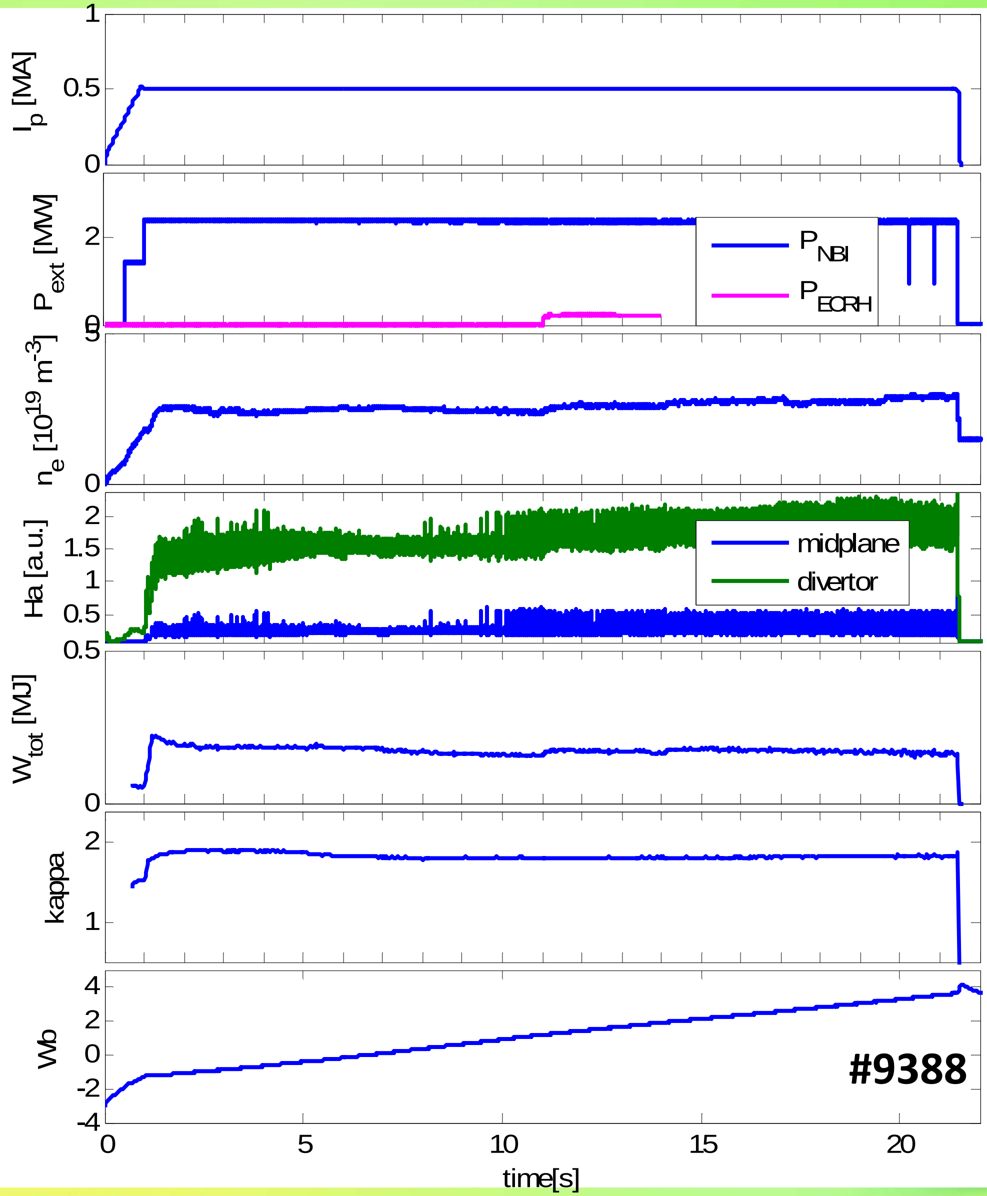
KSTAR contributions to ITER long-pulse operations

Jinseok Ko on behalf of **The KSTAR Team**
National Fusion Research Institute, Daejeon, Korea

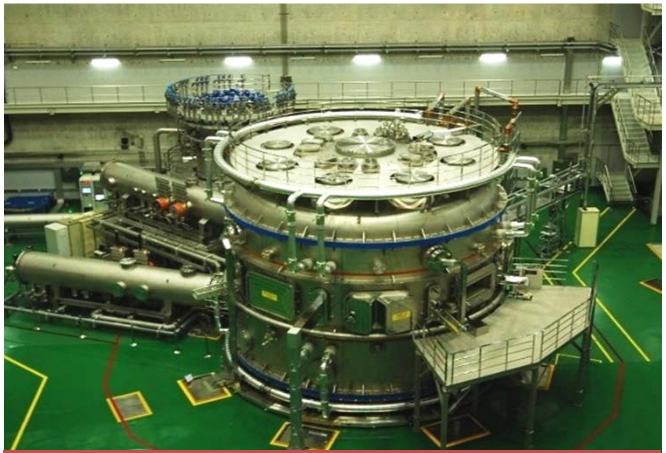
55th APS-DPP Meeting, Denver, CO, USA, Wed 13 Nov 2013

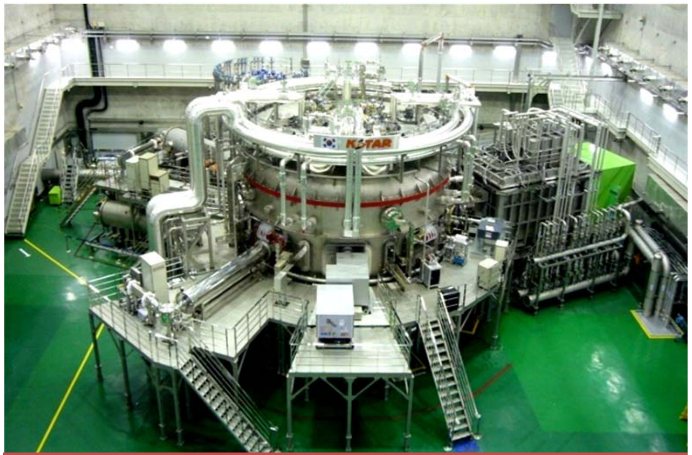
20-sec H-mode flattop this year



- **Stationary line density with better shape (& X-point) control.**
- **Disrupted at 21.4 s NOT because of the flux limit BUT because of the grid electricity limit (MVA limit).**
- **The long-pulse experiments show KSTAR plasmas can sustain 1 MA for more than 50 sec with the current heating capability (~ 3 MW) and motor generator (2 GJ)**
- **Apart from the H/W capabilities, longer pulse will be available with better PF control logics, external CDs, and higher J_{BS}**

Progress is rapid towards KSTAR main missions


2008: First plasma (107 kA)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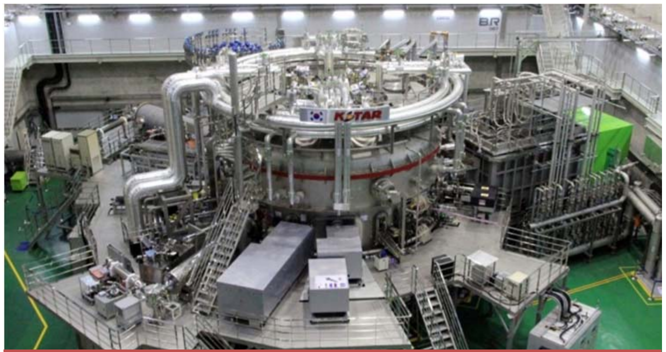
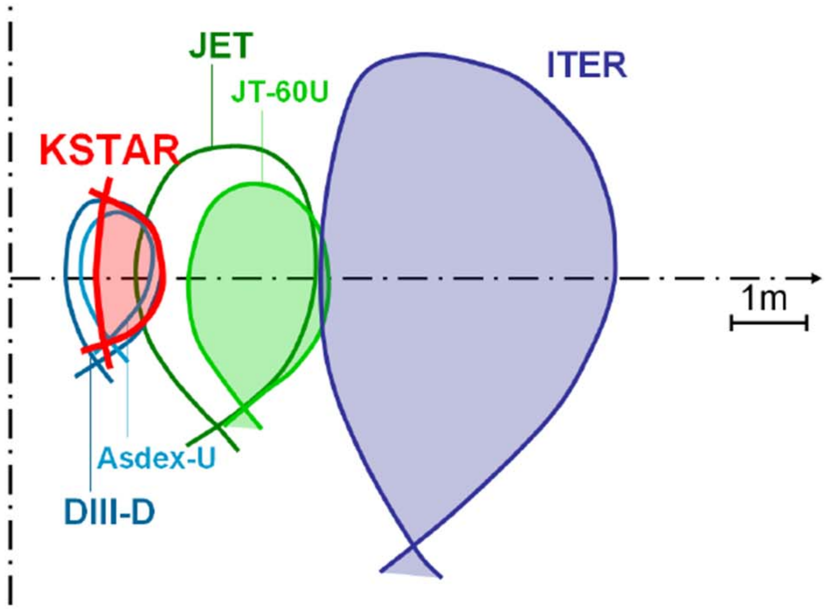

2011-2013: 20-sec H-mode
ELM suppression
Highest β_N (2.5)



- Achieve superconducting tokamak construction and operation experience.
- Explore ITER urgent issues in long pulse H-mode plasmas (MA level).
- Explore the physics and technologies of high performance steady-state operation.
- Extend stability and performance boundary through active profiles/transport control.

