Fusion Reactor Technology I
(459.760, 3 Credits)

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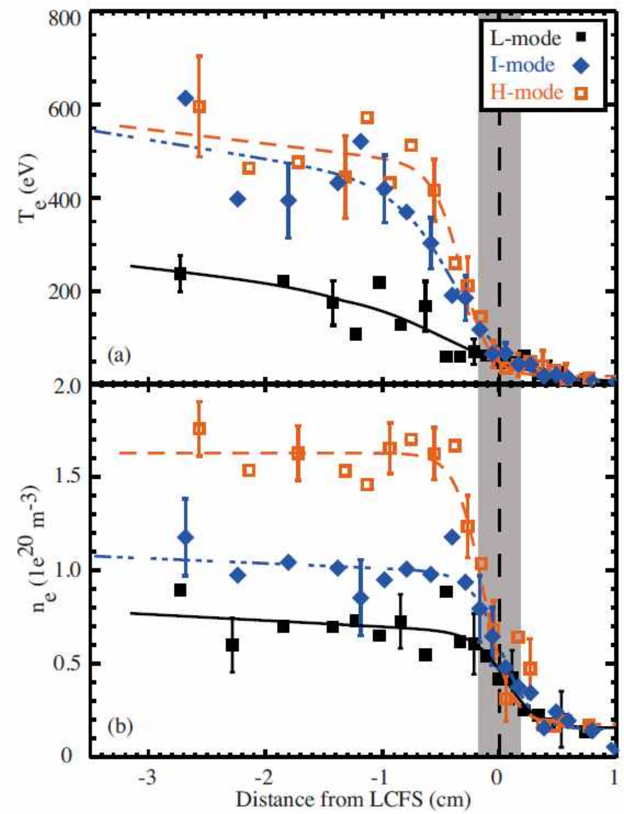
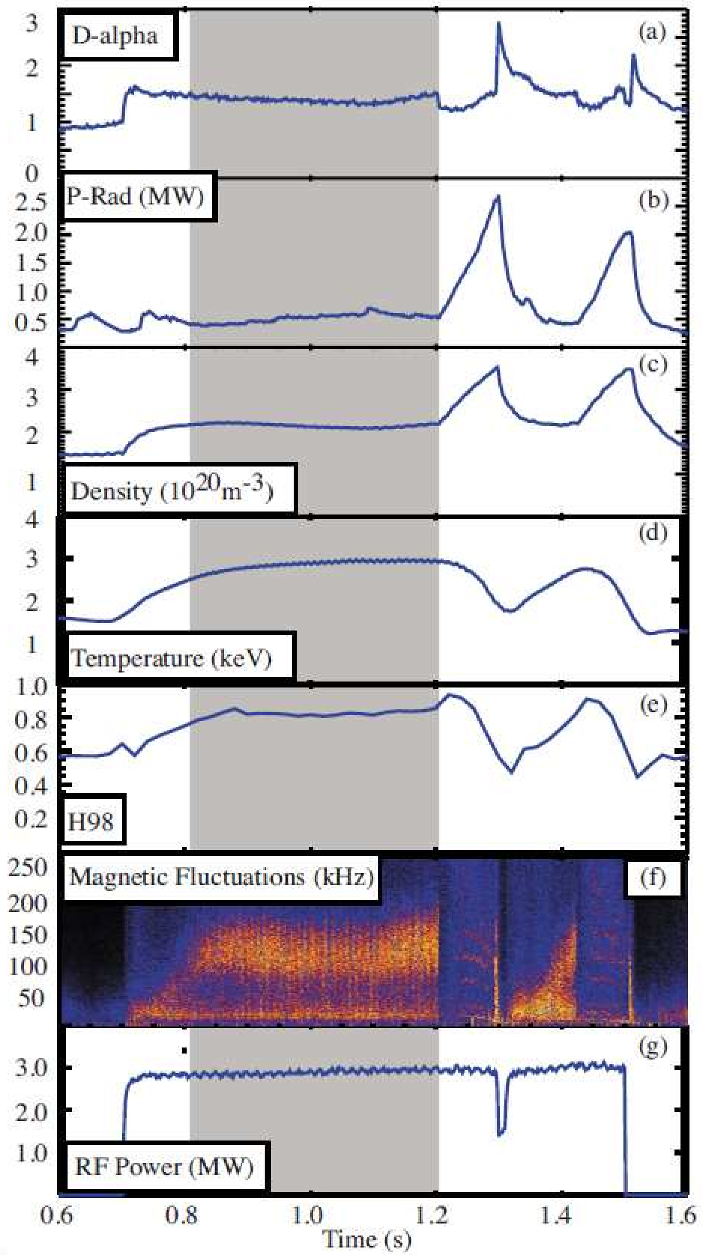
I-mode



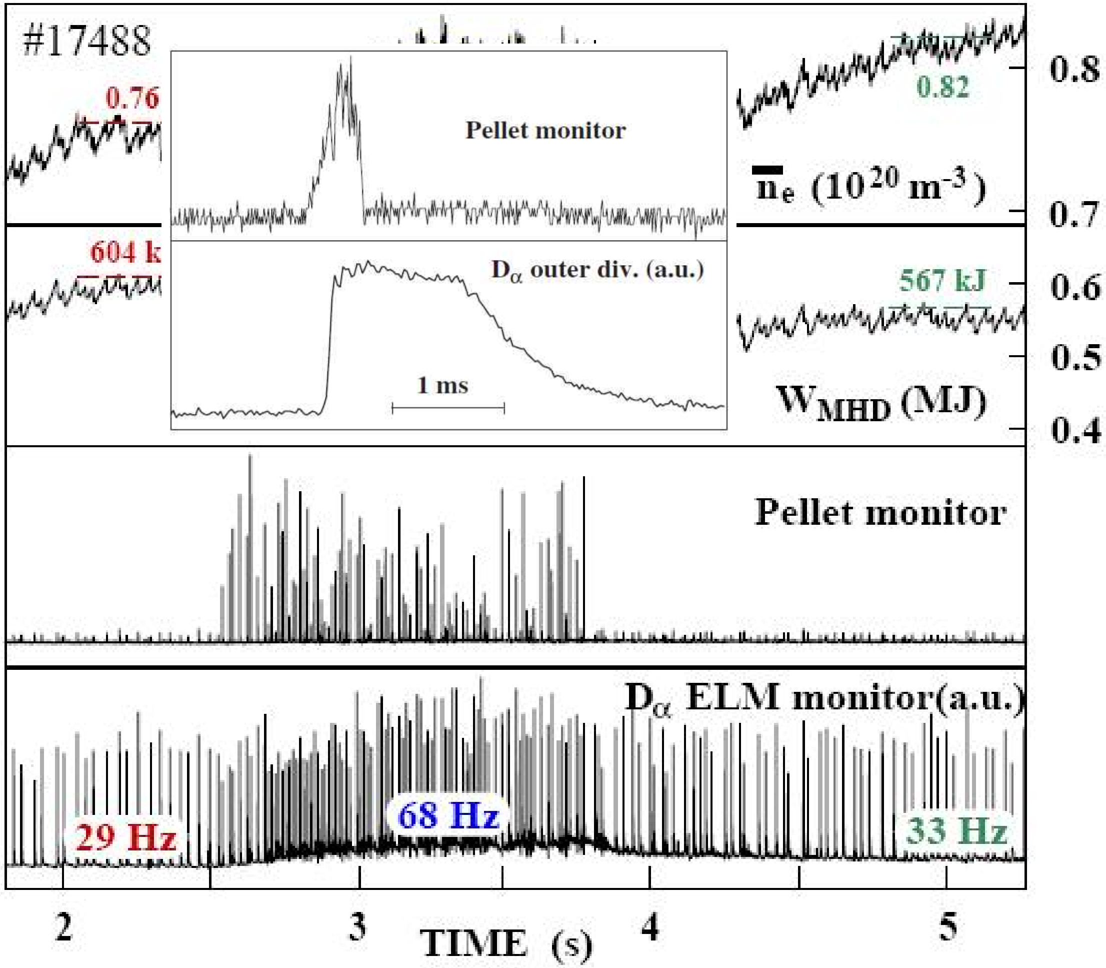


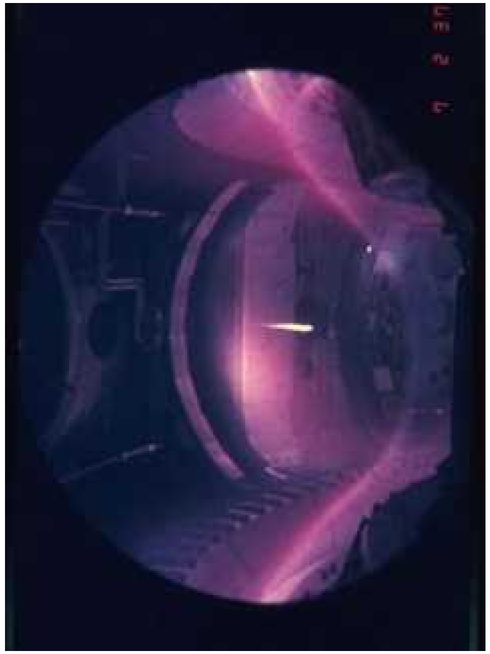
- Only observed in discharges with the *X*-point in the unfavorable drift direction suggesting that edge conditions altered such that the particle and energy transport can be decoupled.

McDermott et al, Phy. Plasmas 16 056103 (2009)

Edge Localised Mode (ELM)

- **Control of ELMs: Pellet pace making**





*1st Paper: P. T. Lang et al, Nuclear Fusion **43** 1110 (2003)*

Edge Localised Mode (ELM)

- **Control of ELMs: RMP (Resonant Magnetic Perturbation)**

Published online: 21 May 2006; doi:10.1038/nphys312

Edge stability and transpc resonant magnetic pertur collisionless tokamak plas

TODD E. EVANS[1]*, RICHARD A. MOYER[2], KEITH H. BURRELL[1], ILON JOSEPH[2], ANTHONY W. LEONARD[1], THOMAS H. OSBORN MICHAEL J. SCHAFFER[1], PHILIP B. SNYDER[1], PAUL R. THOMA AND WILLIAM P. WEST[1]

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A critical issue for fusion-plasma research is the erosion of the first wall of the experimental device due to impulsive heating from repetitive edge magneto-hydrodynamic instabilities known as 'edge-localized modes' (ELMs). Here, we show that the addition of small resonant magnetic field perturbations completely eliminates ELMs while maintaining a steady-state high-confinement (H-mode) plasma. These perturbations induce a chaotic behaviour in the magnetic field lines, which reduces the edge pressure gradient below the ELM instability threshold. The pressure gradient reduction results from a reduction in the particle content of the plasma, rather than an increase in the electron thermal transport. This is inconsistent with the predictions of stochastic electron heat transport theory. These results provide a first experimental test of stochastic transport theory in a highly rotating, hot, collisionless plasma and demonstrate a promising solution to the critical issue of controlling edge instabilities in fusion-plasma devices.

