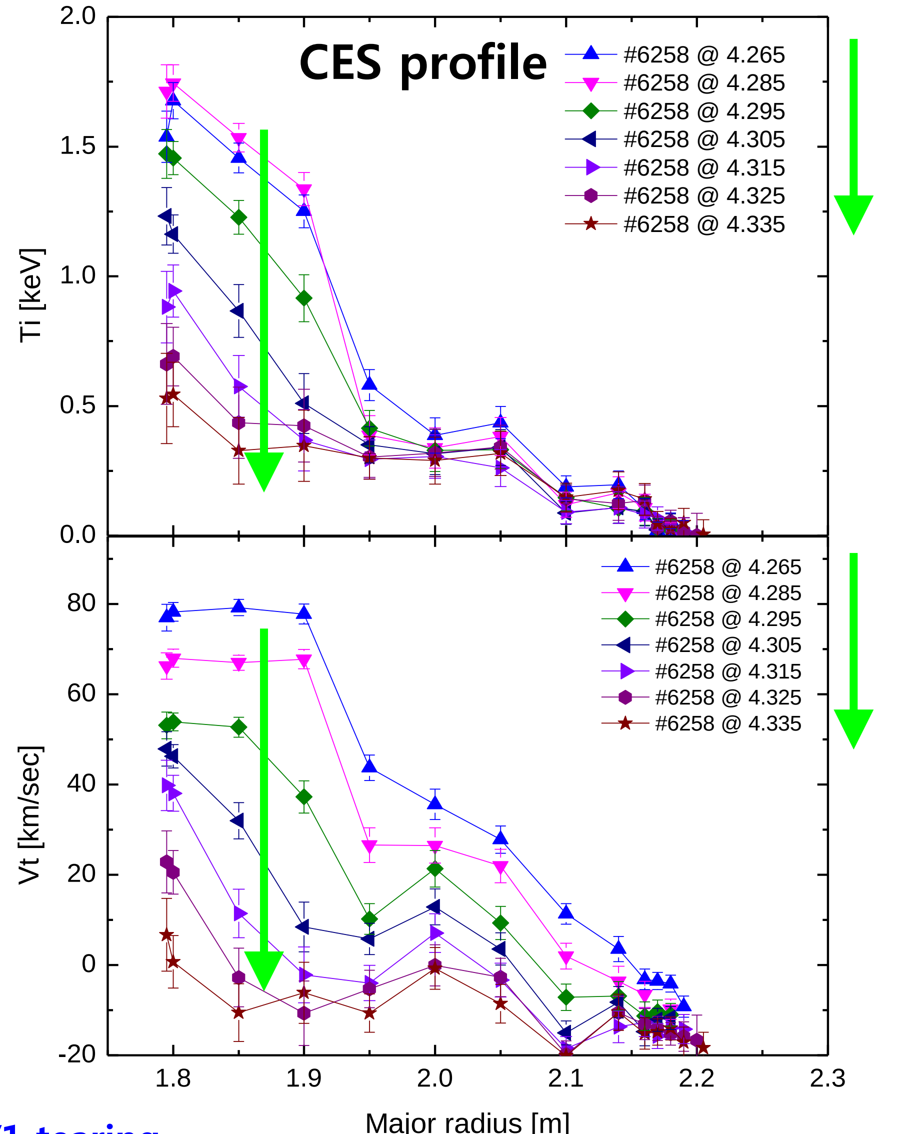
- **Mode locking was one of expected plasma responses to n=1 MP**
- **A key difference in H→L/Locked discharges compared with ELM-suppressed ones is the larger increase of edge Te in H-mode by a factor of ~2.**