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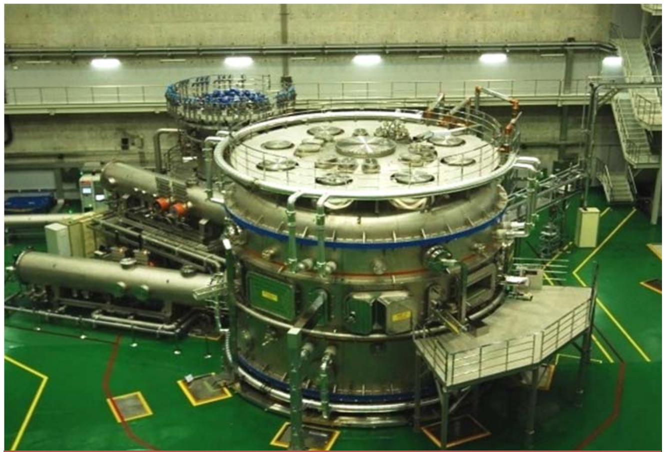

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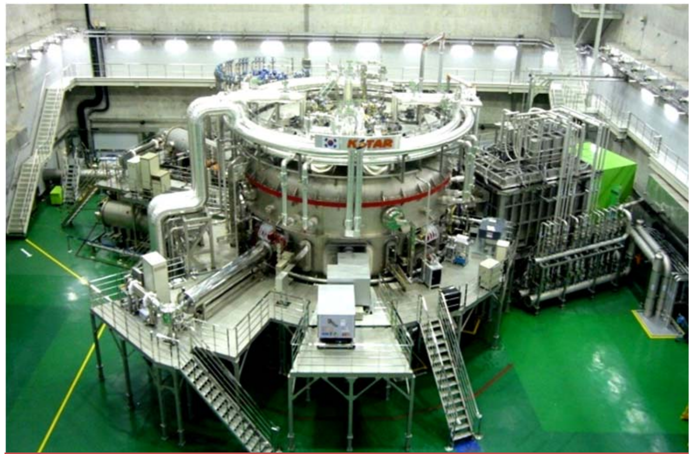

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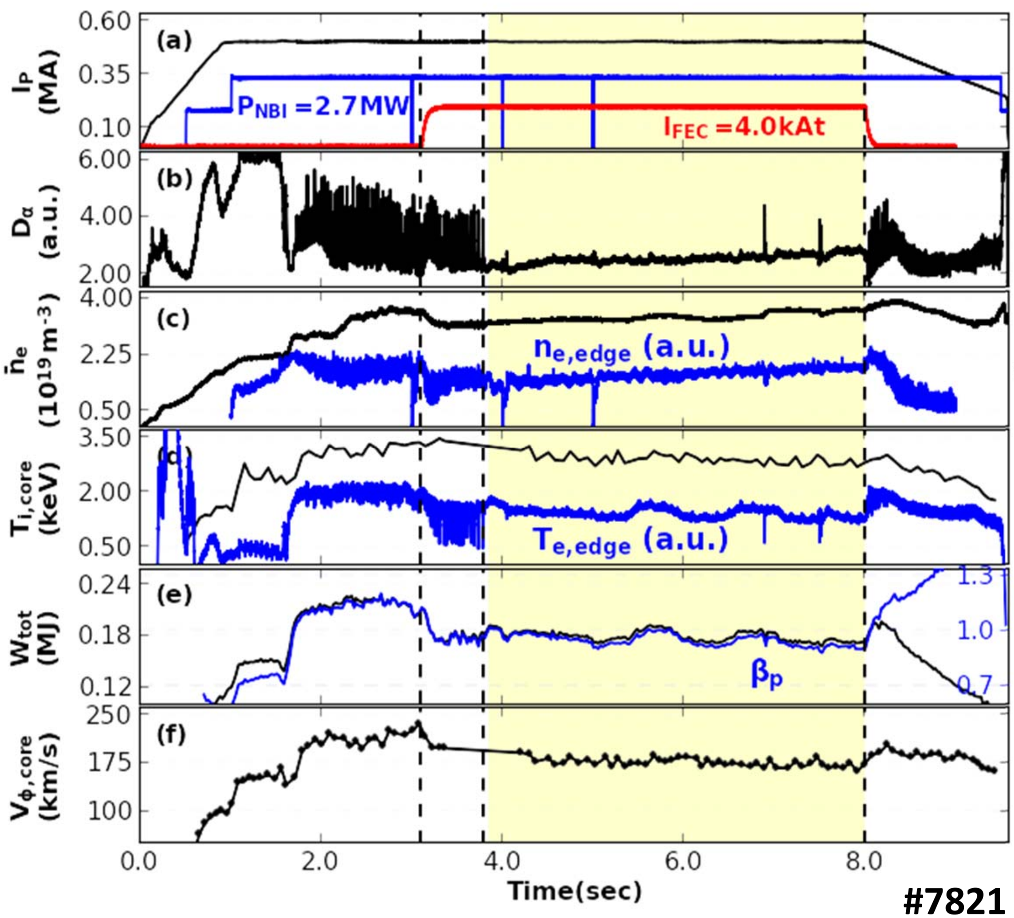
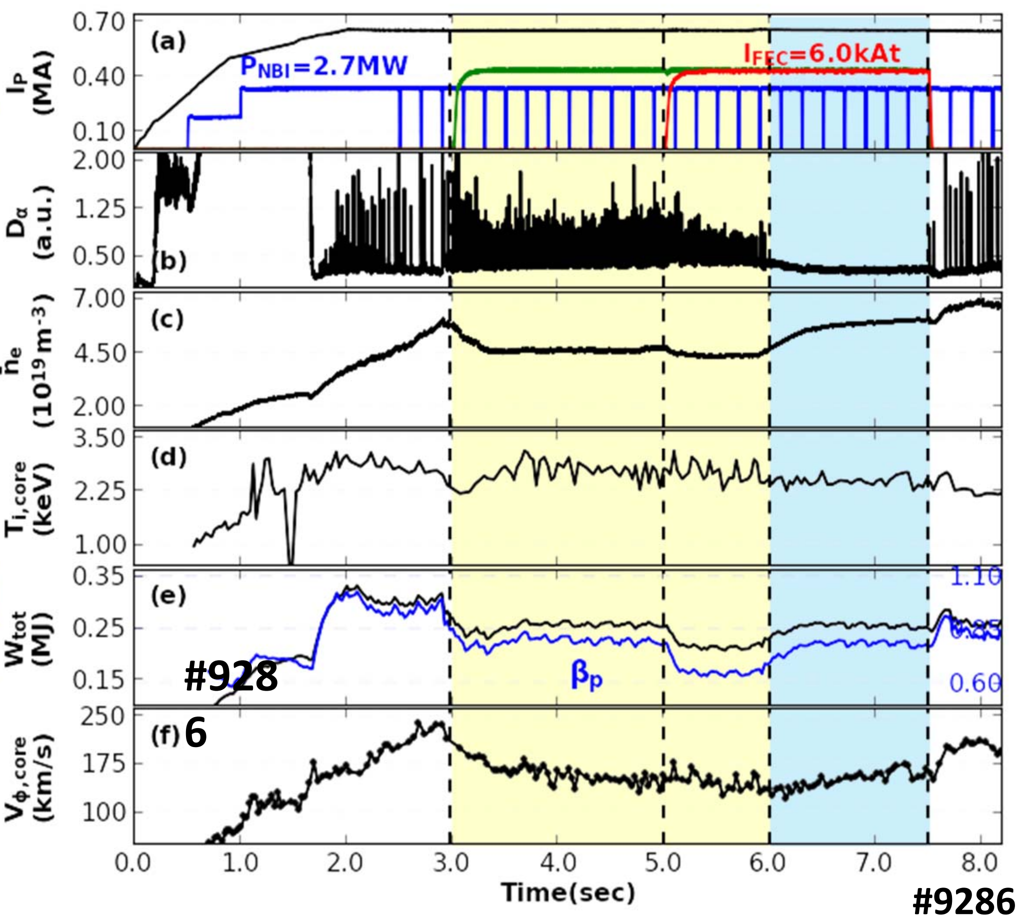
- Achieve superconducting tokamak construction and operation experience.
- Explore ITER urgent issues in long pulse H-mode plasmas (MA level).
  - ELM control
  - Disruption mitigation
- Explore the physics and technologies of high performance steady-state operation.
- Extend stability and performance boundary through active profiles/transport control.
  - Spontaneous rotation / (low) rotation control
  - ITER operation scenarios