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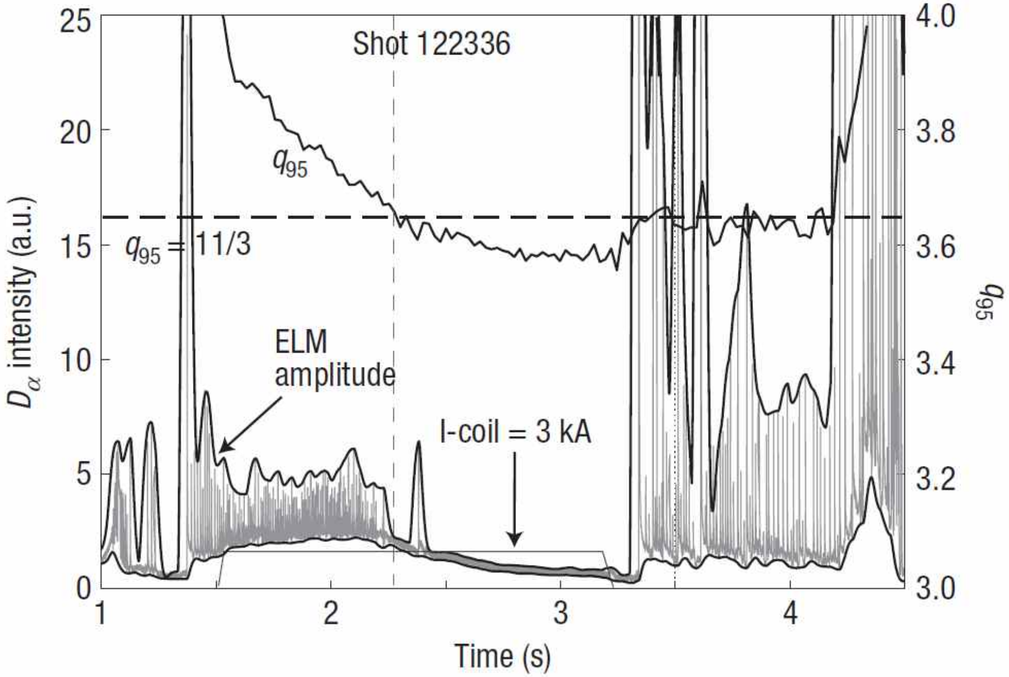
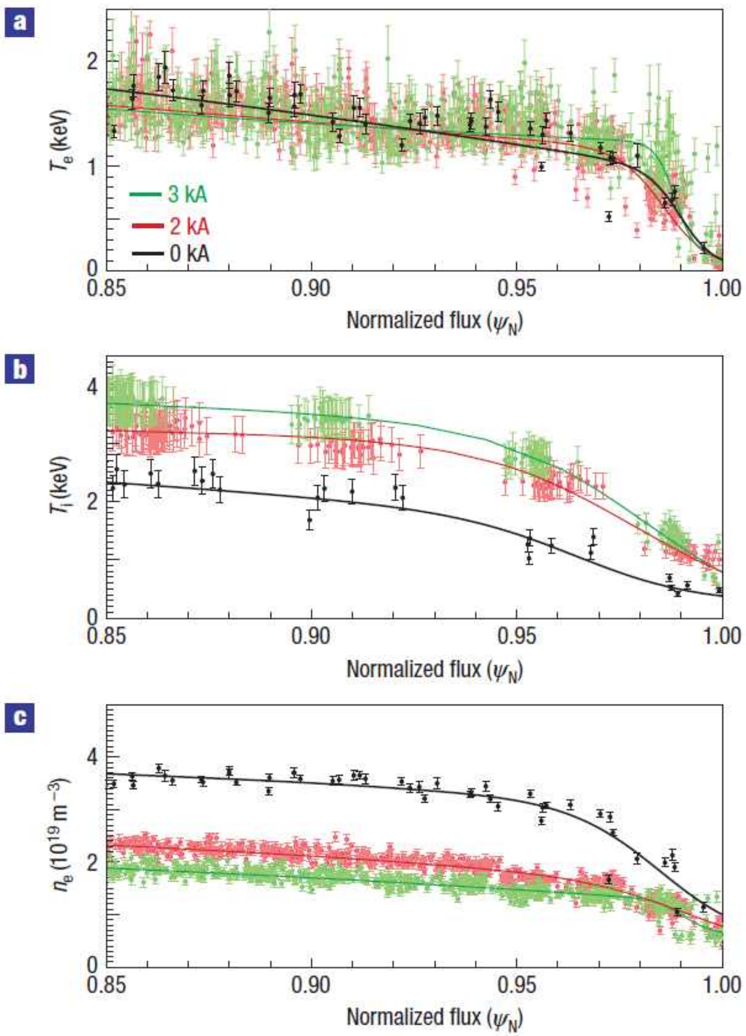
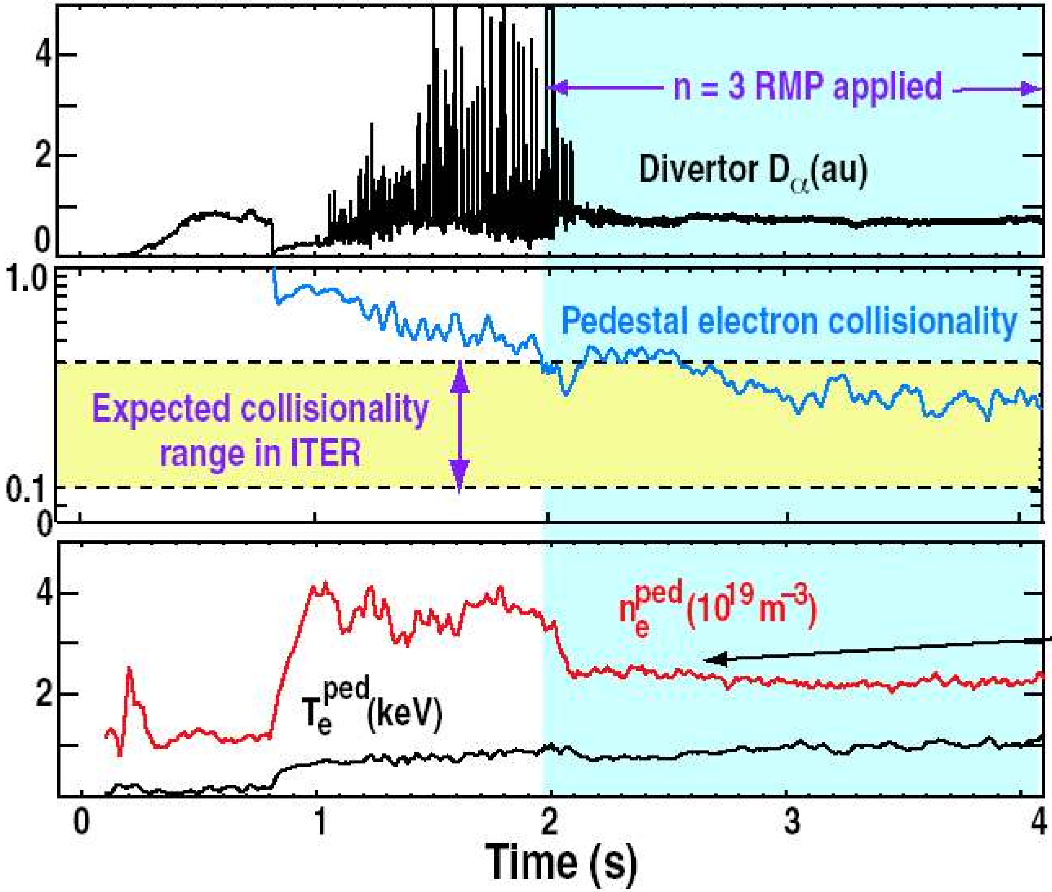
Edge Localised Mode (ELM)

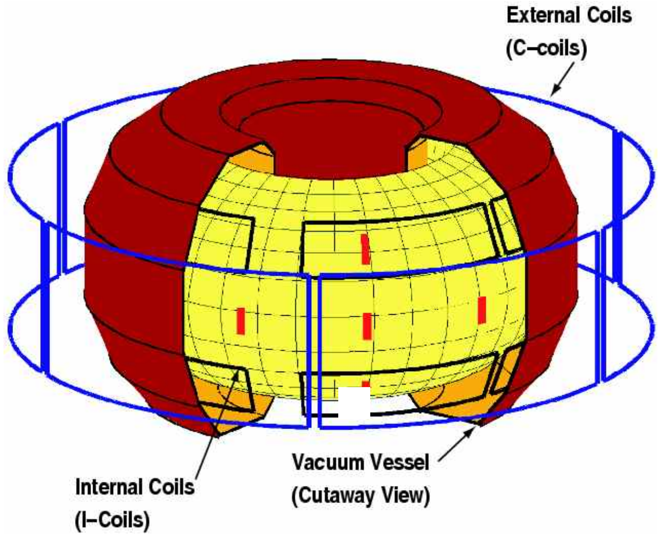




Edge Localised Mode (ELM)

- **Control of ELMs: RMP (Resonant Magnetic Perturbation)**

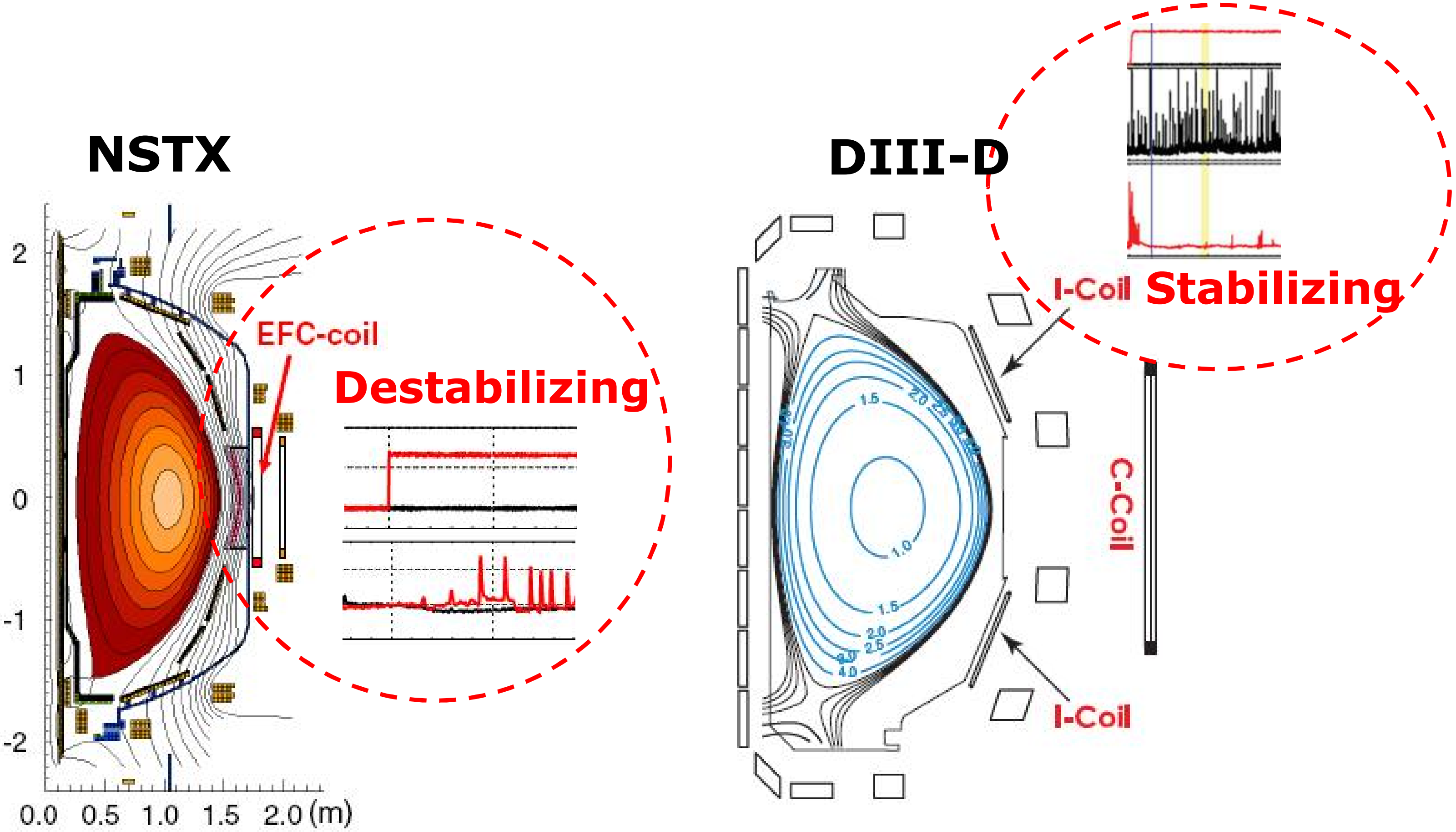




Edge Localised Mode (ELM)

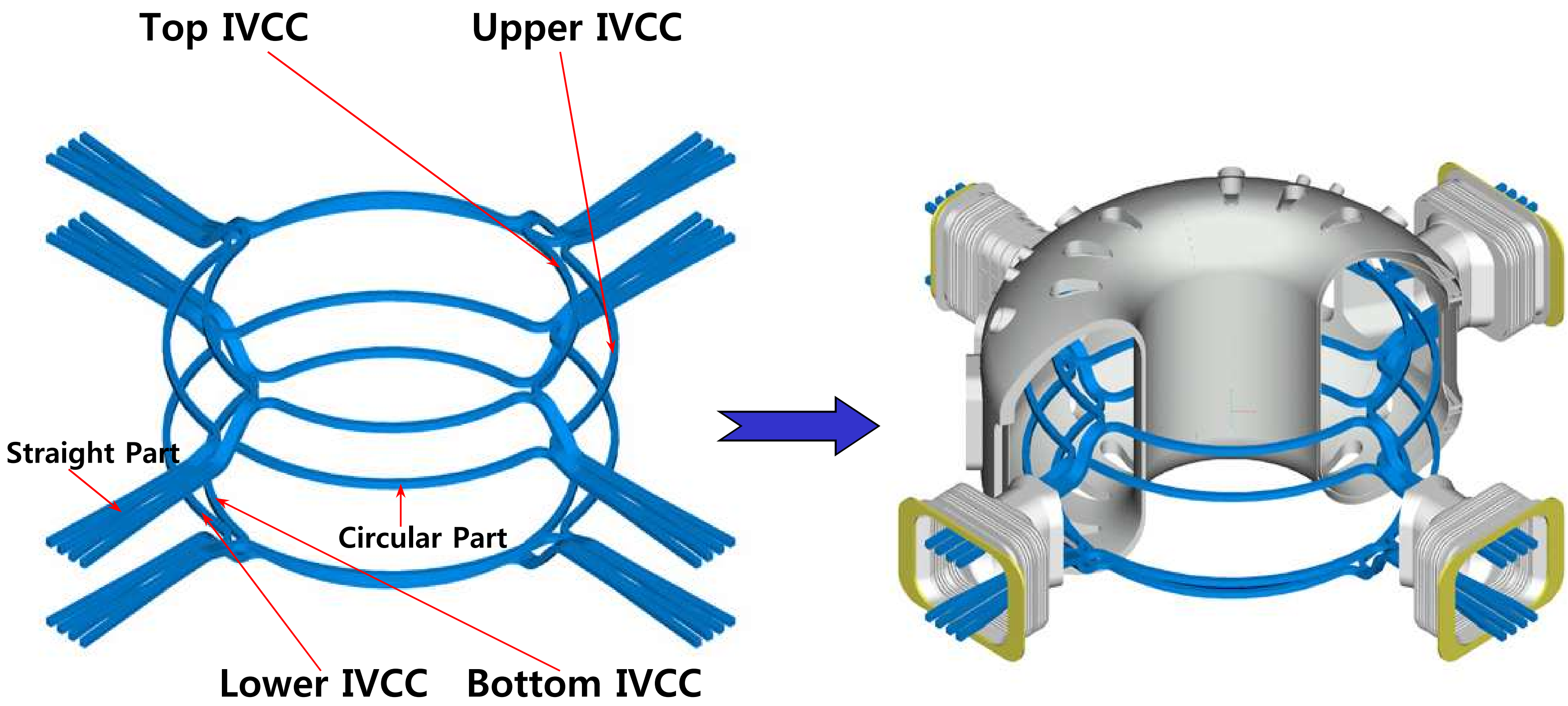
- **Control of ELMs: RMP (Resonant Magnetic Perturbation)**

