Research Topics in 2011 ~ 2014 KSTAR Operation (Draft)

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On be half of the KSTAR Team

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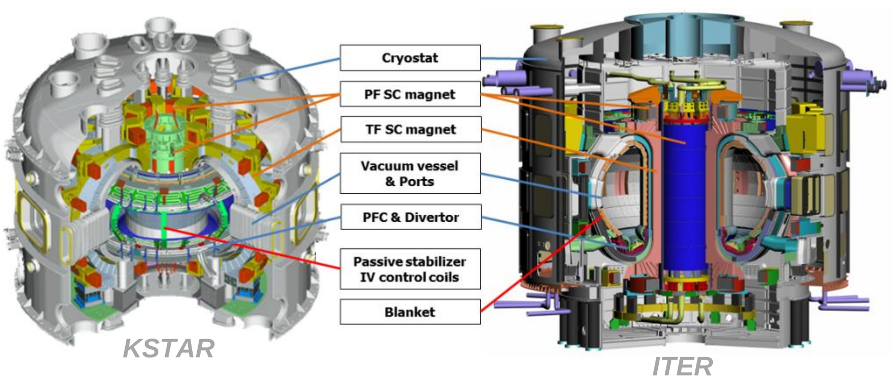
KSTAR project missions

❖ KSTAR Mission

- To achieve the superconducting tokamak construction and operation experiences, and
- To develop high performance steady-state operation physics and technologies that are essential for ITER and fusion reactor development



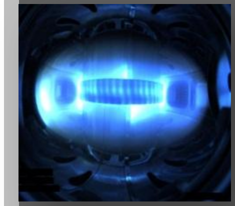
PARAMETERS	Designed	2010 goals
Major radius, R_0	1.8 m	1.8 m
Minor radius, a	0.5 m	0.5 m
Elongation, κ	2.0	2.0
Triangularity, δ	0.8	0.8
Plasma volume	17.8 m^3	17.8 m^3
Bootstrap Current, f_{bs}	> 0.7	-
PFC Materials	C, CFC (W)	C
Plasma shape	DN, SN	DN, *SN*
Plasma current, I_P	2.0 MA	0.5 MA
Toroidal field, B_0	3.5 T	3.5 T
Pulse length	300 s	5 s
β_N	5.0	1.0
Plasma fuel	H, D	D
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Auxiliary heating /CD	~ 28 MW	2.0 MW

Long-term KSTAR Operation Plan

Operation Phase I 2008 ~ 2012	Operation Phase II 2013 ~ 2017	Operation Phase III 2018 ~ 2022	Research for Commercialization
Operational Technology for Superconducting Tokamak	**Technology for Long-pulse operation**	**High performance AT operation Technology**	**DEMO Advanced Technology Test**
Achieve Target Operational Performance (D-type, H-mode, D-D plasma)	Role of Pilot prior to Completion of ITER	Role of a ITER Saterlite and Leading AT Operational Technology	Optimization of AT-mode Operation

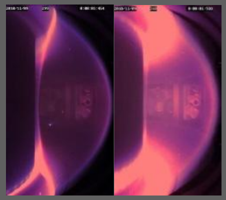
ITER 1st plasma ('19)

First Plasma ('08)



133kA
0.25sec
1.5Tesla

Divertor plasma ('10)



720kA
6.7sec
1 ~ 3.5Tesla

H-mode operation ('11)

Fast stabilization ('12)

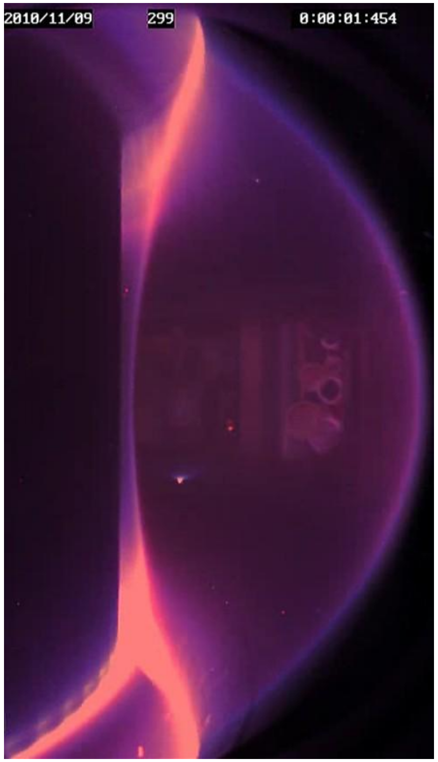
Five-year operation plan (in phase I&II)