Long-pulse ELM suppression was made using low n RMPs



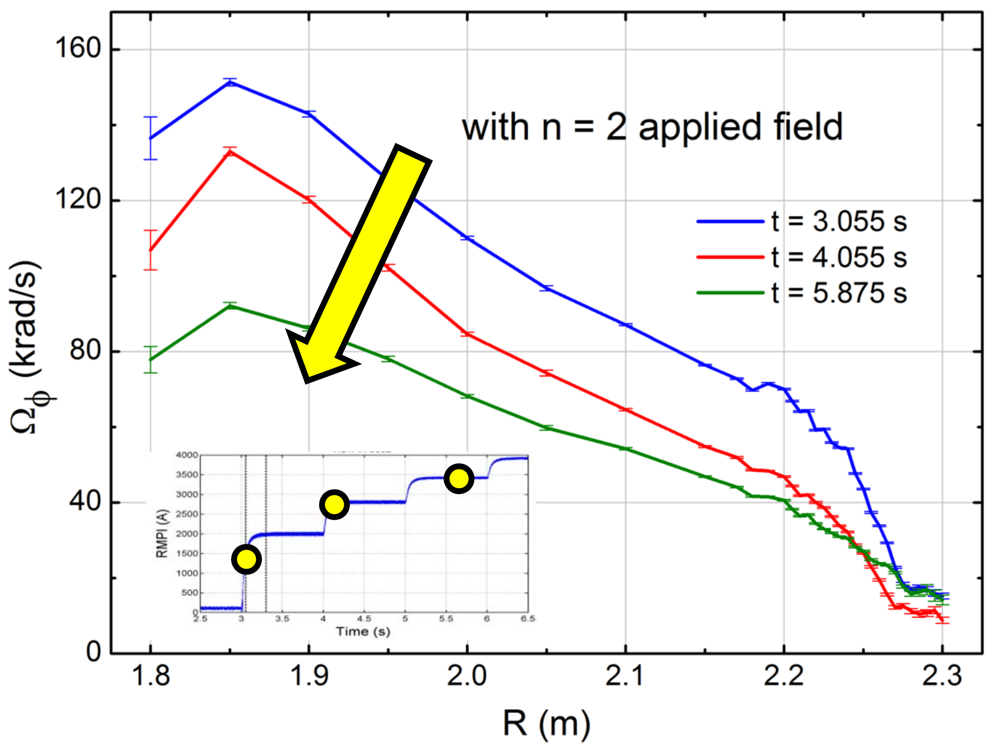


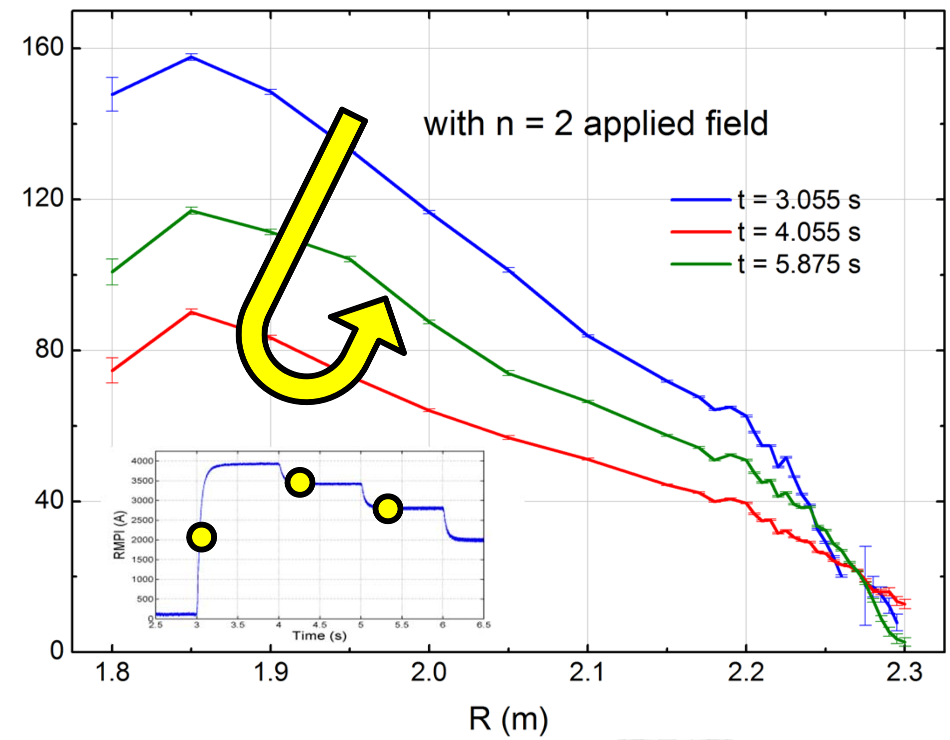
ELM-suppression using n=1 RMP at q_{95}~6.0

ELM-suppression using n=2 RMP at q_{95}~4.0

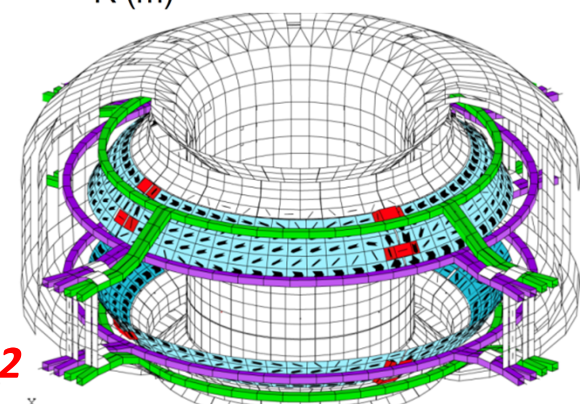
Y.M. Jeon et al, PRL 2012

Long-pulse rotation control is possible using in-vessel control coil



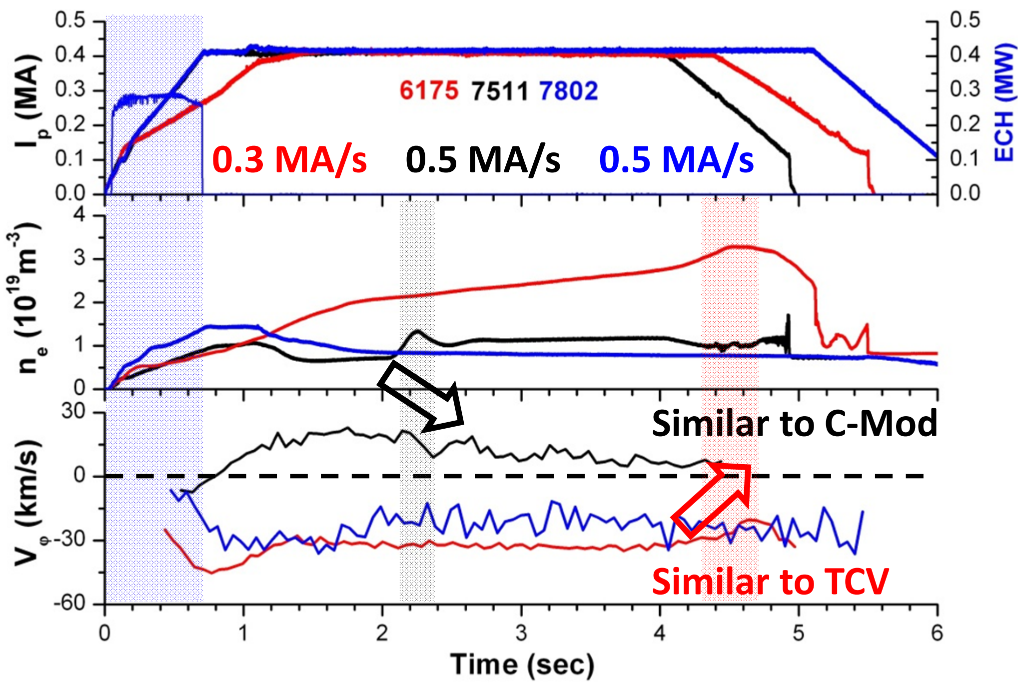


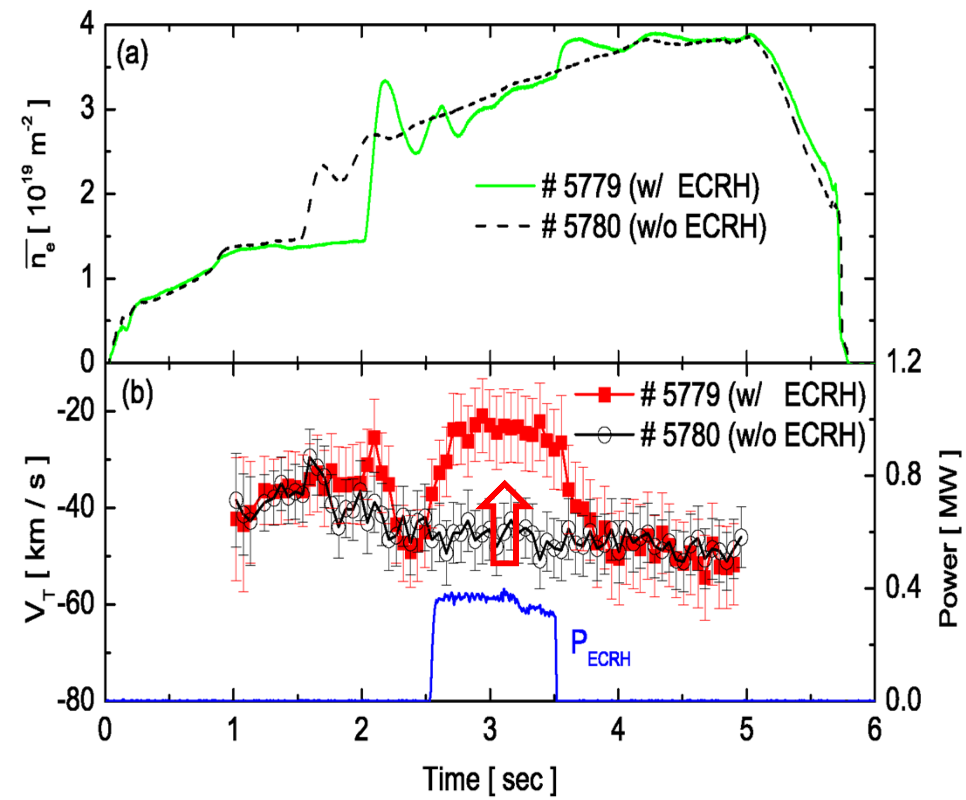
- **Rotation reduction by n = 2 applied field is global.**
- **Non-resonant (NTV) – No mode locking**
- **No hysteresis – Important for control**



S.A. Sabbagh, Y.S. Park (Columbia U.), 2012

KSTAR is a good test-bed for Ohmic rotation study with a reliable XICS diagnostic