- RMPs can be destabilizing and/or stabilizing



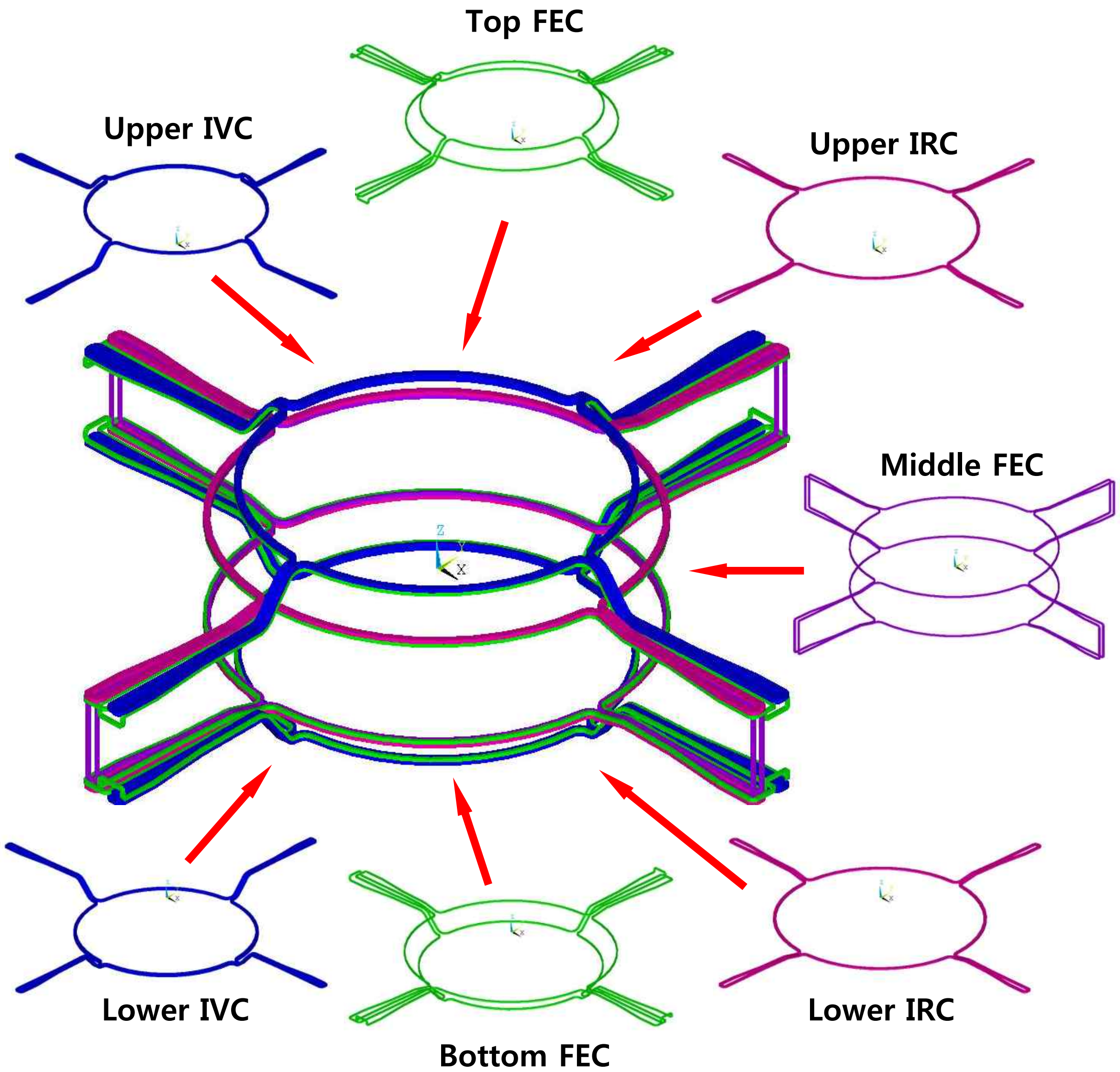
Courtesy from Jong-kyu Park (PPPL)

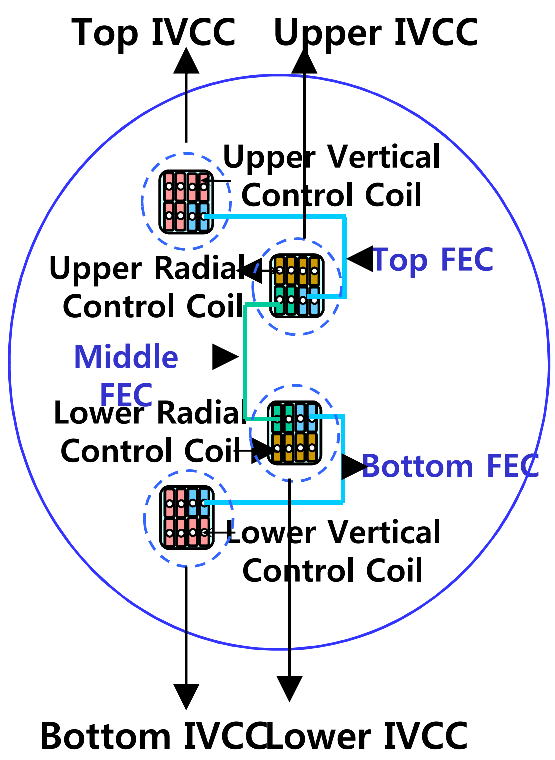
KSTAR Has A Versatile In-Vessel Control Coil (IVCC) System



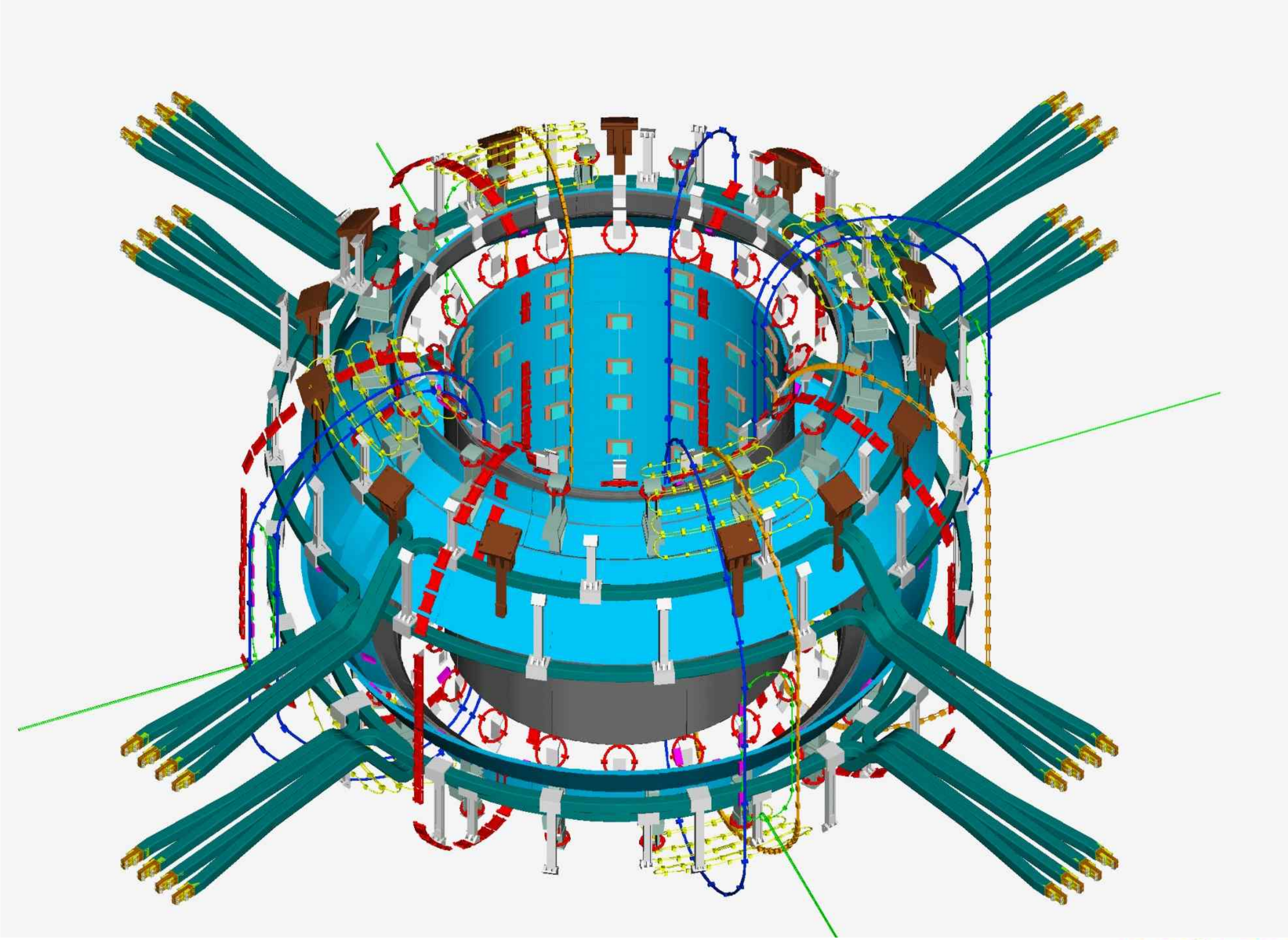
- Four coils for position control and FEC (or RWM)
- Each coil is split into four quadrants (or segments) and inserted into the vessel through the vacuum port

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



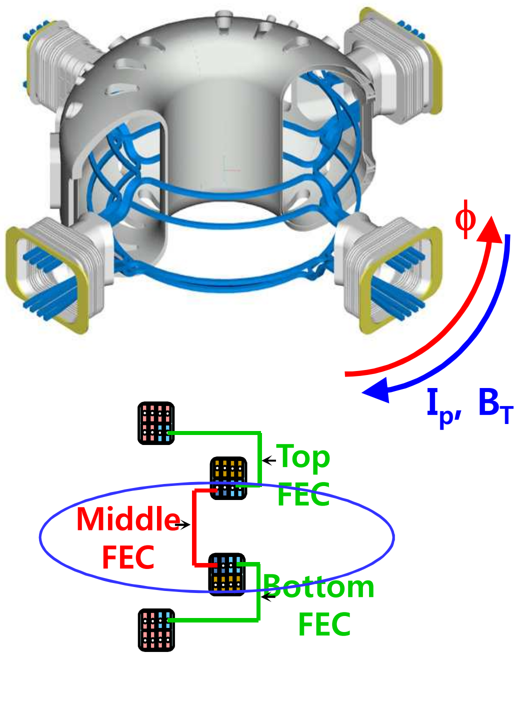


KSTAR Has A Versatile In-Vessel Control Coil (IVCC) System

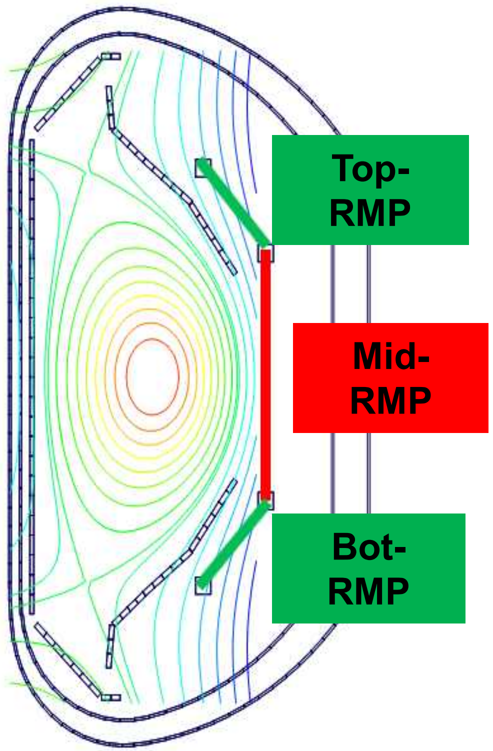


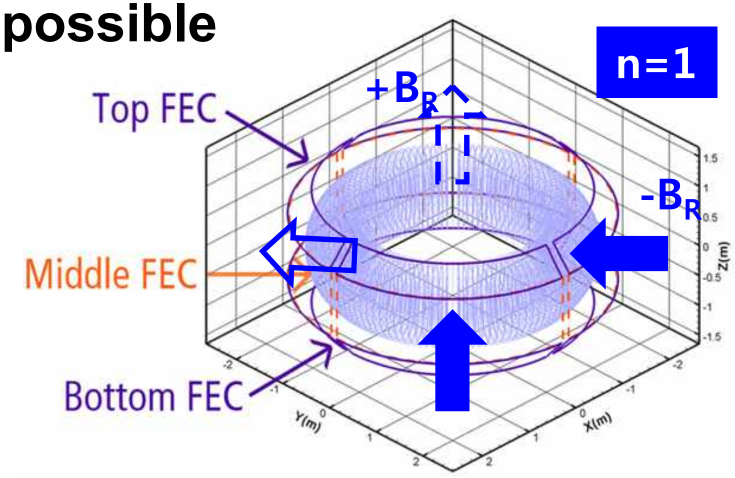
KSTAR Can Provide Wide Spectra of Magnetic Perturbations

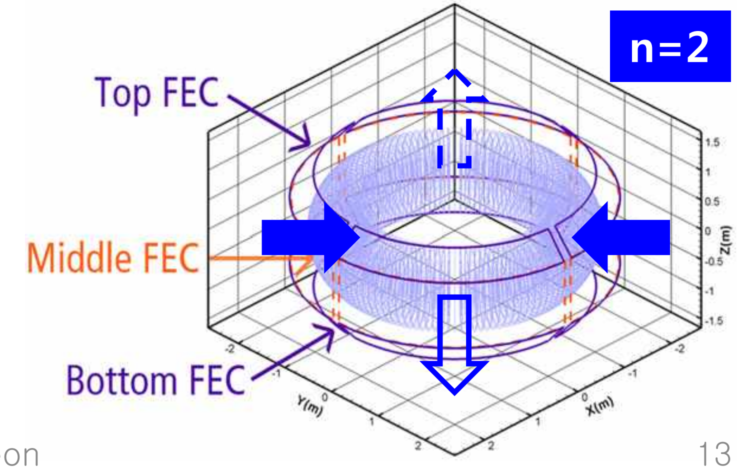
- **3-by-4 3D field coils available having 2 turns for each**
  - all internal and segmented with saddle loop configurations
  - n=1 and 2 applicable
- **Wide spectra of magnetic perturbations are possible**
  - Poloidal helicity change for n=1
  - Even/odd parity change for n=2