→May correlated with edge collisionality

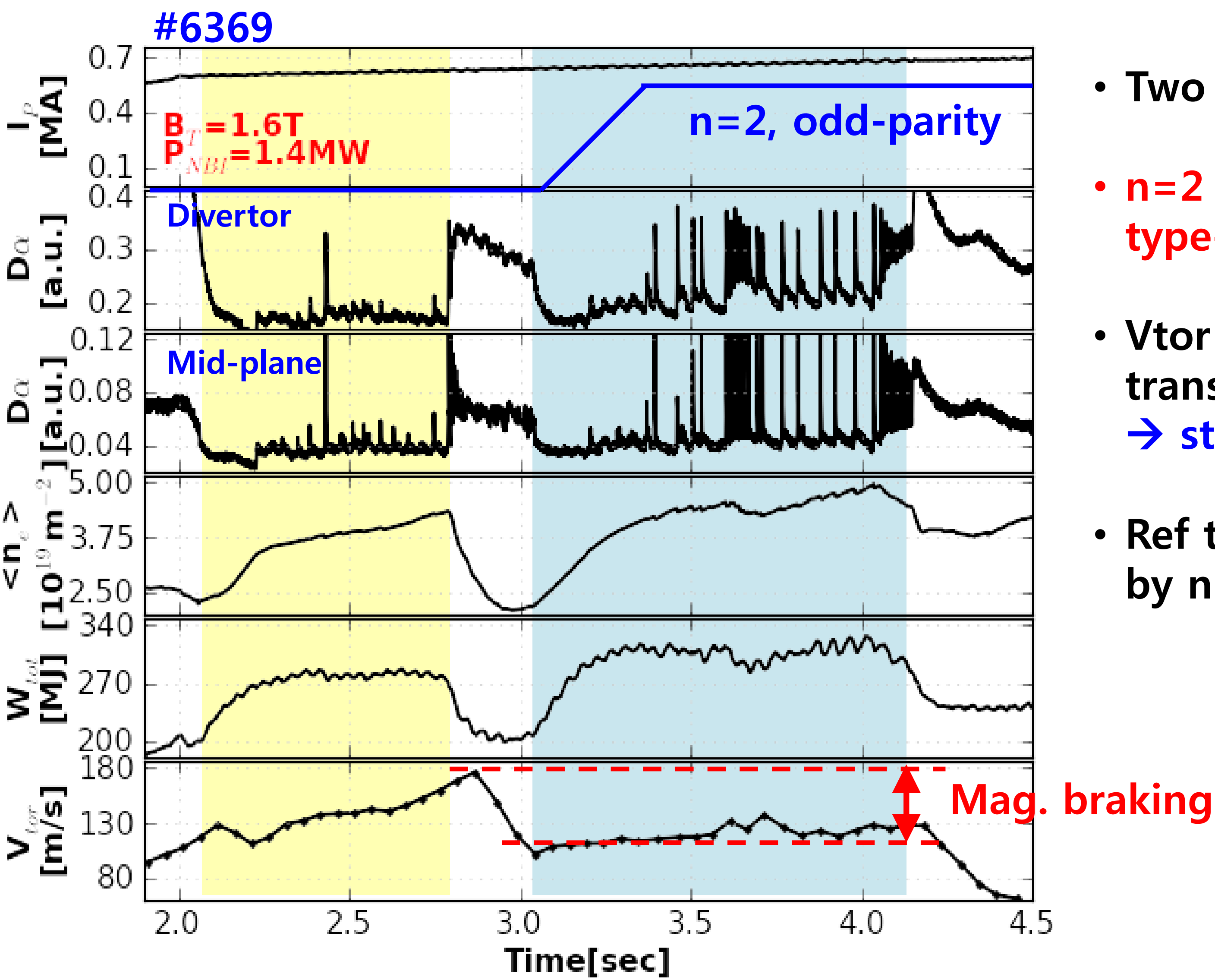
Strong Magnetic Braking by n=1 MP Observed : Complete Locking Without Killing Plasmas







ELMs Triggered by n=2 With Odd Parity



- Two ELM-free H-mode periods
- n=2 with odd-parity triggered type-I ELMs
- Vtor didn't changed by L/H transition
  → strong mag. braking
- Ref to ELM triggering on NSTX by n=3 MP

Summary And Discussion

1. Versatile IVCC system in KSTAR

- Axisymmetric + non-axisymmetric (n=1, 2)
- Three poloidal coils → wide spectra of MPs
- Various applications: IVC, IRC + FEC, RWM, RMP

2. ELM control by applying non-axisymmetric MPs

- ELMs suppressed completely by n=1 MP
- Various ELM responses
  : suppression, excitation, mitigation, locking, triggering
- Saturated pedestal evolutions with specific change of mag. fluctuations
- Strong mag. braking by n=1 MPs

3. Worth to note that ...

- Variety of ELM responses to different mag. spectra
- Wide controllability of ELMs by applying MPs
- Important to understand what made different responses such as

mitigation ←→ excitation
suppression ←→ triggering