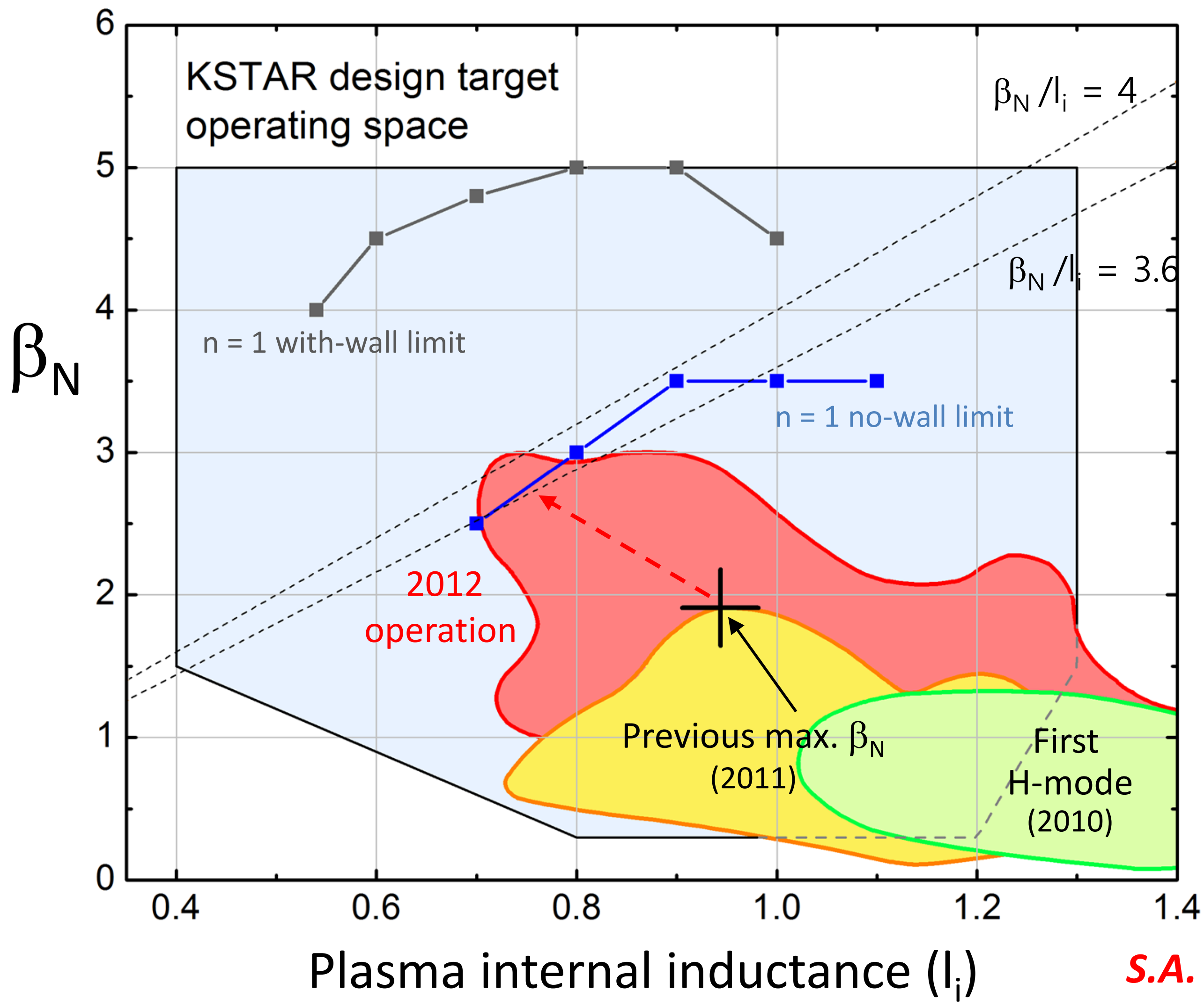


- Core rotation depends on ramp-up conditions.
- No MHD activities during the ramp-up
- New possibilities for rotation mechanism studies

- Rotation damping due to on-axis ECH also observed in KSTAR (consistent with other devices)
- NTV torque caused by internal kink modes?

J. Seol et al, PRL 2012

Plasmas have reached and exceeded the computed n = 1 ideal no-wall limit

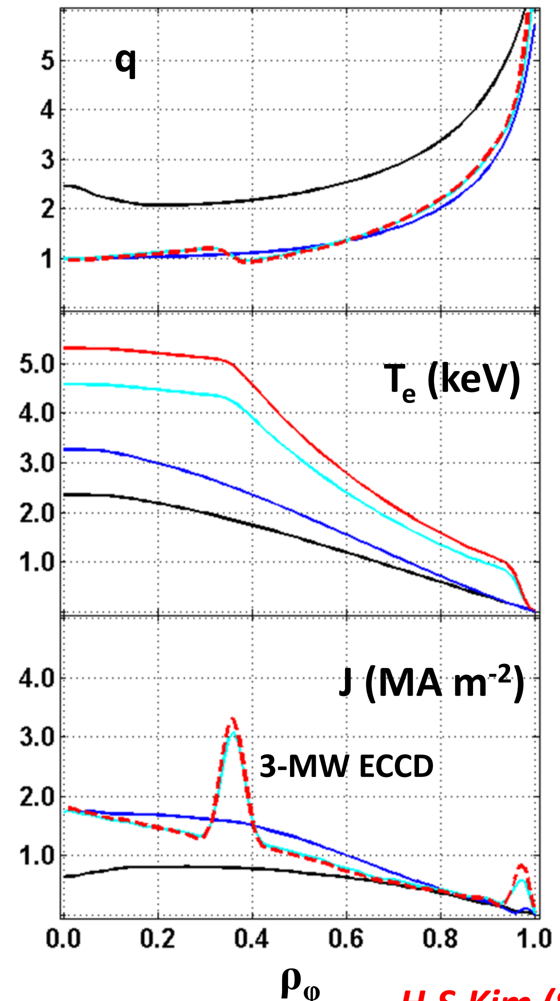


- **Exceeded published no-wall MHD stability limit (computed by DCON).**
- **Optimized B_T & Ip: 1.3 – 1.5 T, 0.5 – 0.7 MA**
- **Max β_N/li > 3, β_N ~ 2.5, li ~ 0.7**

S.A. Sabbagh, Y.S. Park (Columbia U.), 2013

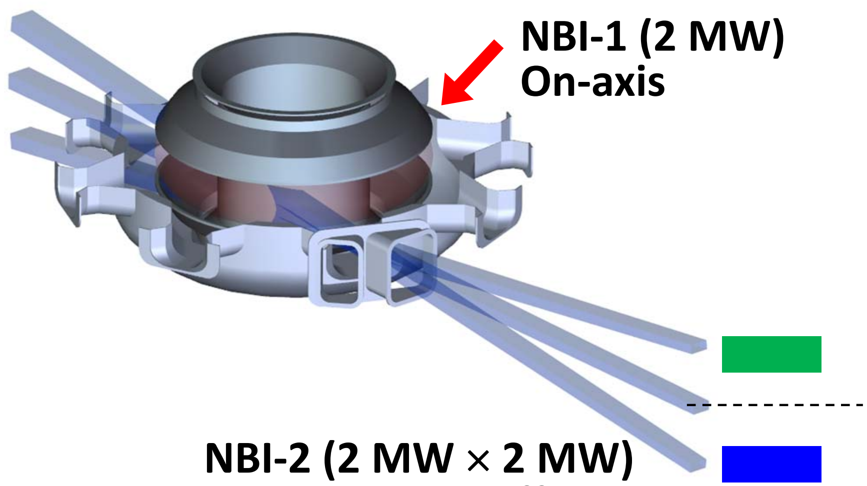
Predictive studies on operation scenarios with CRONOS integrated modeling suites*

Advanced inductive, q95 ~ 3
(BT/Ip = 1.88T/1 MA)



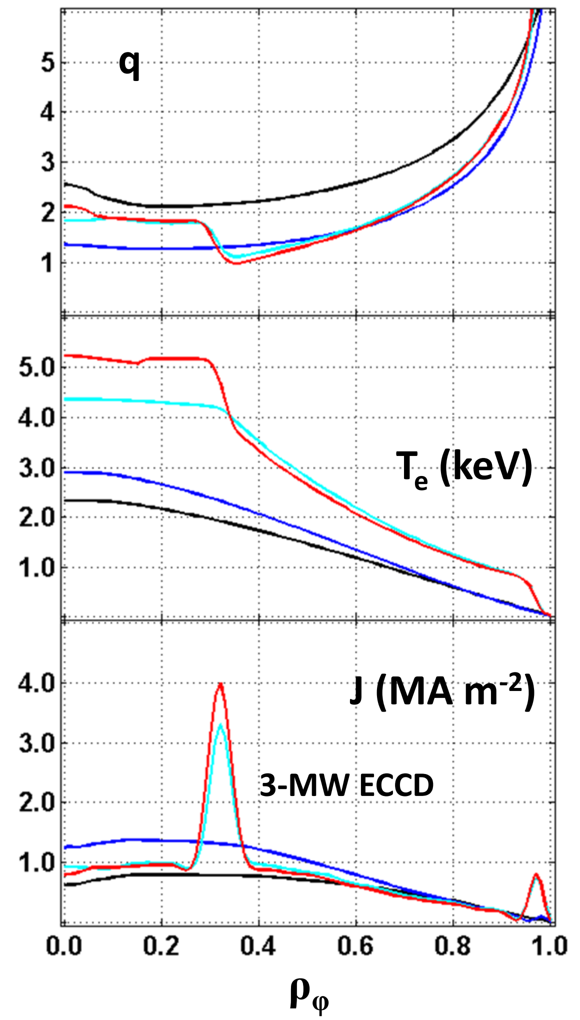
* IRFM

- Simulations aim at checking accessibility to the ITER operation scenarios with the near-term KSTAR resources.
- With re-deployment of the NBI sources and upgrade of ECCD, regimes of interest are marginally accessible (study is ongoing).