KSTAR Picture-Framed IVCC

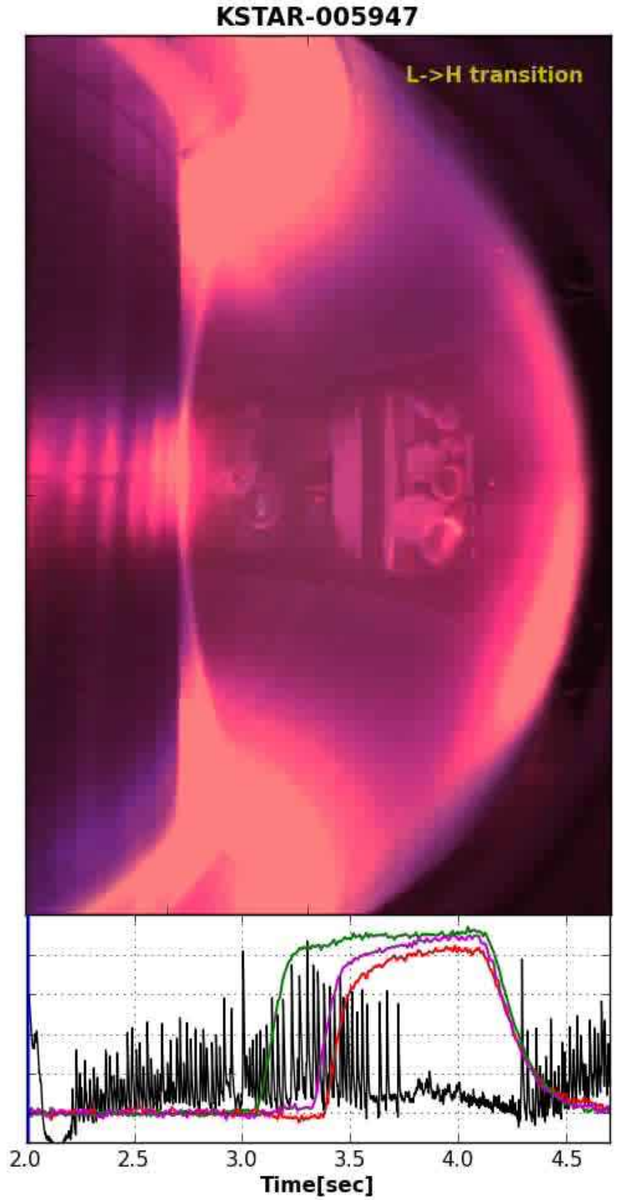






ELM Mitigation/Suppression by 3D-MP

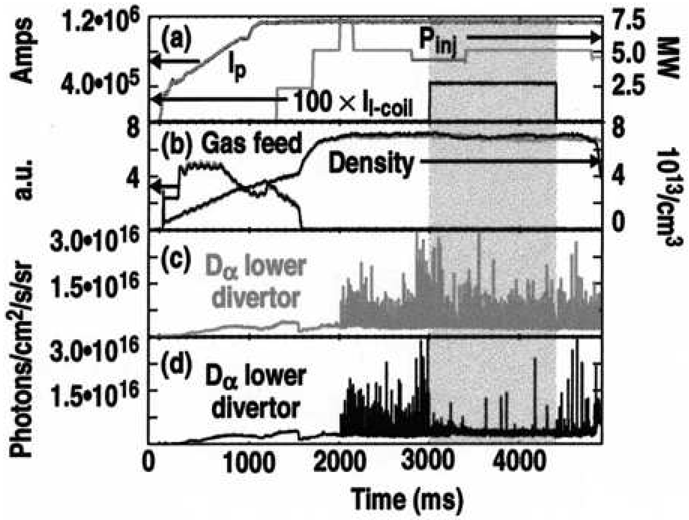
- COMPASS-D (n=1): triggered (2001)
- DIII-D (n=3): suppressed (2004)
- JET (n=1 or 2): mitigated (2007)
- NSTX (n=3): triggered (2010)
- MAST (n=3): mitigated (2011)
- ASDEX-U (n=2): mitigated/suppressed (2011)



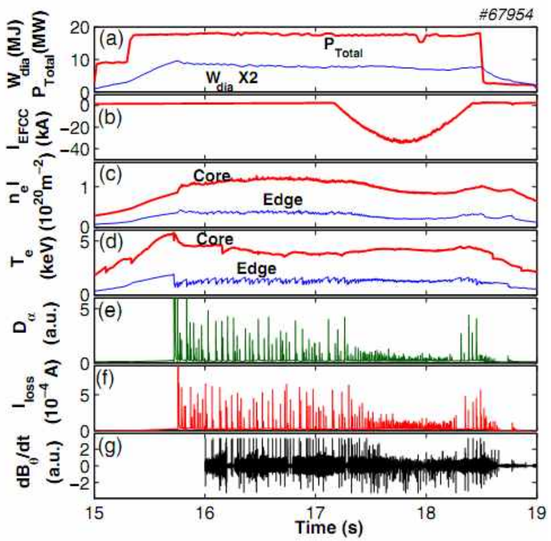
From now …

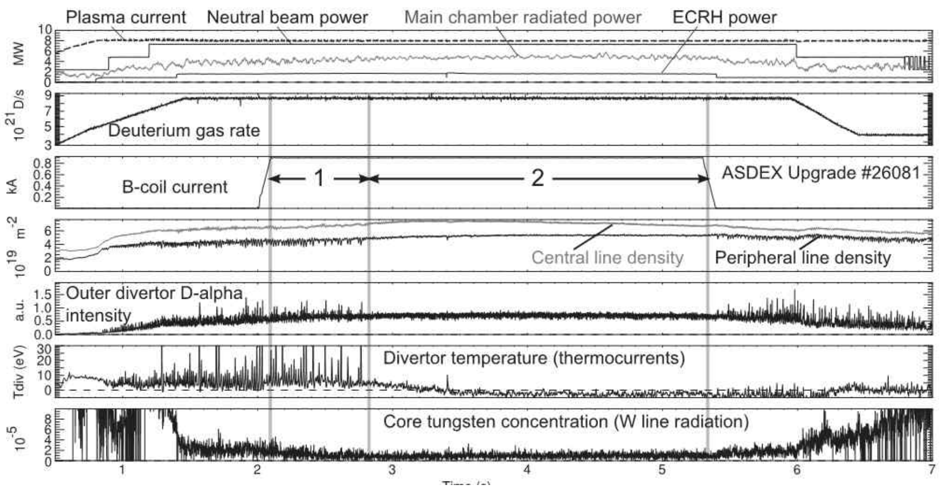
- KSTAR (n=1): ELMs suppressed (2011)

MP ELM controls in other tokamaks



- DIII-D (TE Evans et al, PRL 2004)
  - n=3; ELMs suppressed.
  - Stochastic boundary claimed.
- JET (Y Liang et al, PRL 2007)
  - n=1; ELMs mitigated (i.e. reduced crash amplitude)
- ASDEX-U (W Suttrop et al, PRL 2011)
  - n=2; ELMs mitigated.





POSTECH PDS²O

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

θ

B_P

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

ϕ

n=1, 180 phase

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

n=1, mid-RMP alone

				top
+	+	-	-	mid
				bot

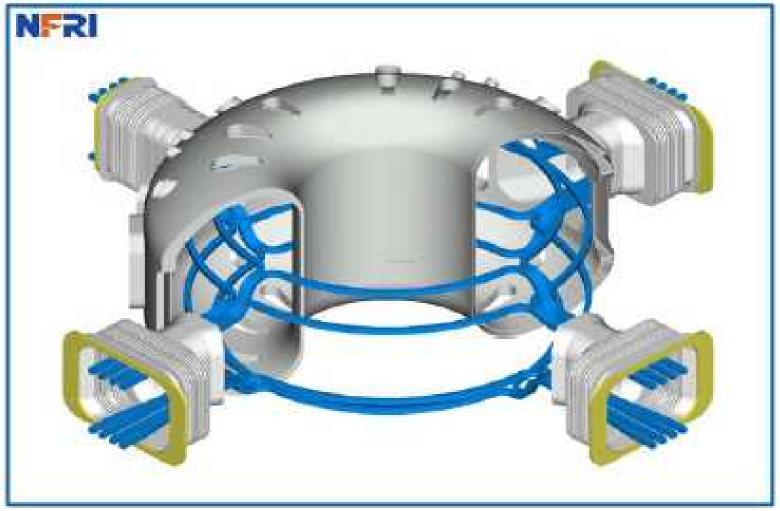
n=2, even parity

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

n=2, odd parity

+	-	+	-	top
				mid
-	+	-	+	bot

n=1 MP applied



- Injection time = 3~6 s
- Current in each coil = 1.5 kA
- Relative phase = 90° btw adjacent coil sets

Top coils	+	+	-	-
Mid coils	-	+	+	-
Bot coils	-	-	+	+

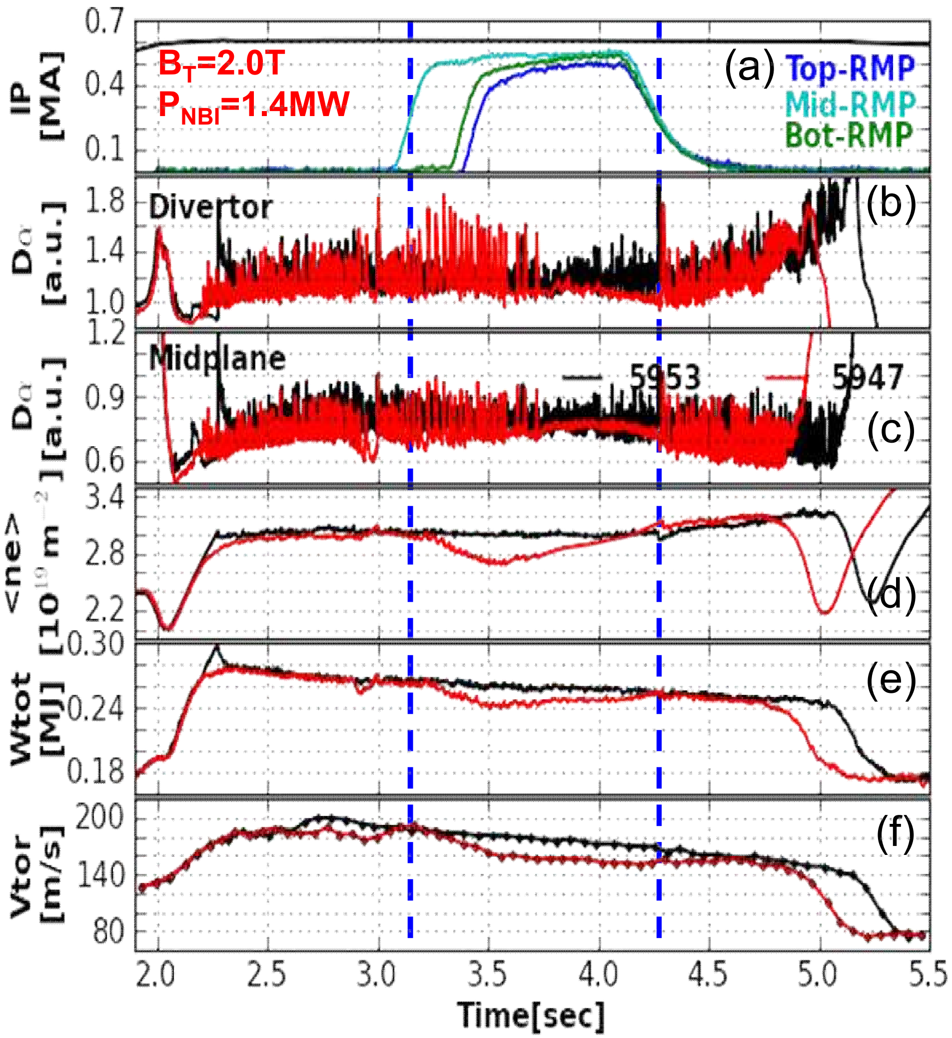
↑ Poloidal direction

← Toroidal direction (co-current)

KSTAR

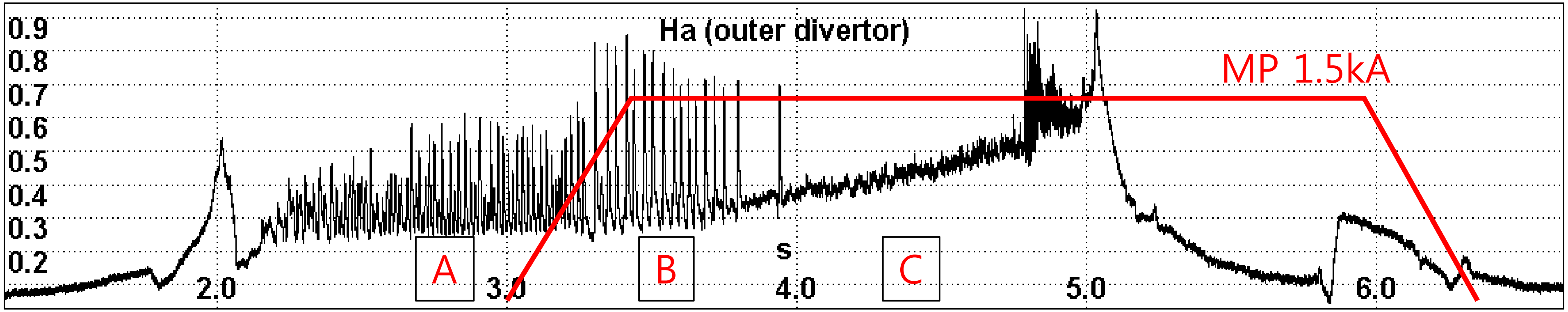
POSTECH FPDS2O

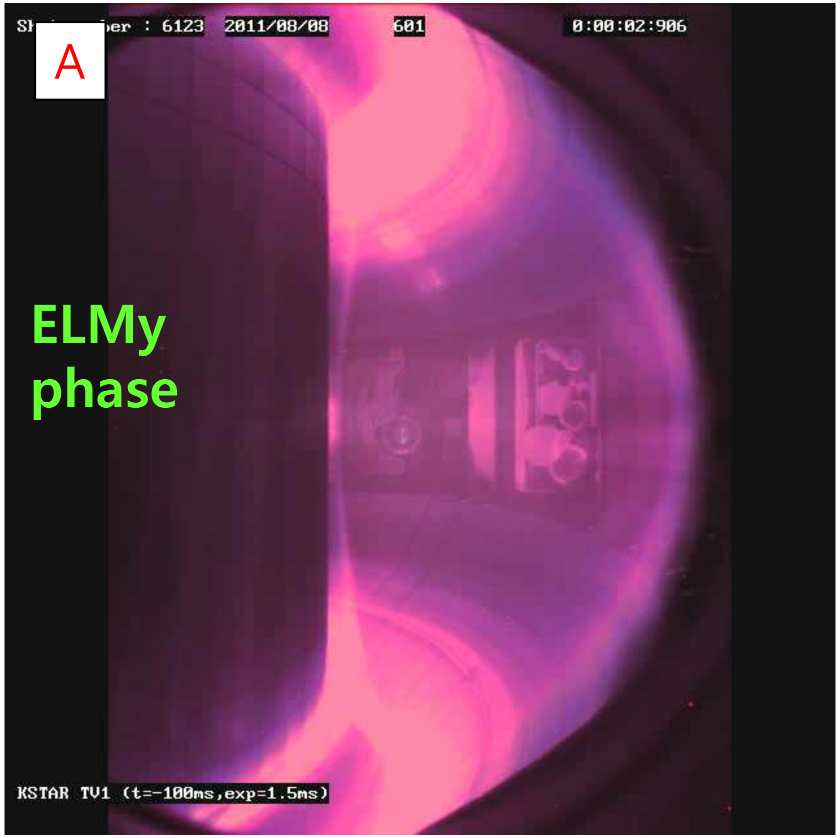
ELMs Suppressed For the First Time by n=1, +90 RMP