Campaign	2009	2010	2011	2012	2013
Operation Time	'09. 8 ~'09.12	'10.6 ~'10. 11	'11. 4 ~'11. 9	'12. 3 ~'12. 8	'13. 3 ~'13. 8
Experimental goals	• Startup stabilization • ECH pre-ionization • ICRF wall conditioning	• Shape control • L-mode • MHD study • Wall conditioning	• H-mode physics • ELM controls • Pedestal study • Non-inductive heating	• H-mode physics • ITER shape • Particle controls • Plasma wall interaction	• Profile control • Current drive • Bootstrap fraction
Operation Parameters	• B_T : 2 ~ 3.5 T • I_p > 0.3 MA • t_p > 2 s • Te ~ 1 keV • Shape ~ Circular • Gas : D_2	• B_T : 2 ~ 3.5 T • I_p > 0.5 MA • t_p > 5 s • Ti ~ 1 keV • Shape ~DN (κ1.8, δ0.5) • Gas : D_2	• B_T : 2 ~ 3.5 T • I_p > 1 MA • t_p > 10 s • Ti ~ 3 keV • Shape ~ DN & SN • Gas : D_2	• B_T : 2 ~ 3.5 T • I_p > 1 MA • t_p ~ 20 s • Ti ~ 3 keV • Shape ~ DN & SN • Gas : D_2	• B_T : 2 ~ 3.5 T • I_p > 2 MA • t_p ~ 20 s • Ti ~ 5 keV • Shape ~ DN & SN • Gas : D_2
Magnetic Control	• TF : 35 kA [3.5 T] • PF : +/-4 kA (~2 Wb) • Grid : 50 MVA	• TF : 35 kA [3.5 T] • PF : +/-10 kA (~4 Wb) • IVCC : VS • Grid: 50 MVA	• TF : 35 kA [3.5 T] • PF : +/-15 kA (~6Wb) • IVCC : VS, RMP • Grid: 100 MVA	• TF : 35 kA [3.5 T] • PF : +/-15 kA (~6Wb) • IVCC : VS, RMP, IRC • Grid: 100 MVA	• TF : 35 kA [3.5 T] • PF : +/-20 kA (~8Wb) • IVCC : VS, RMP, IRC • Grid+MG: 200MVA
Vacuum Conditioning	• Inboard limiter + Boronization + ICRF DC	+ Divertor + Passive stabilizer + In-vessel coil + PFC baking	+ PFC baking (350 C) + Cryopump (LSN) + SMBI	+ Cryopump operation + PFC cooling + MGI	+ Cryopump operation
Heating & Current Drive	• ECH(110G): 0.2MW, 2s • ICRH: 0.3MW, 1s	• ECH(110G): 0.5MW • ICRH: 1MW • NBI: 1MW	• ECH(84/110G): 0.5MW • ECCD(170G): 1MW • ICRH : 1.5MW • NBI: 1.7MW	• ECH(84/110G): 0.5MW • ECCD(170G): 1MW • ICRH : 1.5MW • NBI : 5MW • LHCD : 0.3MW	• ECH(84/110G): 0.5MW • ECCD(170G): 1MW • ICRH : 1.5MW • NBI : 5MW • LHCD : 0.3MW
Diagnostics	+ XICS / Soft X-ray / Hard X-ray/ Resistive Bolometer / Probe / Reflectometer • e-beam	+ Thomson (5ch)/ ECEI / IRTV / Image Bolometer / CES / neutron / XICS-2 / Ellipsometry /	+ FIR / Div. bolometer / X-ray pinhole / Coherence imaging/ fast-ion / etc	+ MSE / MIR / BES / CX-NPA /etc	+ To be determined

The detailed parameters could be changed according to budget and situations.

2010 operation goals were achieved.