H.S.Kim (SNU), 2013

Fully non-inductive, q95 ~ 4
(BT/Ip = 1.88T/0.8 MA)



Stable long-pulse MA operations are supported by Integrated disruption mitigation system (DMS)*

*Under development

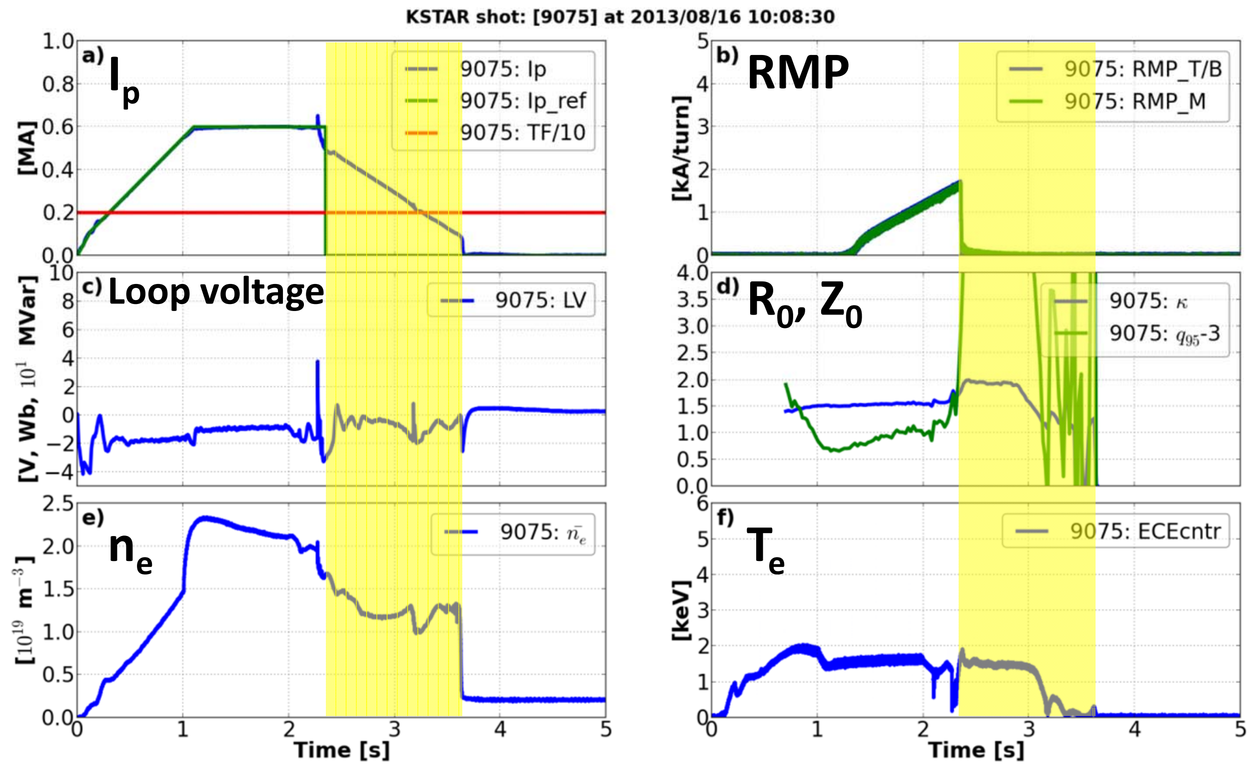
Detection

- Fast and reliable shape (Z) estimators for n = 0 (VDE)
- Lock mode / saddle coils for n > 0 (MHD)
- Externally (Ip, PFC fault, NBI fault etc)

⇩

Response

- Slow (hundreds of msec): asynchronous Ip ramp-down
- Fast (tens of msec): MGI shutdown



Soft-landing was achieved by async ramp-down during a locked mode

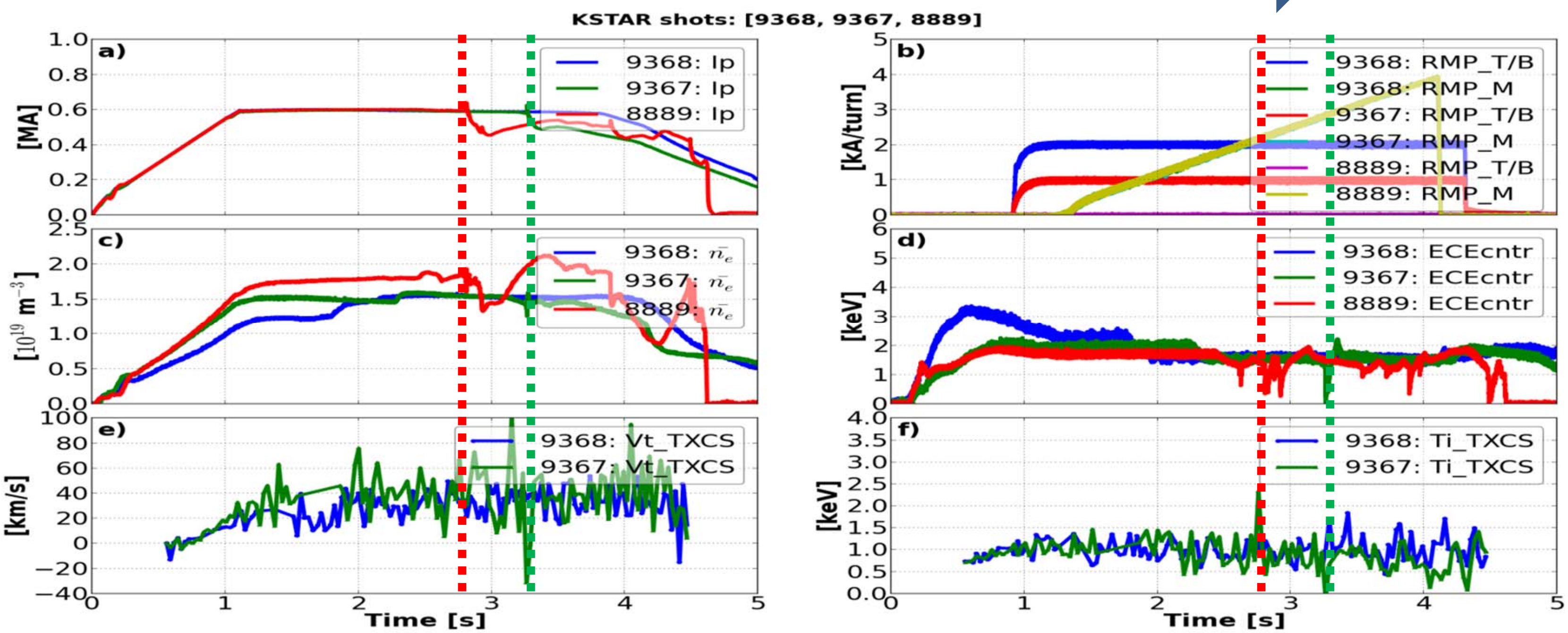
Mode locking: emulated by RMP

J. Kim, ITPA-MHD, 2013

Flexible 3D coil systems validate its effect on locking

- **KSTAR and ITER use various non-axisymmetric field controls such as EF corrections (n = 1, 2), RMW (n = 1, 2, …), and ELM (n = 3, 4).**
- **Mixed RMP experiments in KSTAR: Higher n = 2 field leads screening the effect of final locking by n = 1.**

Early locking | #8889 (n=2, 0 kAt) → #9367 (n=2, 2 kAt) → #9368 (n=2, 4 kAt) | No locking

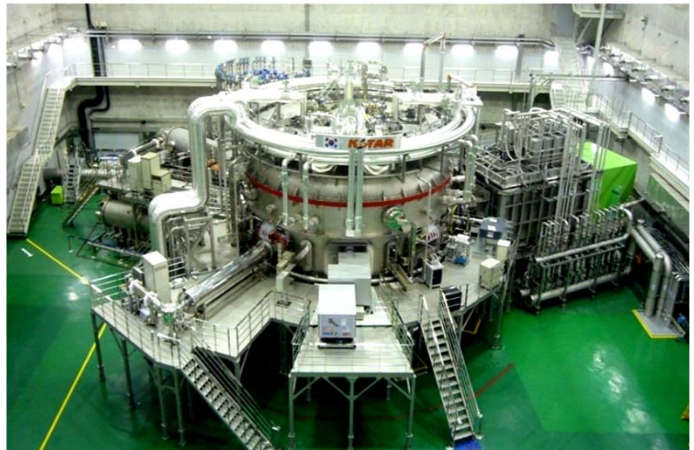


n=1 & 2 even

+	-	+	-
-	+	+	-
+	-	+	-

Progress is rapid towards KSTAR main missions

2008: First plasma (107 kA)



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2011-2013: 20-sec H-mode
ELM suppression
Highest β_N (2.5)

- ELM control
- Disruption mitigation

- Spontaneous rotation / (low) rotation control
- ITER operation scenarios

- Achieve superconducting tokamak construction and operation experience.
- Explore ITER urgent issues in long pulse H-mode plasmas (MA level).
- Explore the physics and technologies of high performance steady-state operation.
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Progress is rapid towards KSTAR main missions for ITER/DEMO

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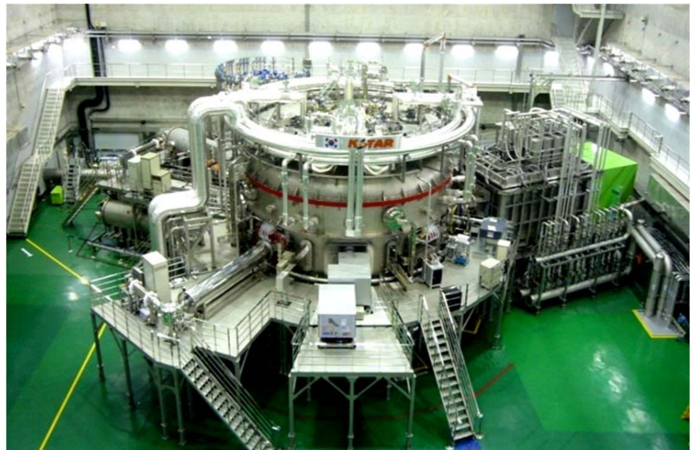