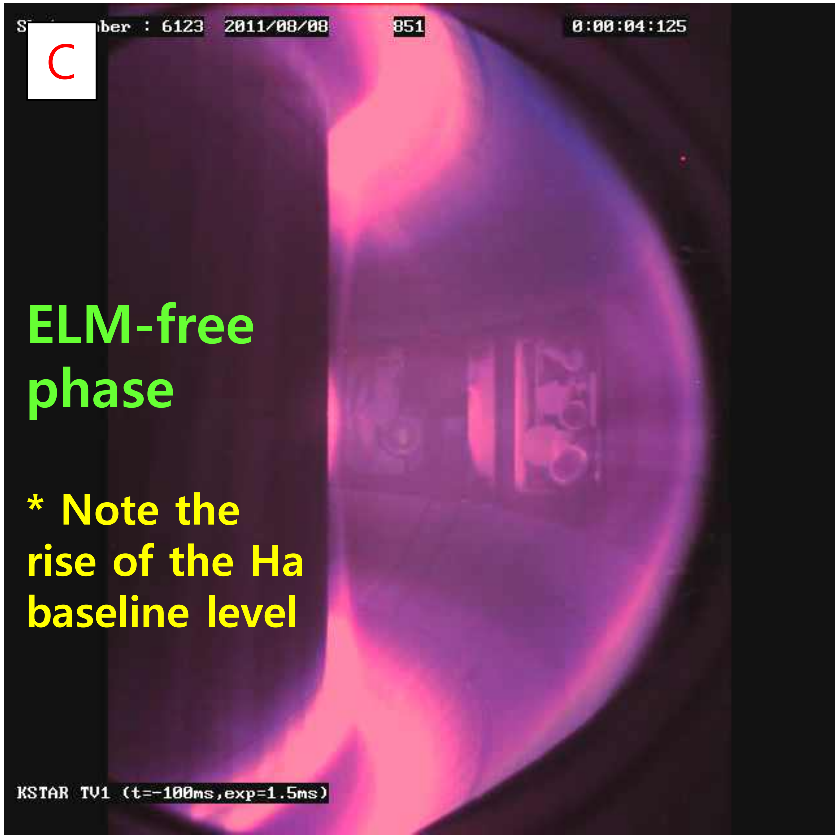


- **90 phasing RMP strongly mitigated or suppressed ELMs**
  - In JET, ELM mitigated by n=1 (Y.Liang, PRL, 2007)
- **Two distinctive phases** observed
  - **(1)ELM excitation phase**
  - **(2)ELM suppression phase**
- **Density** (~10%) pumping out initially. Then, increased when ELM suppressed
- **Stored 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

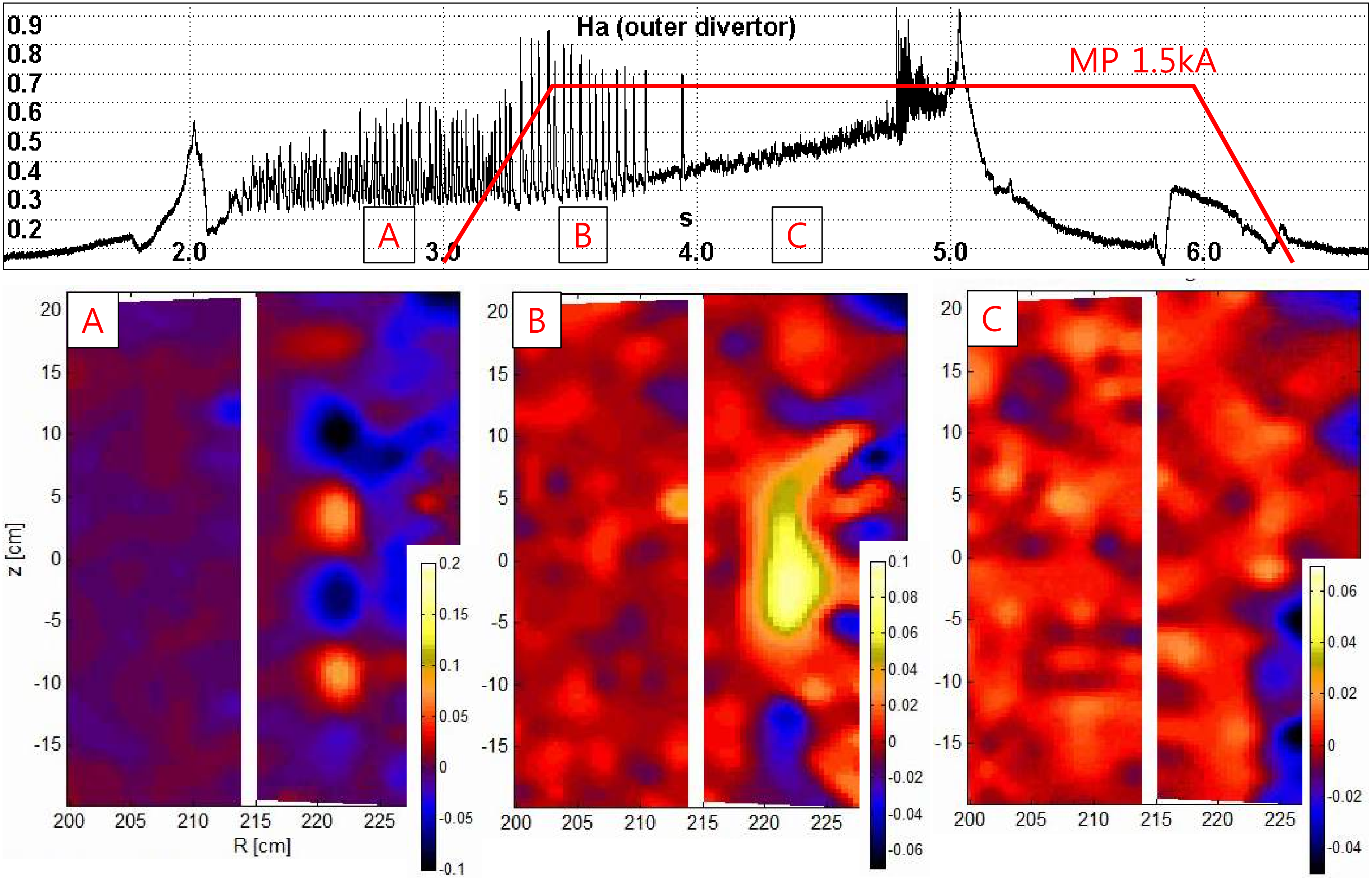
Three phases





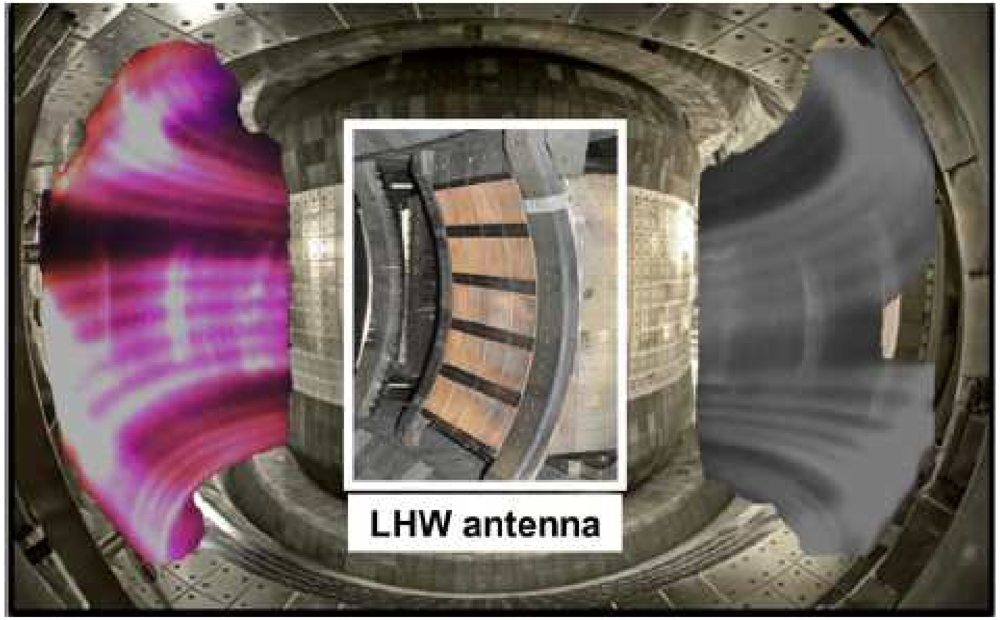


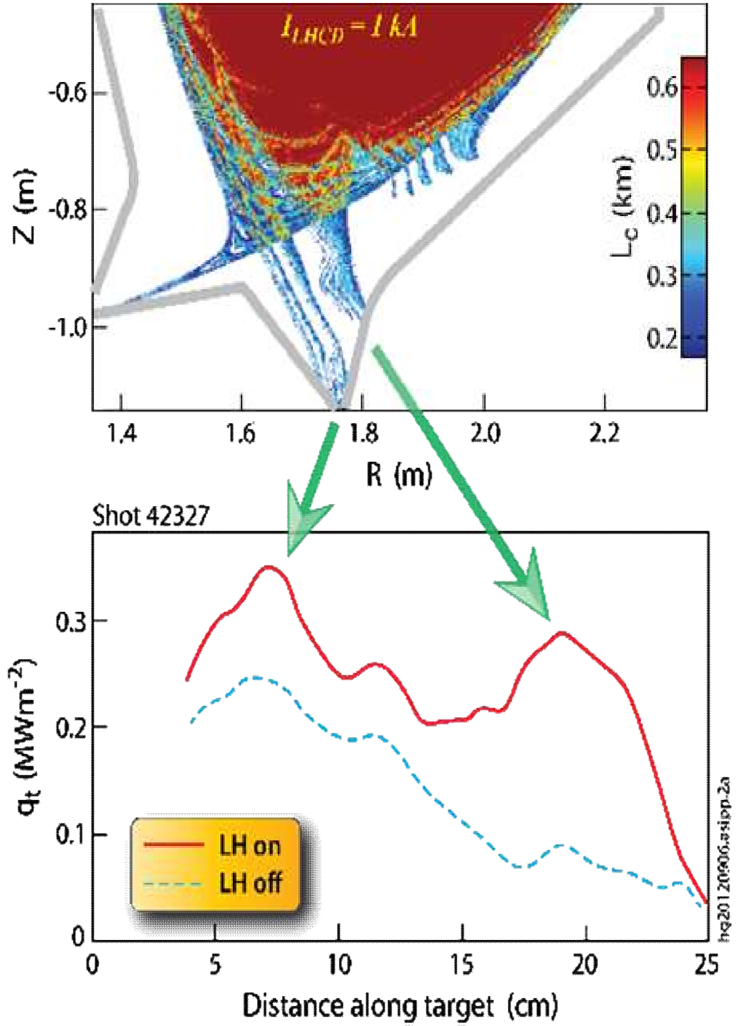
Changes of the ELM structure



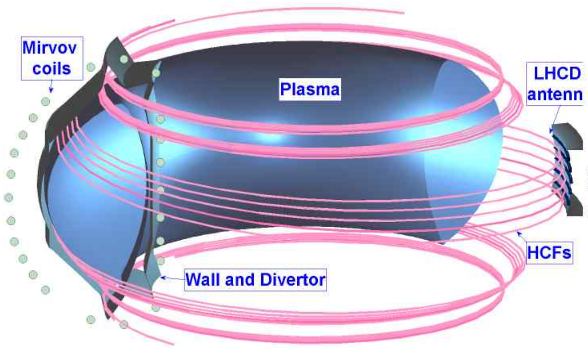
Demonstrated for the 1st time Edge magnetic topology change by LHCD

ASIPP



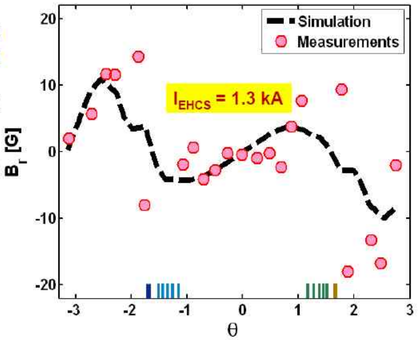


Helical Radiation Belts (helical current sheets)



Poloidal Projection of SOL Field Lines

Measurement of Magnetic perturbation due to EHCS

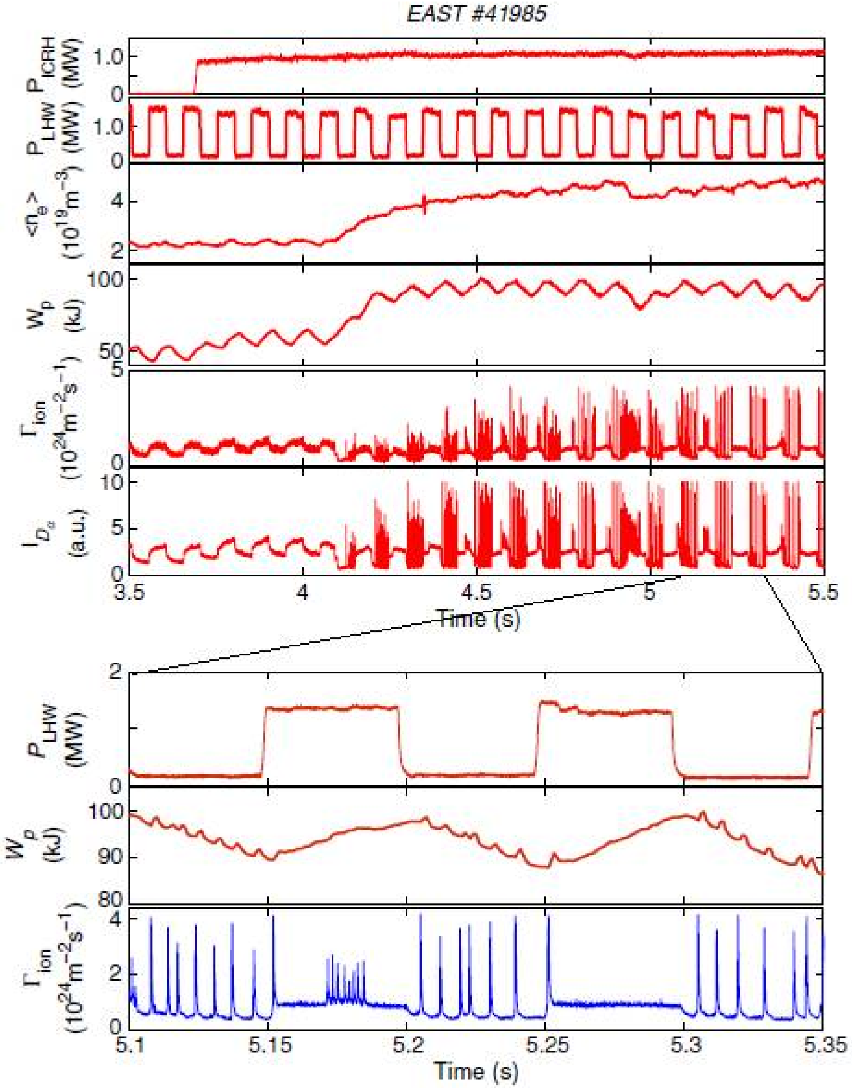


Change of Edge Magnetic Topology

Y. Liang, …, L. Wang et al., PRL 110, 235002 (2013)

Strong mitigation of ELMs with LHCD

ASIPP



◆ICRF-dominated + 10Hz LHW modulation (LHW-off: 50ms ~ ½τ_E)