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ELM suppression
Highest β_N (2.5)

Phase II (2013-2017)

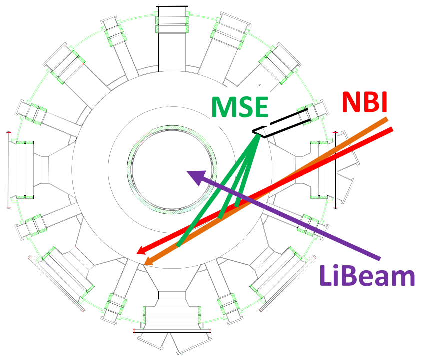
- High performance ($\beta_N \sim 3$, > 50 s)
- Steady-state ELM/disruption control
- Divertor loads / impurity control
- Metal wall effects
- Real time profile control
- Hybrid mode, low rotation, Ti ~ Te

Phase III (2018-2025)

- ITER steady-state mode ($\beta_N > 3.5$, 300 s)
- DEMO mode (AT-mode) with $\beta_N > 4.5$
- Bootstrap fraction of > 70 %
- 100% non-inductive
- Technology feasibility for DEMO (advanced divertor / materials)

Backup

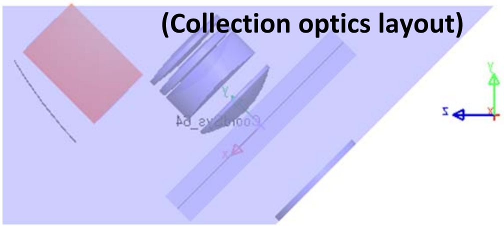
MSE (& ZE): Commission in 2015

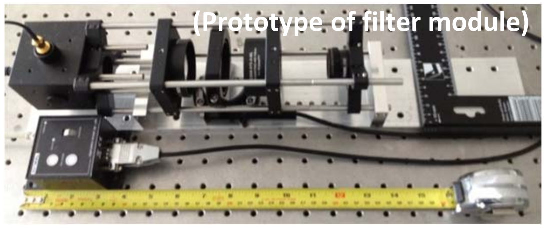


- PEM (Photo-Electric Modulator)-based MSE (30 channels) under design phase collaborating with Eindhoven Univ. of Tech (TU/e), The Netherlands.
- The development path also includes the Li-beam Zeeman effect diagnostic for the pedestal region.

2013

- Design of front optics
  - Sharing the collection optics with the existing CES: Signals will be separated into 550 nm and 650 nm via a dichroic beam splitter.
  - Low thermal-birefringence materials will be used to avoid random change in the polarization in thermally harsh environment.
- Design of bandpass filter module
  - Precise characterization of the bandpass filters and development of the filter module prototype.
  - PC-based software to control the filter pass band (tilting).





2014

- Procurement and assembly (after 2014 campaign)

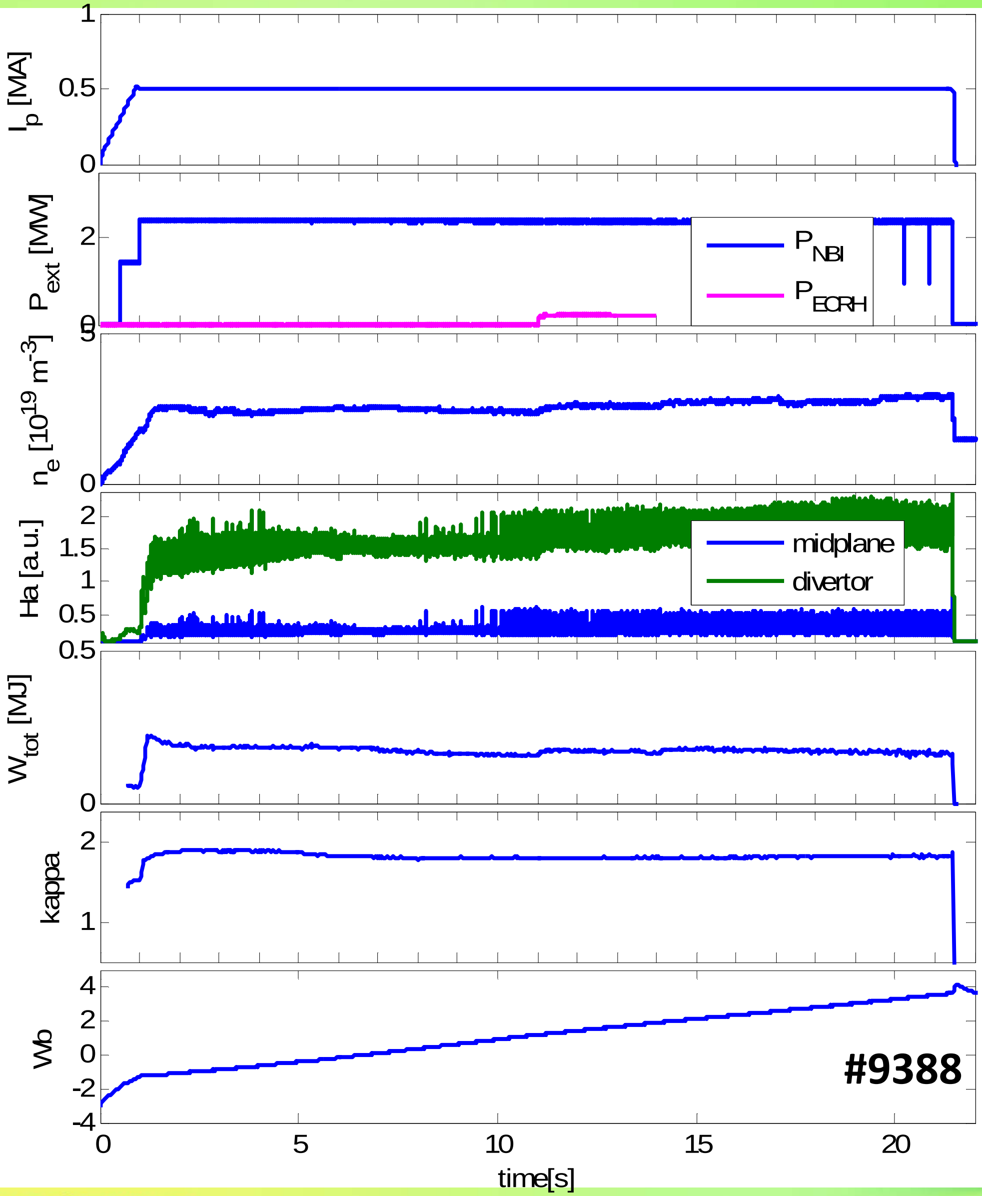
2015

- Commission

2016

- Application to the real-time feedback control of J(r)

20-sec H-mode flattop this year



- **Stationary line density with better shape (& X-point) control.**
- **Disrupted at 21.4 s NOT because of the flux limit BUT because of the grid electricity limit (MVA limit).**
- **The long-pulse experiments show KSTAR plasmas can sustain 1 MA for more than 50 sec with the current heating capability (~ 3 MW) and motor generator (2 GJ):**

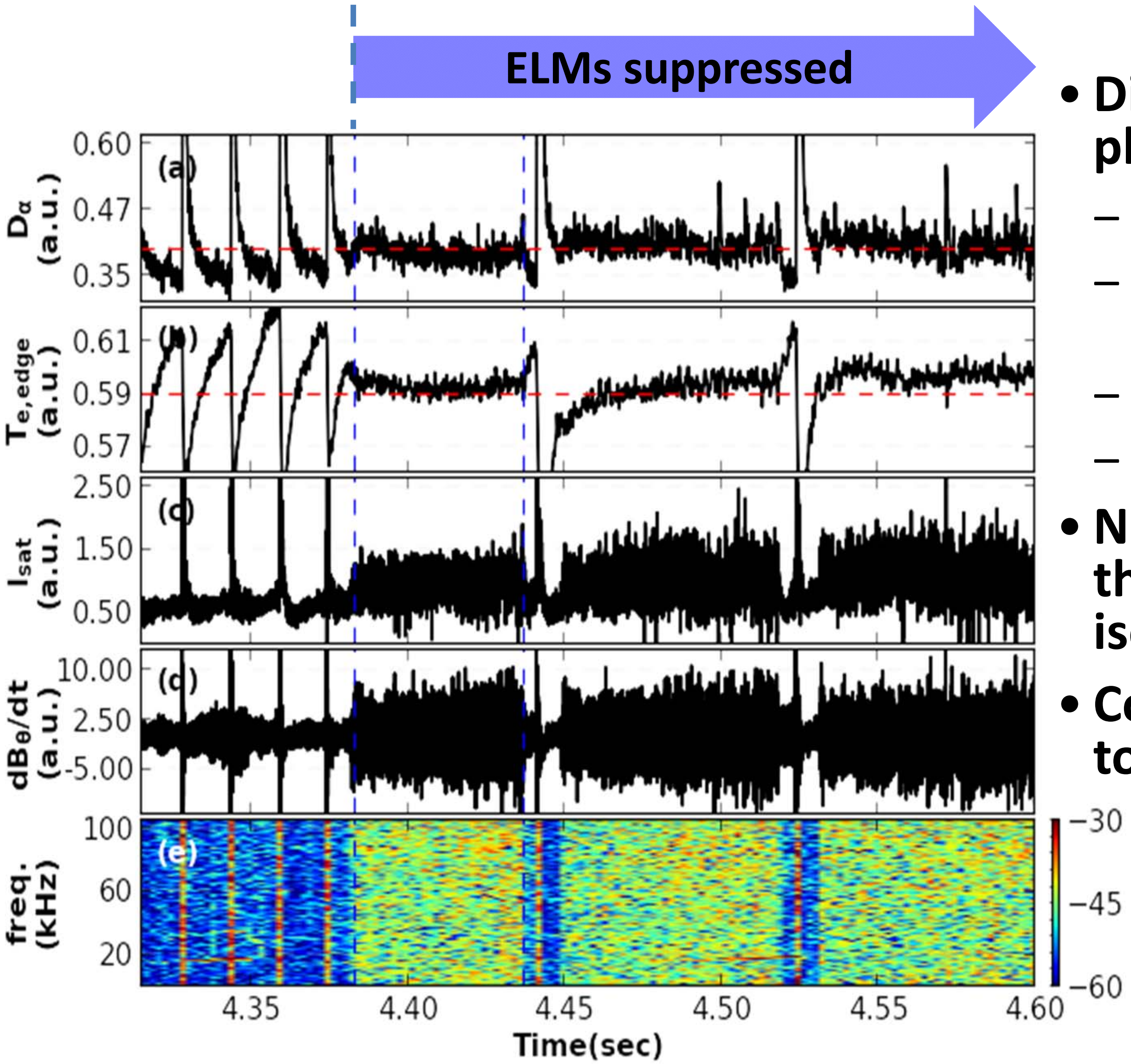
3.8 Wb (up to 1 MA ramp-up)