◆H_{98}=0.8; $W_{dia}|_{L\rightarrow H}$: 50 →100kJ

◆LHW off: f_{ELM} ~150Hz

◆LHW on: ELMs disappear or sporadically appear w/ f_{ELM}~600Hz

◆Peak particle flux: ↓ by 2-4

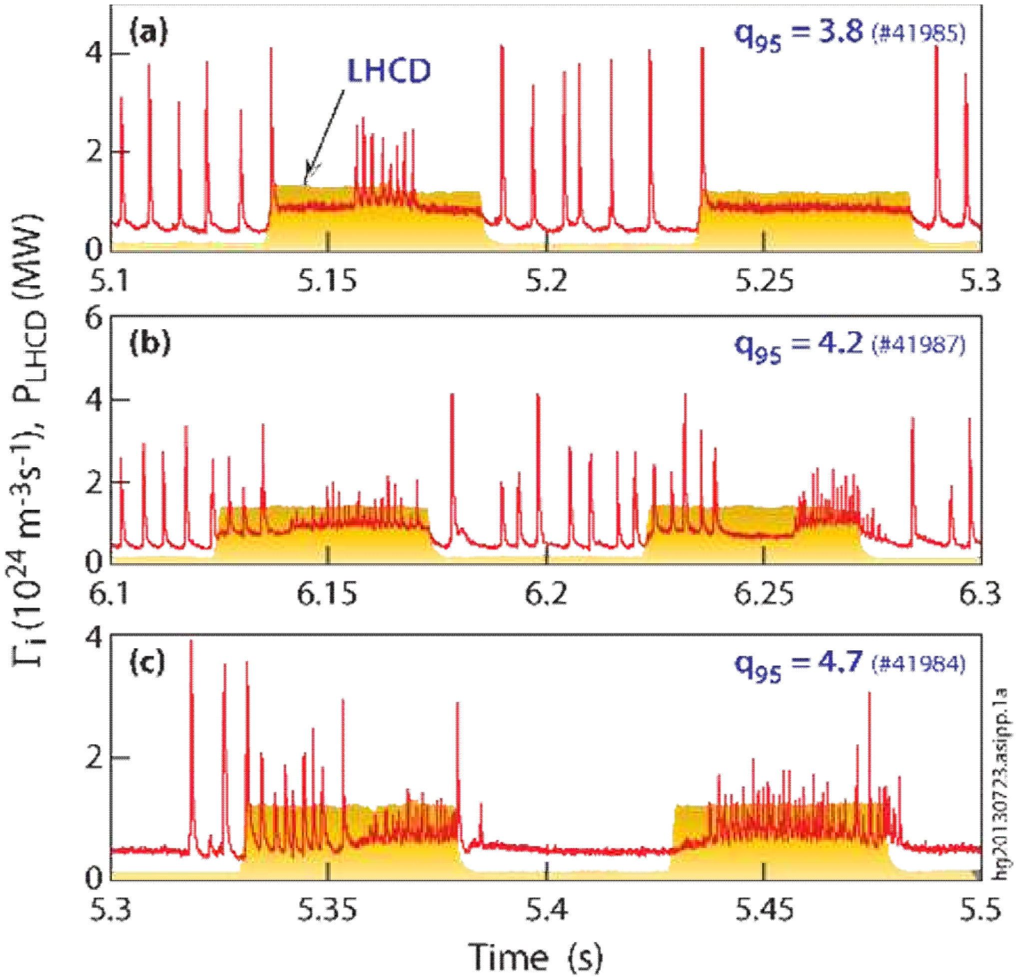
◆W_{dia} varied slightly: within ±5%

◆A quick reduction of $\Gamma_{i,div}$ during inter-ELM can be seen when LHW was switched off.

Y. Liang, …, L. Wang et al., PRL 110, 235002 (2013)

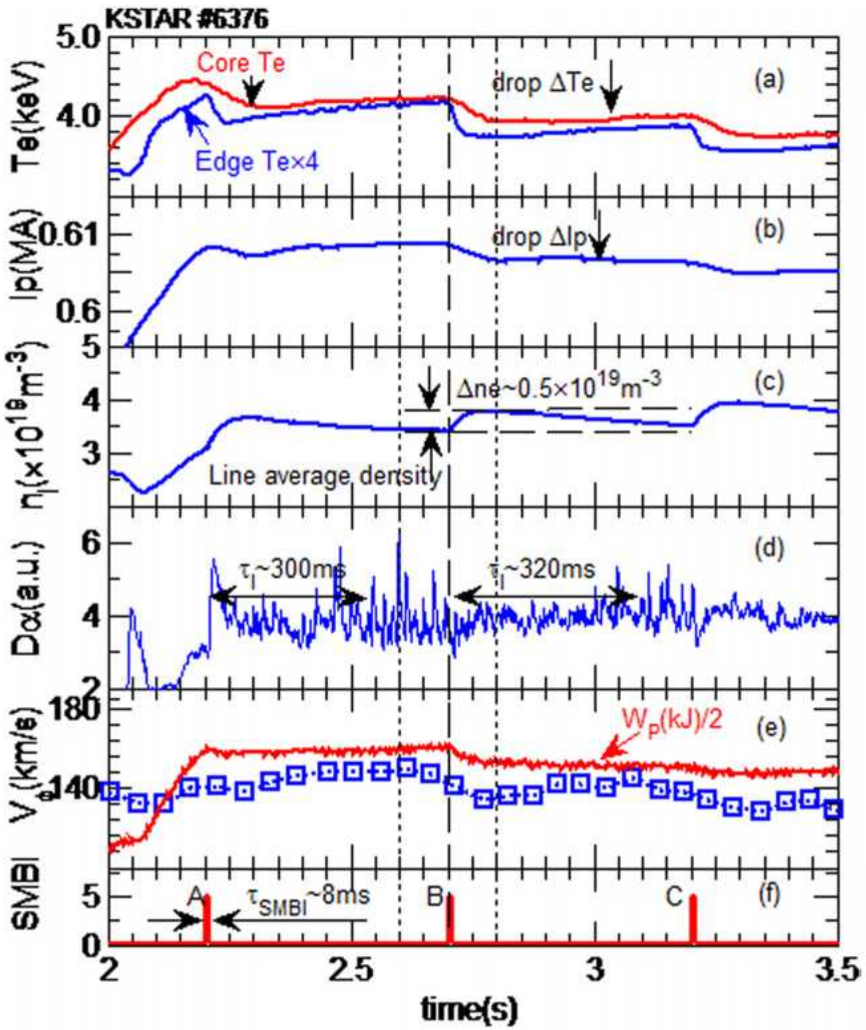
Flexible boundary control with LHCD

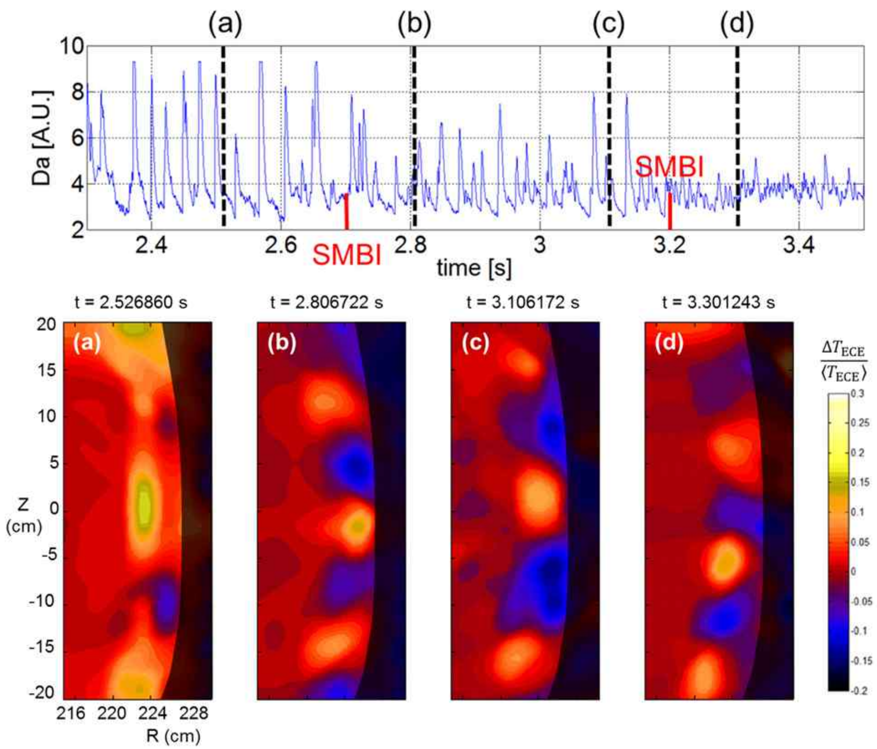
ASIPP



- The long pulse H-mode was achieved with dominant LHCD, with additional ICRH.
- LHCD induces drives n=1 helical currents at edge, leading to 3D distortion of magnetic topology, similar to RMP
- LHCD appears to be effective at controlling ELMs over a broad range q_{95}, in contrast to fixed RMP coils.