+ 0.1 Wb/s × 50 s

11.3 Wb < 12 Wb MG limit

- **Longer pulse will be available with better PF control logics, external CDs, and higher J_{BS}**

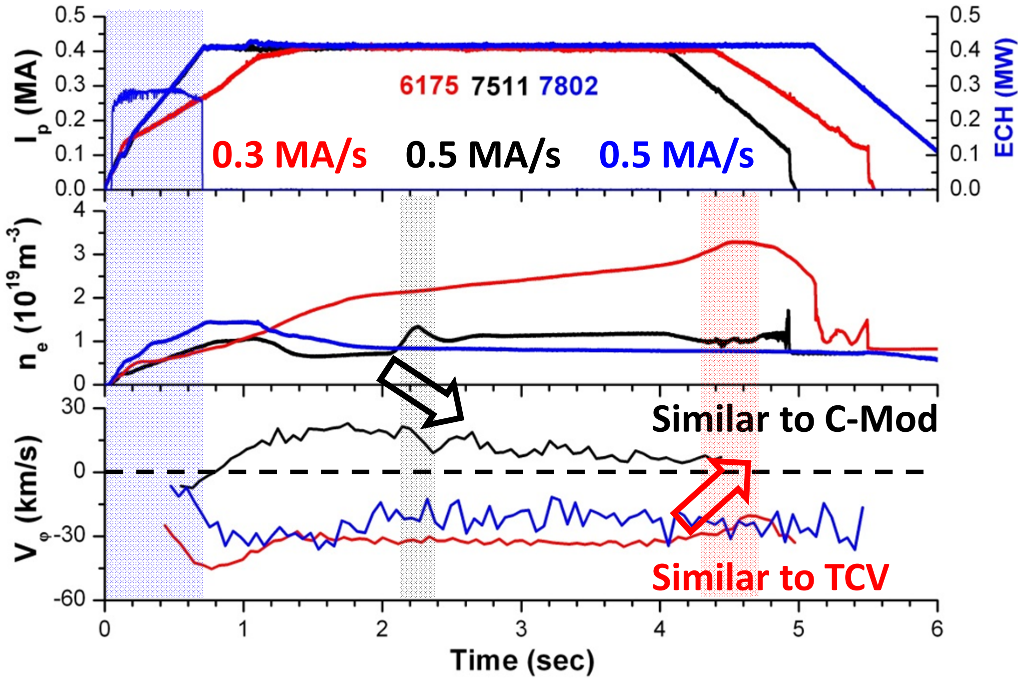
Persistent, rapidly bursting event in plasma edge plays a key role on ELM suppression

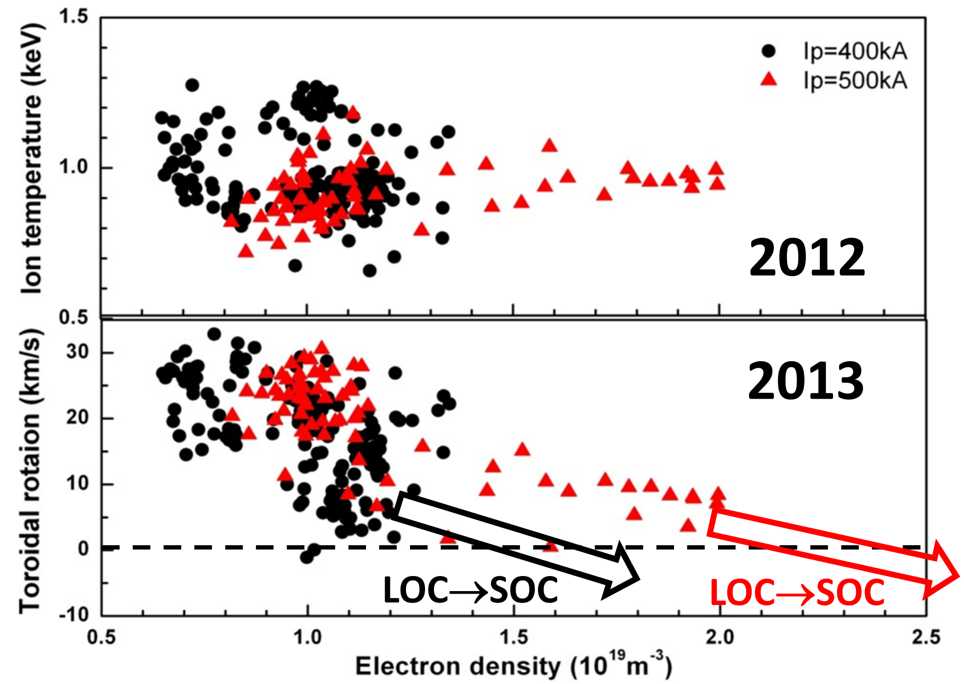


- **Distinctive fast time scale phenomena:**
  - **Rapid increase of Isat fluctuations**
  - **Rapid increase of broadband magnetic fluctuations**
  - **Increase in Dα base level**
  - **Saturated growth of Te,edge**
- **Notice that all these return back to the original condition just before isolated ELM crash.**
- **Could be a key physics mechanism to suppress ELMs under RMP fields.**

Y.M. Jeon et al, PRL 2013 (submitted)

KSTAR is a good test-bed for Ohmic rotation study with a reliable XICS diagnostic

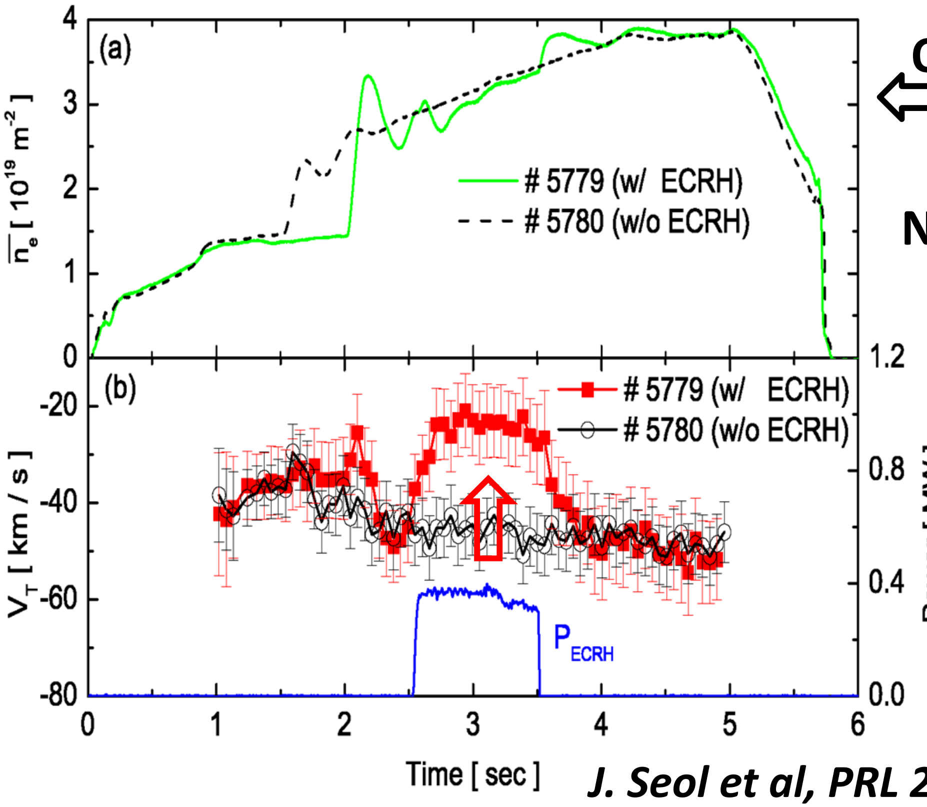




- Core rotation depends on ramp-up conditions.
- No MHD activities during the ramp-up

- No or weak ne dependence on rotation reversal (Rice 2011 → Rice 2012?)
- Weak dependence on LOC-SOC transition