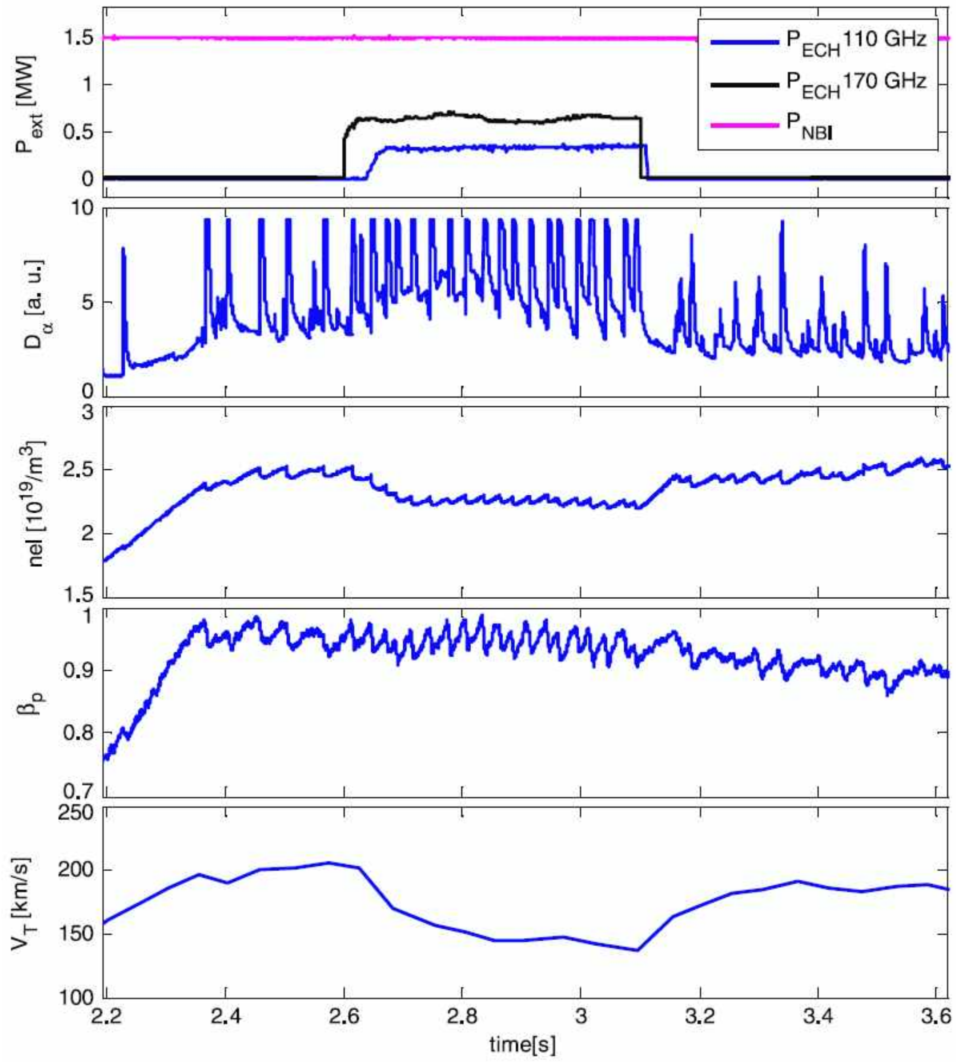
ELM Control by SMBI





Jayhyun Kim et al., Nucl. Fusion ***52*** *114011 (2012)*

ELM Control by ECH/CD

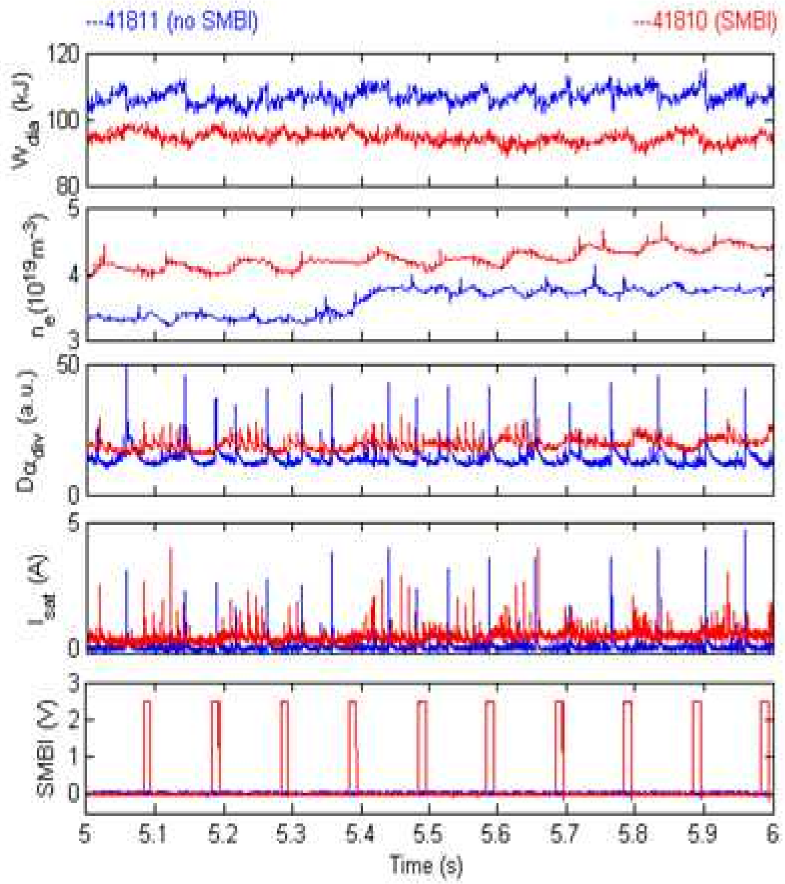


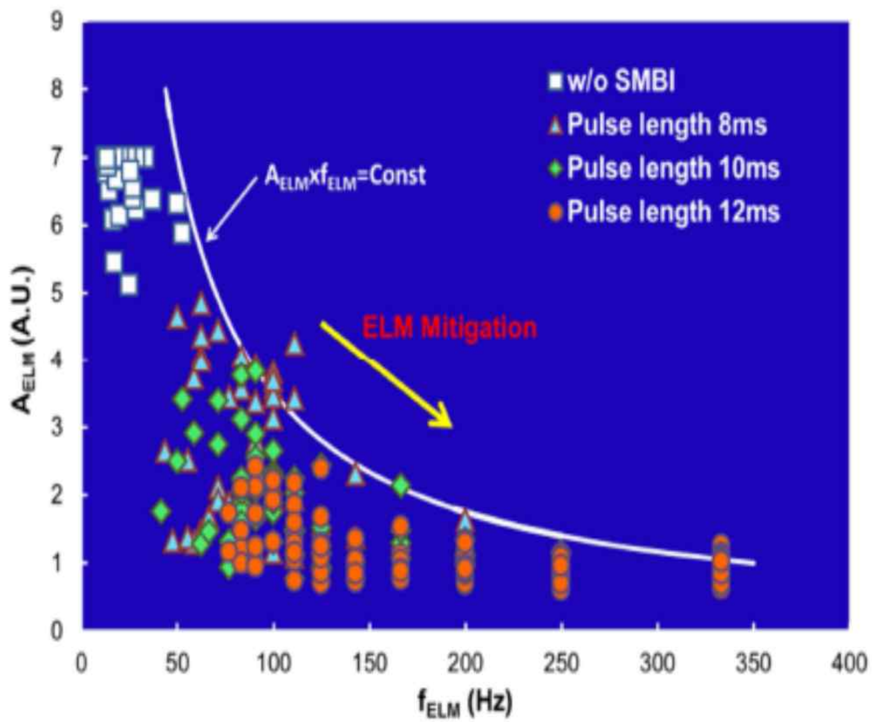
Jayhyun Kim et al., Nucl. Fusion ***52*** *114011 (2012)*

ELM control by SMBI

ASIPP

SMBI: Supersonic Molecular Beam Injection, Initially developed by SWIP.CN, successfully applied on HL-2A, KSTAR & EAST

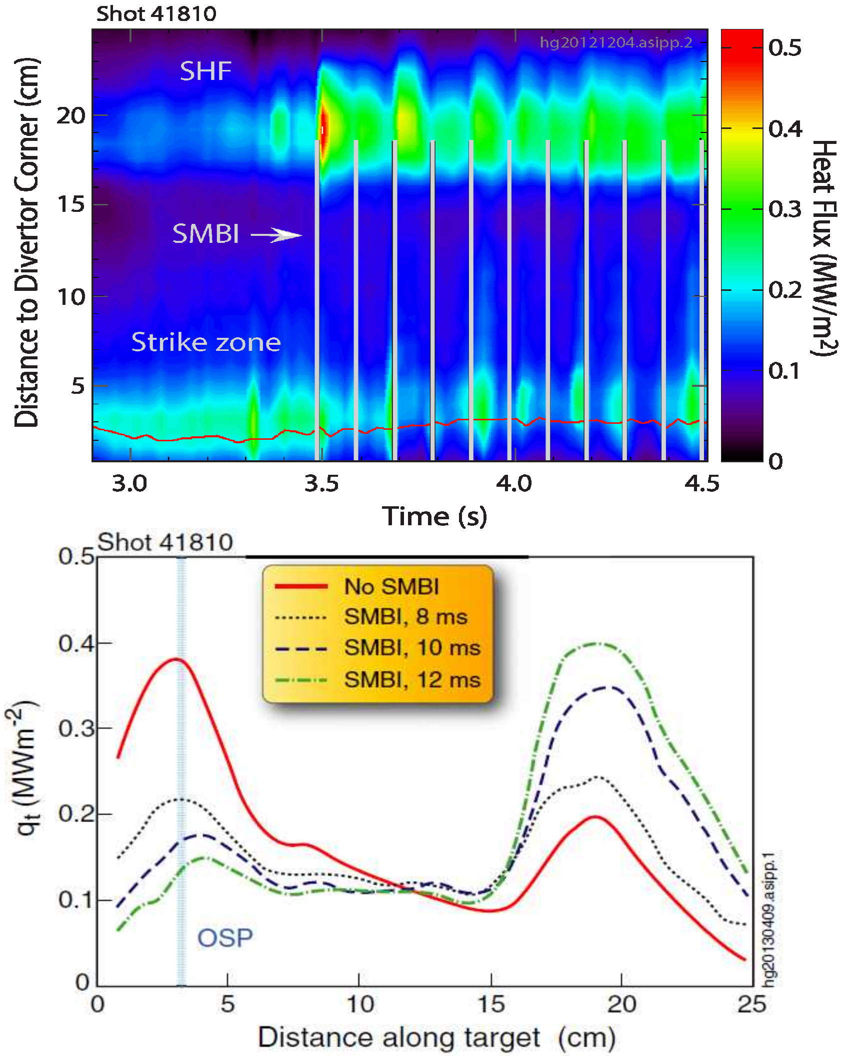




X. L. Zou et al., 24th IAEA FEC, San Diego

SHF can be actively controlled with SMBI

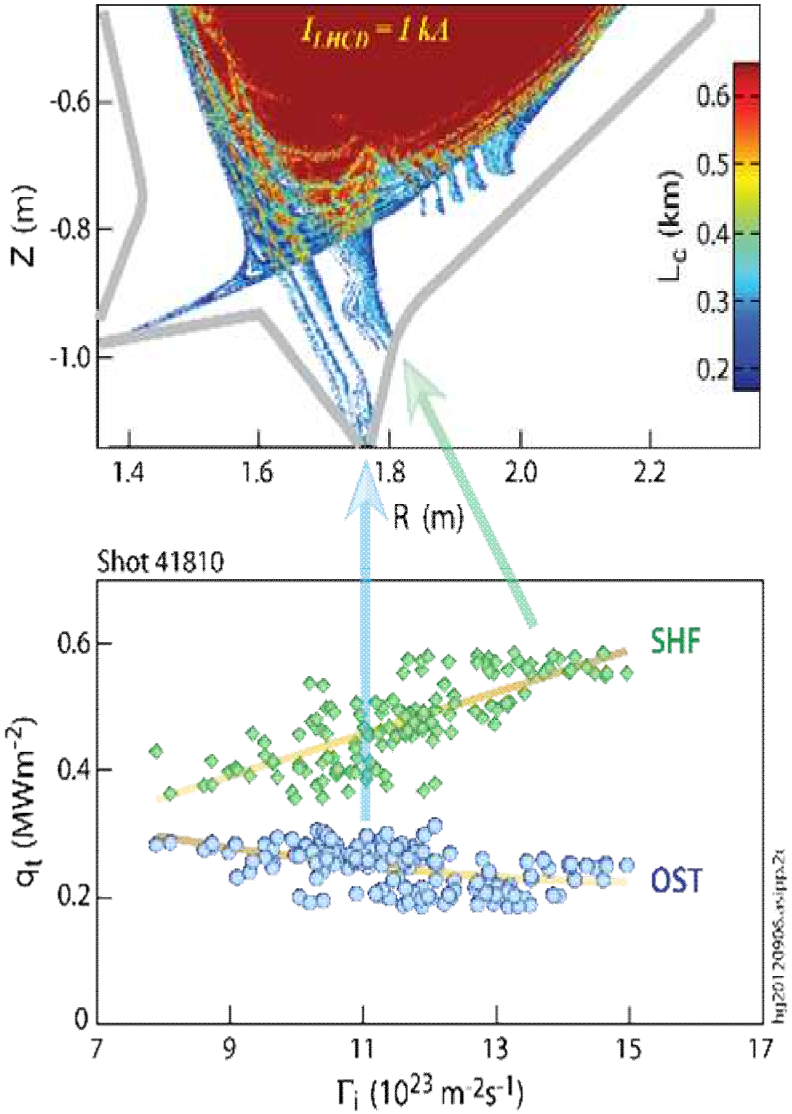
ASIPP



- **Striated Heat Flux (SHF) region in the far-SOL can be actively controlled with SMBI.**
- **Characteristic of LHCD heating scheme**
- **SMBI significantly enhancing SHF, while reducing peak heat fluxes near strike point.**
- **Achieving similar results with conventional gas puff or Ar seeding.**

SHF can be actively controlled by regulating edge particle fluxes

ASIPP



- **For SHF: $q_{SHF} \sim \Gamma_i T_{ped}$, $T_{ped} \sim 350$ eV**
  ➔ q_{SHF} increases with Γ_i.

- **At OST: $q_{OST} \sim \Gamma_i T_{div}$, $T_{div} \sim \Gamma_i^{-1}$,**
  ➔ q_{OST} remains similar.

- **A unique physics feature of ergodized plasma edge by LHCD.**

- **Allowing control of the ratio of q_{SHF}/q_{OST}, thus divertor power deposition area via control of divertor plasma conditions.**

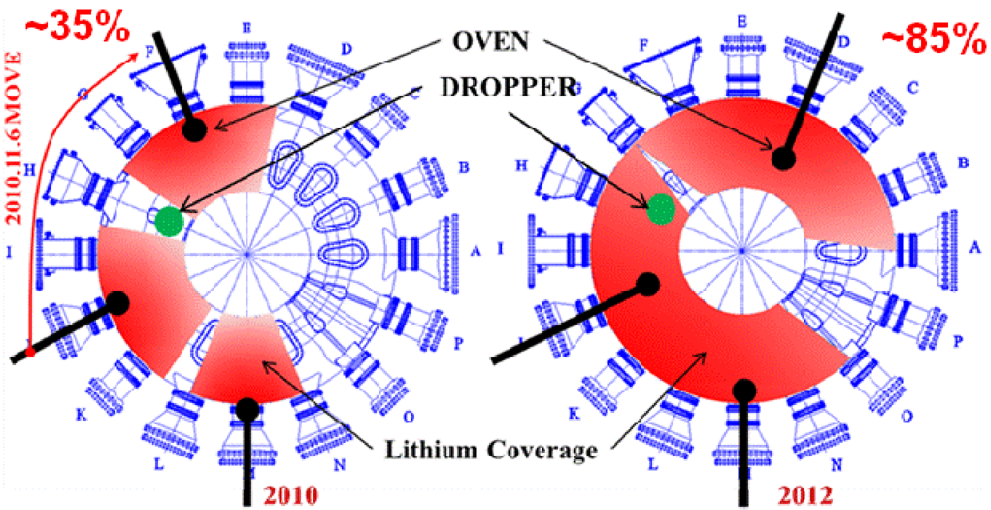
J. Li et al., **Nature Phys. 9** 817 (2013)

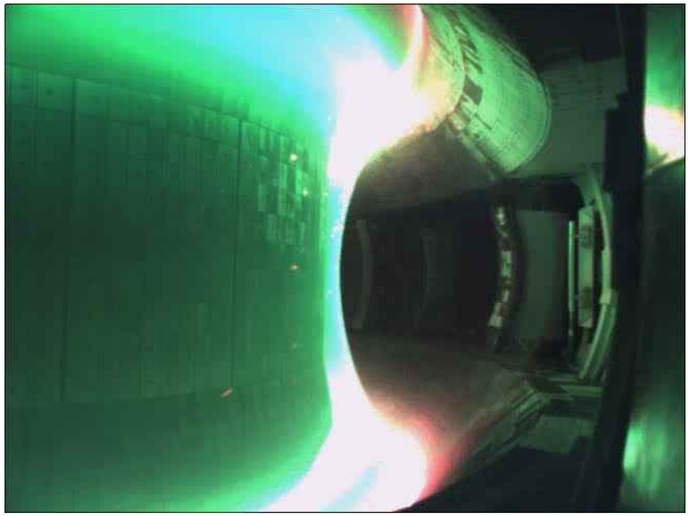
Lithium wall conditionings

ASIPP

- **Reduce recycling**
- **Suppress impurities**
- **Benefit ICRF &LHCD coupling**
- **Mitigate ELMs**

- Increasing Li Coverage (85% @2012 vs 30% @2010)
- Active Li injection to help operate long pulse H-mode
- Need one more oven for full surface coating.



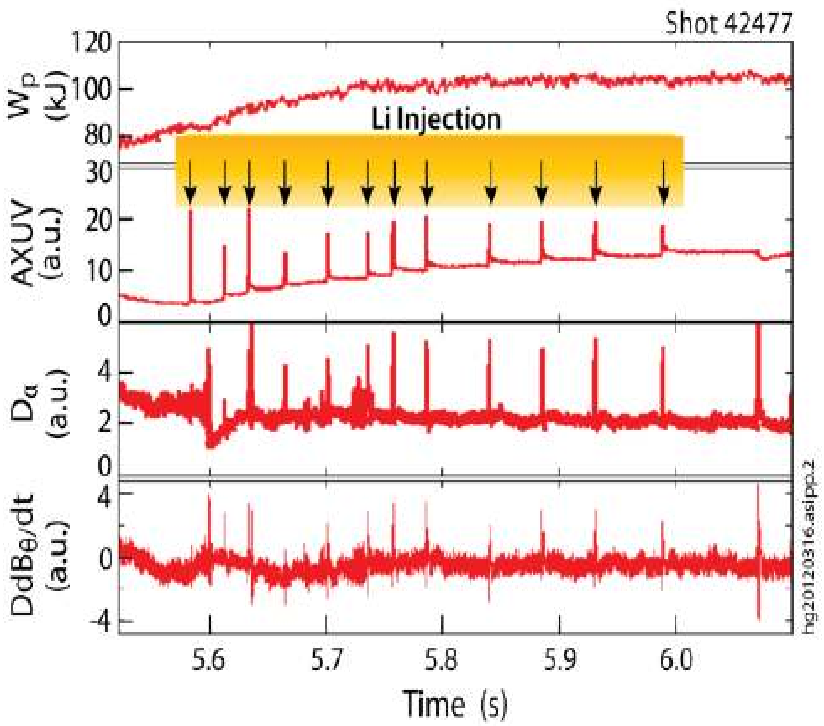


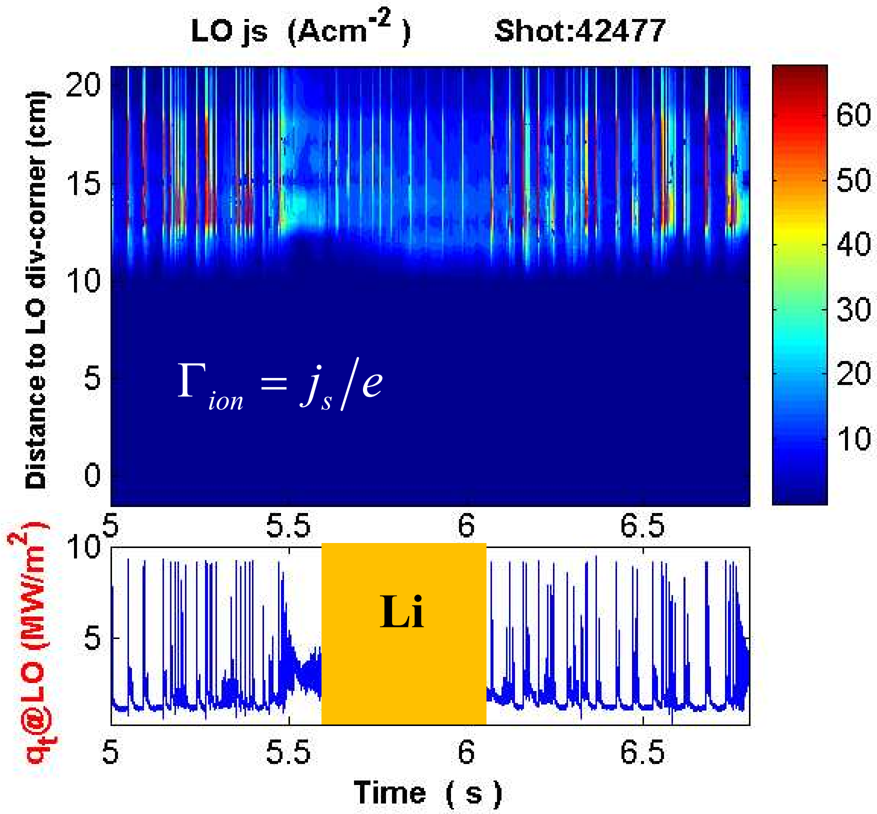
green light emissions from lithium

Demonstrated for the 1st time ELM Pacing by Innovative Li-granule Injection

ASIPP

Collaborated with PPPL





- Triggering ELMs (~25 Hz) with 0.7 mm Li granules @ ~45 m/s.
- ELM trigger efficiency after L-H transition: ~100%.
- Much lower divertor particle/heat loads than intrinsic type-I ELMs.

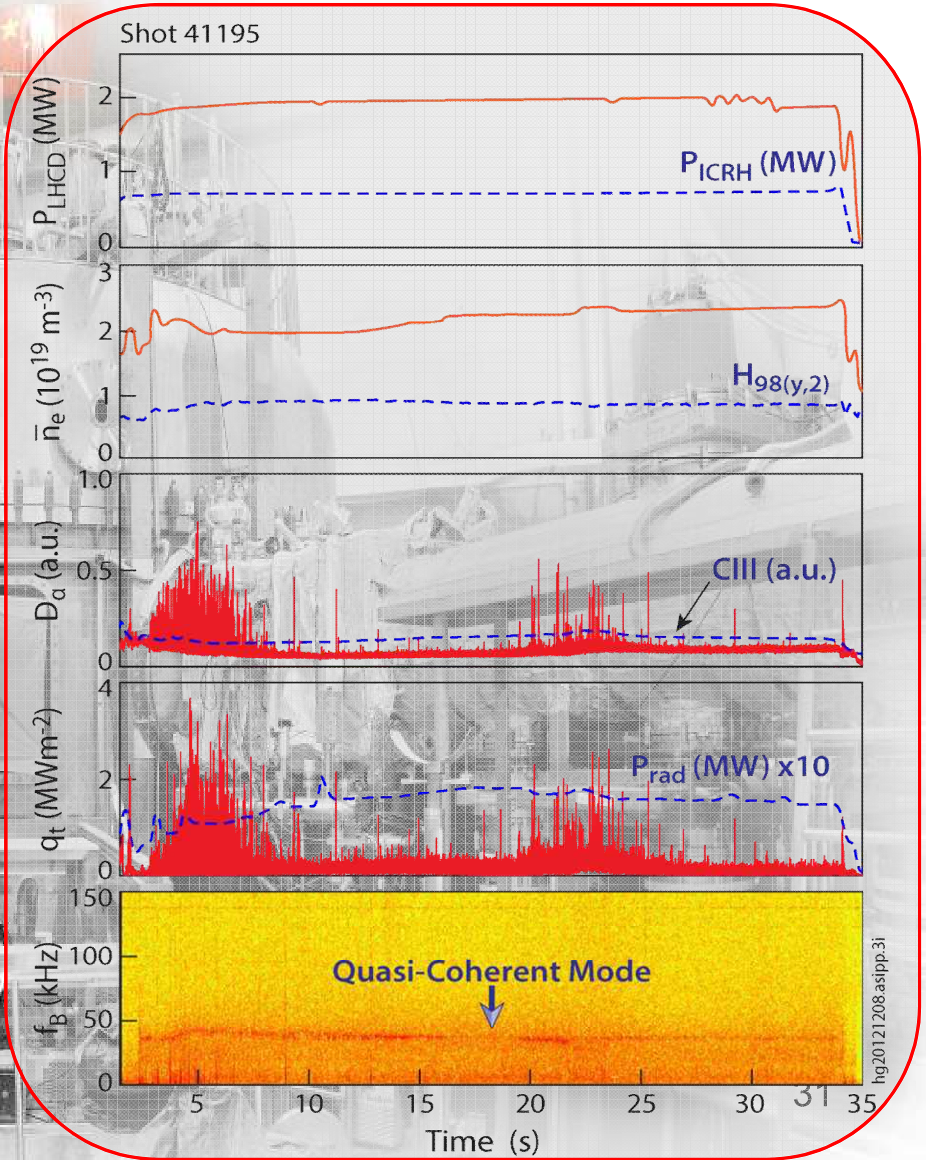
D. Mansfield et al., Nucl. Fusion ***53*** *113023 (2013)*

Achieved long pulse H-mode over 30s w/ small ELMs to minimize transient heat load

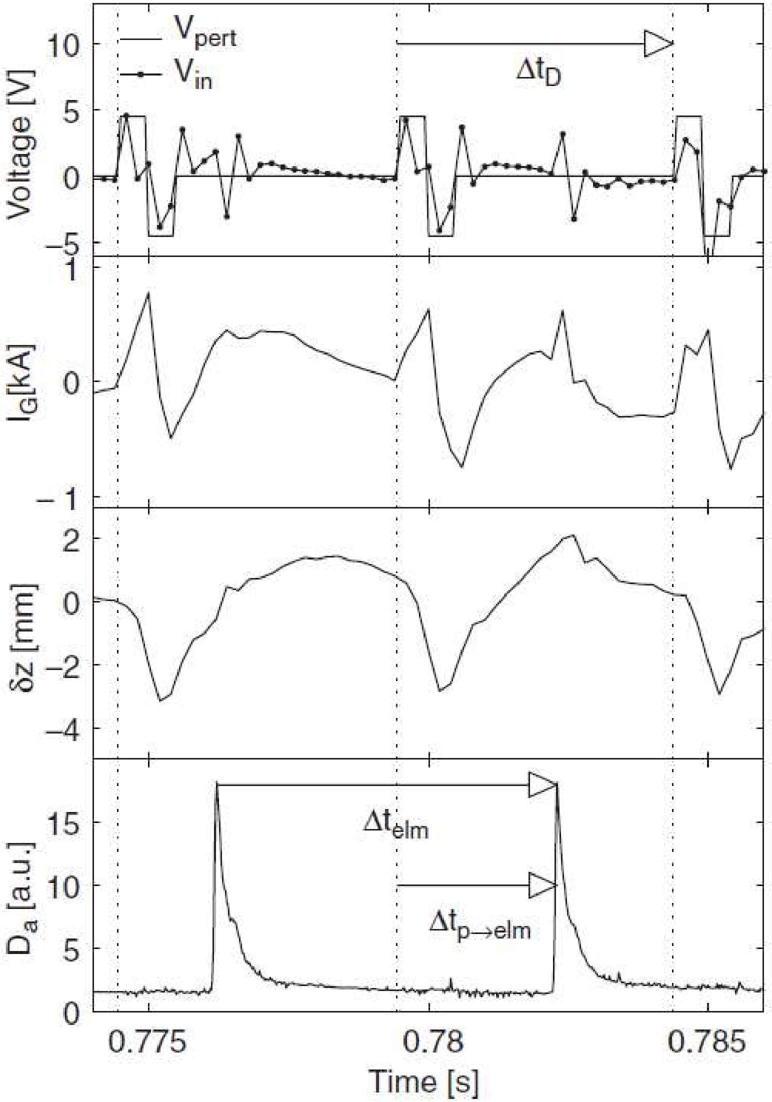
ASIPP

- Predominantly small ELMs with $H_{98} \sim 0.9$, between type-I and type-III ELMy H-modes.
- Target heat flux is largely below 2 MW/m^2.
- Accompanied by QCM, continuously removing heat and particles.

J. Li et al., Nature Physics **9** 817 (2013)



ELM Control by Vertical Jogs

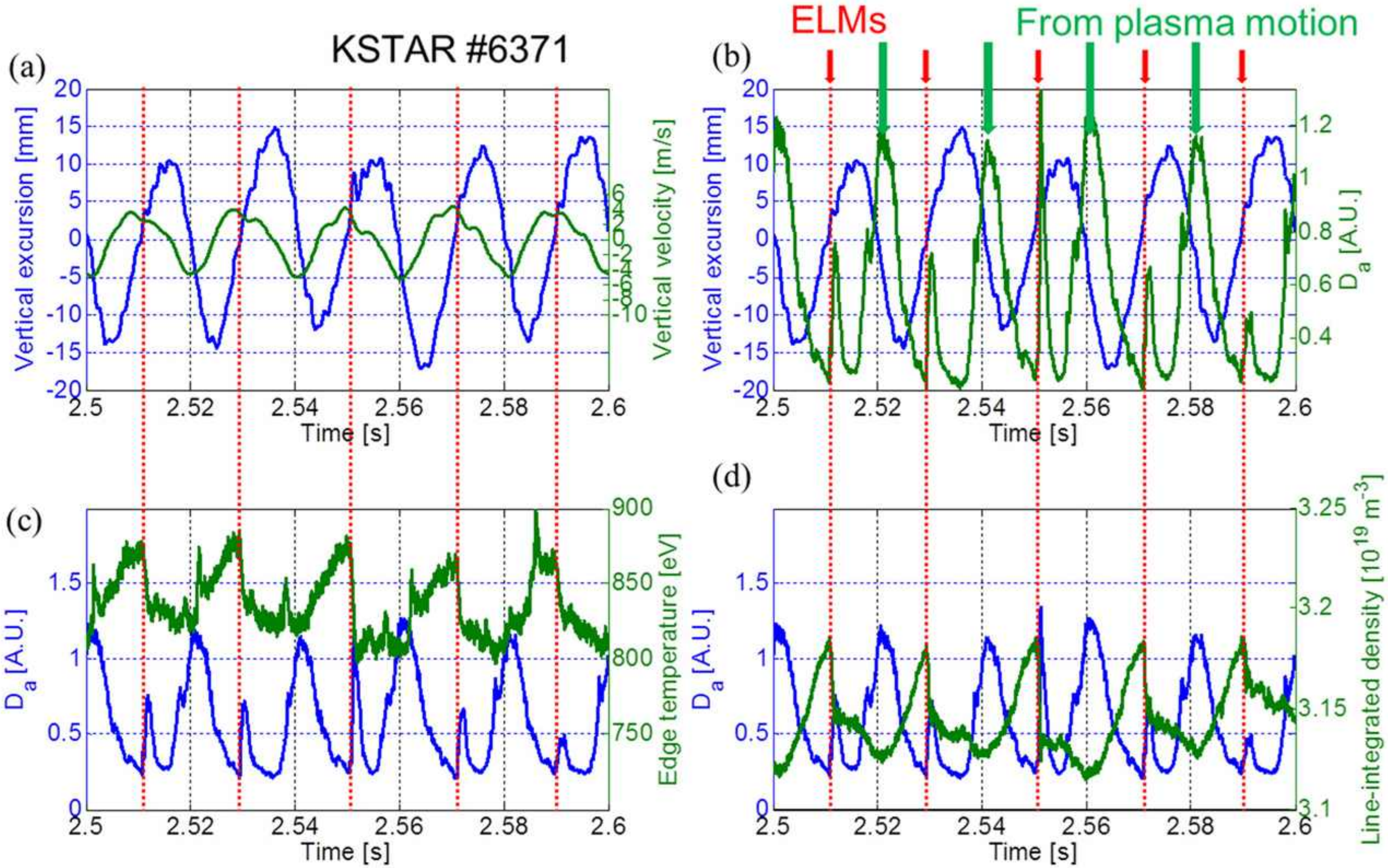


- Experiments on the TCV tokamak have shown that rapid vertical movement of diverted ELMy H-mode plasmas can affect the time sequence of ELMs.

- The effect is attributed to the induction of an edge current during the movement of the plasma column in the spatially inhomogeneous vacuum field of a single-null configuration.

*A.W. Degeling et al., PPCF **45** 1637 (2003)*

ELM Control by Vertical Jogs



Jayhyun Kim et al., Nucl. Fusion ***52*** *114011 (2012)*