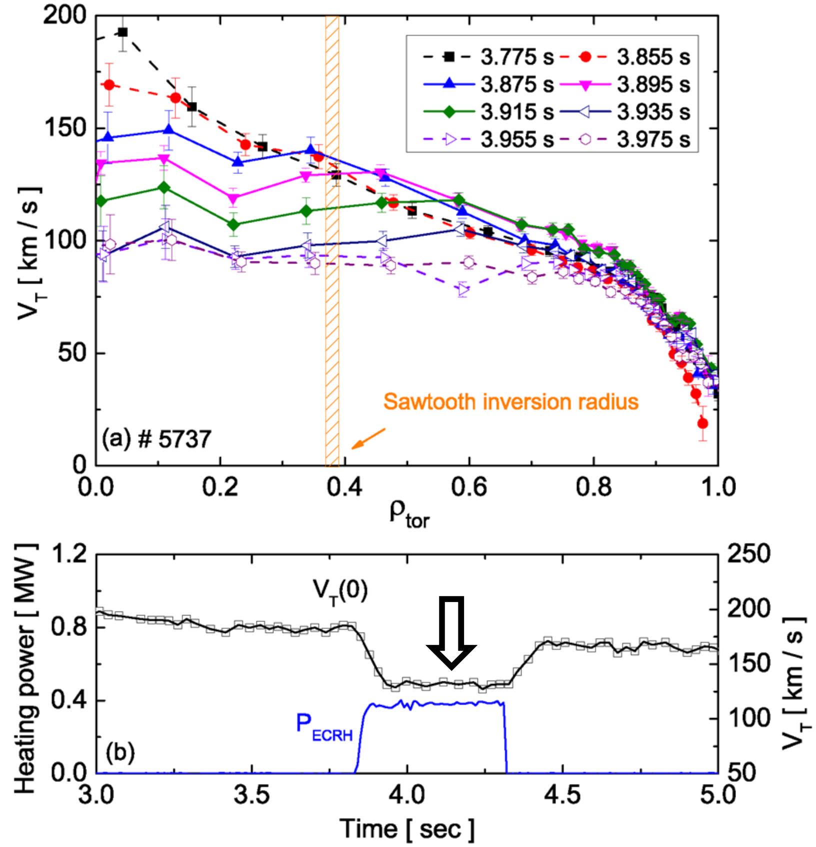
Rotation damping by on-axis ECH in Ohmic & NBI-heated plasmas



Ohmic

NBI-heated

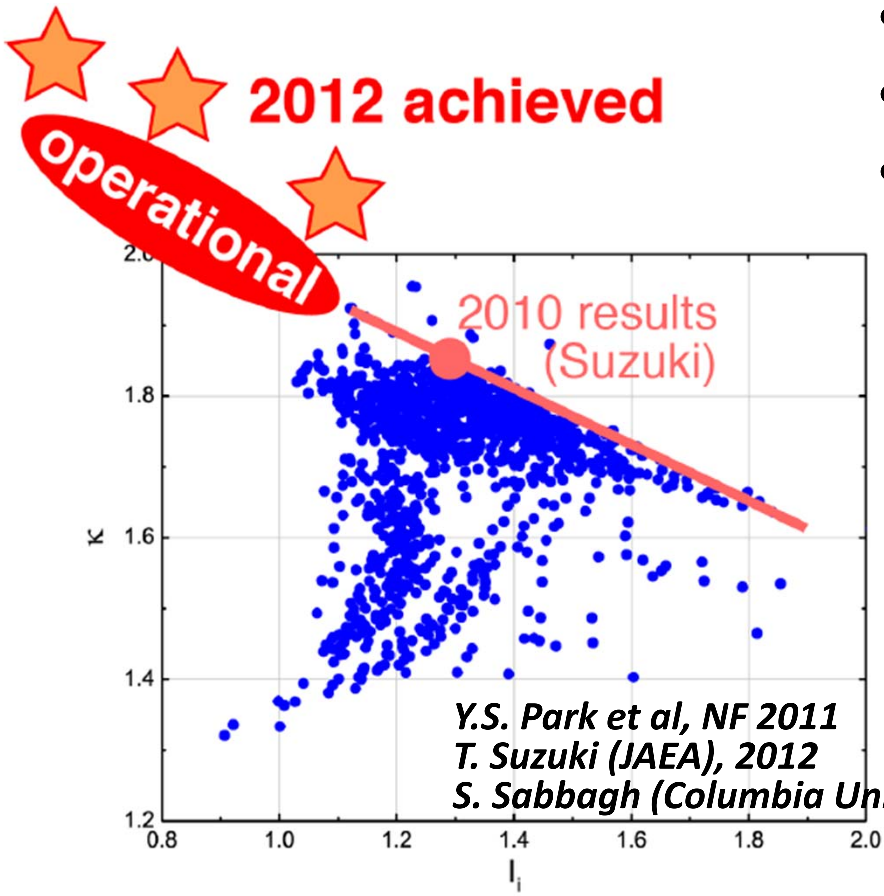
J. Seol et al, PRL 2012

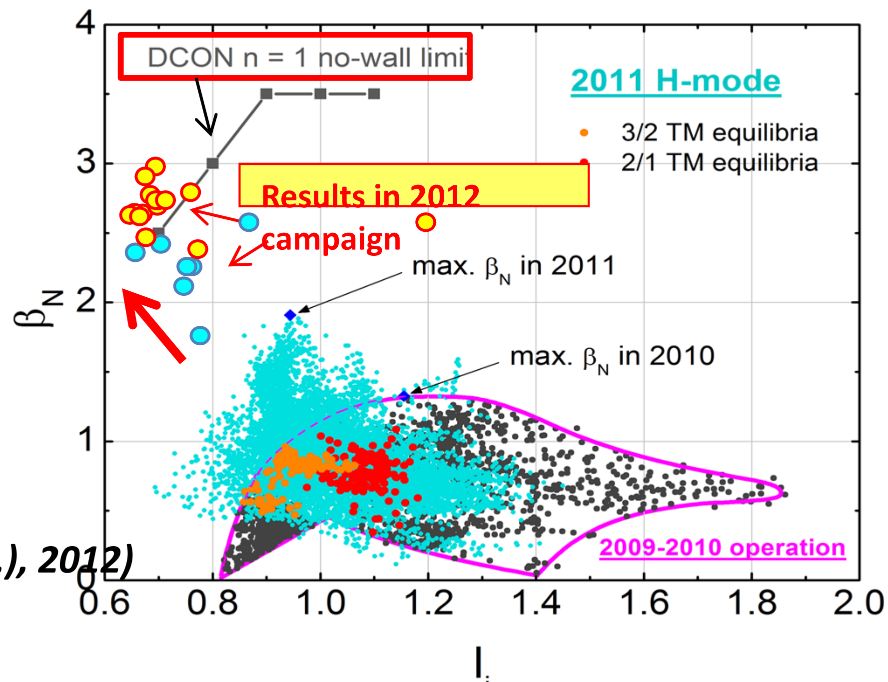


- **Rotation damping due to on-axis ECH observed in many tokamaks**
  - **Consistently observed in KSTAR (2011 – 2013)**
  - **Important to understand the damping mechanism for ITER operation**
- **Strong candidate for the cause: NTV torque caused by internal kink modes**

Better ramp-up scenarios extended operation windows

- **Exceeded no-wall MHD stability limit**
- **Optimized B_T & Ip: 1.3 – 1.5 T, 0.5 – 0.7 MA**
- **Max β_N/li ~ 4.1, β_N ~ 2.5, li ~ 0.7**



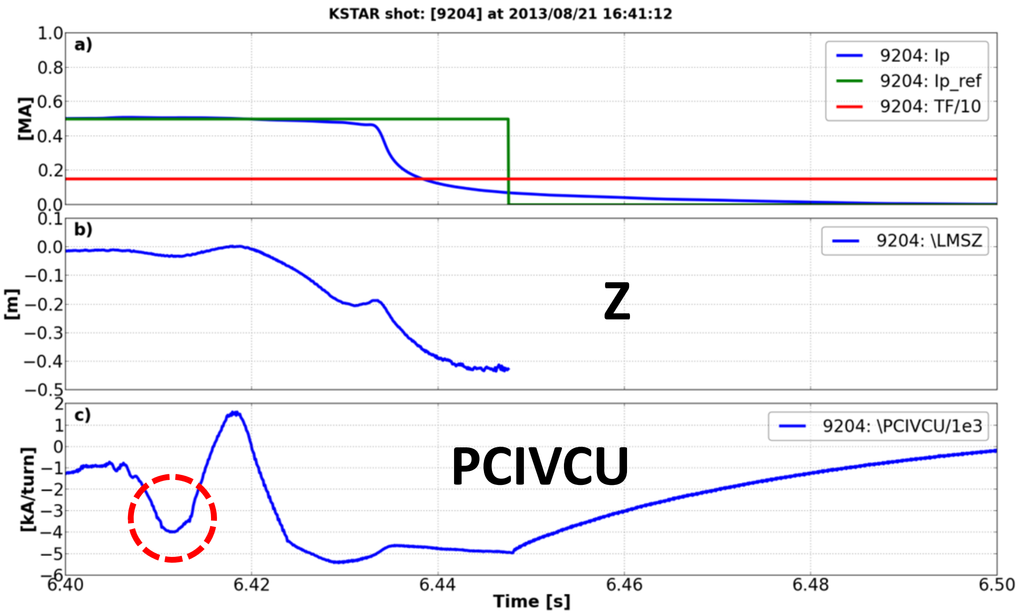


Y.S. Park et al, NF 2011
T. Suzuki (JAEA), 2012
S. Sabbagh (Columbia Univ.), 2012)

- **Operation regime largely extended to lower li and higher κ.**
- **Raised limit in κ at lower li enables higher Ip operations.**

Integrated disruption mitigation system (DMS) under development

- Detection from plasmas
  - n = 0 (axisymmetric) events such as VDE: Better Z estimator required ('PCIVCU' was used in 2013 instead).
  - n > 0 events such as MHD mode locking: Locked mode and saddle loop coils ('Ip fault' was used in 2013 instead).
- Detection from device
  - NBI & PFC faults: Delivered to PCS by Central Control System (CCS)
  - MVA fault (out of electricity): Directly issued by PCS



- Response
  - Slow (a few hundreds of msec): Asynchronous Ip ramp-down
  - Fast (a few tens of msec): MGI shutdown