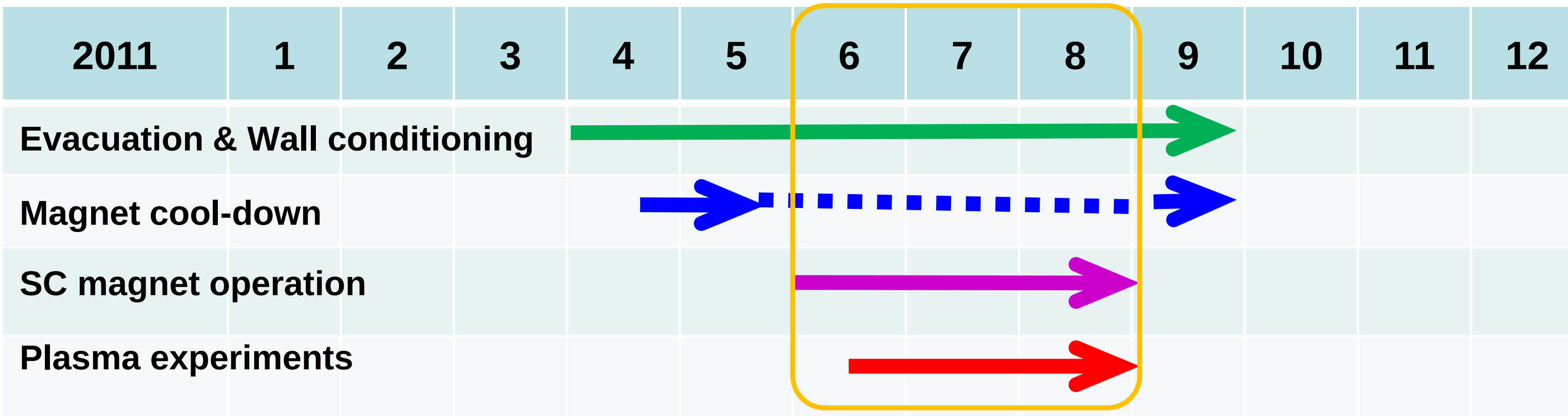
- **Reliable startup**
  - Compensation of magnetic error due to Incoloy material
  - Reliable Ohmic startup or ECH assisted startup
- **Vertical position stabilization**
  - Upper/lower PF coil separation & In-vertical control coil
  - Stable vertical position control using new z-estimator.
- **Plasma shaping control**
  - High elongation (kappa) up to 1.9 controlled by feed forward control
  - Double null(DN) and selectively single null(SN) operations
- **Plasma current ramp**
  - Max. plasma current up to 720 kA (#4340)
  - Max. pulse length up to 6.7 s (#4445) with 5.6 s NBI
- **H-mode**
  - H-mode was a goal of 2011 campaign
  - According to shaping control, NBI, and boronization



2011 operation goals

- **Attainment of the Plasma Performance :**
  - 1 MA, 10 sec operation
  - ISO flux control
  - Density feedback control
  - Reliable, reproducible H-mode
- **Perform H-mode/Pedestal studies**
  - Control pedestal current using ECCD/ICRH
  - ELM control by RMP
- **Set-up KSTAR-specific operation**
  - Ip reversal for counter NBI for rotation study
  - Evaluate the effects on SC during ramping up and soft landing
- **Perform Joint Research**
  - Domestic : KSTAR user community
  - International : KO-US, KO-JA , KO-CN, KO-EU, other parties on bi-lateral agreement

Schedule in 2011



- April : Evacuation start and leak detection
  Wall conditioning (baking the tile and vacuum vessel)
- April : Cryo-facility operation and magnet cool-down (300 K ~ 4.5 K)
  Discharge cleaning and diagnostic commissioning
- May : SC magnet and power supply operation
  (PF : +/- 15kA, IVC : 10 kA)/Magnetic diagnostics calibration
- June ~ July : Plasma experiments
  (Plasma shaping and heating)
  (Domestic and international joint experiments)
- August : Closing the experiments and magnet warm-up

Major research topics in 2011 ~ 2014

- **Long pulse H-mode experiments**
  - Long pulse Type I ELMy plasma (ITER scenario)
  - H-mode scaling(collisionality, Ti, Te)
  - ELM suppression / pedestal physics
  - Diverter physics(Shaping, Material)
  - NTM at high beta operation
- **3-D magnetic effect research**
  - RMP/NRMF experiments and analysis
  - intrinsic rotation
  - RWM/Locked mode
- **Disruption research (ITER relevant)**
  - Disruption mitigation
  - Run away electron
- ***Advance operation modes (long term)***
  - *RI / QH modes*
  - *high bootstrap mode*
  - *reverse shear / ITB*

These items are draft and not final official version.

Issues for the collaboration with PPPL

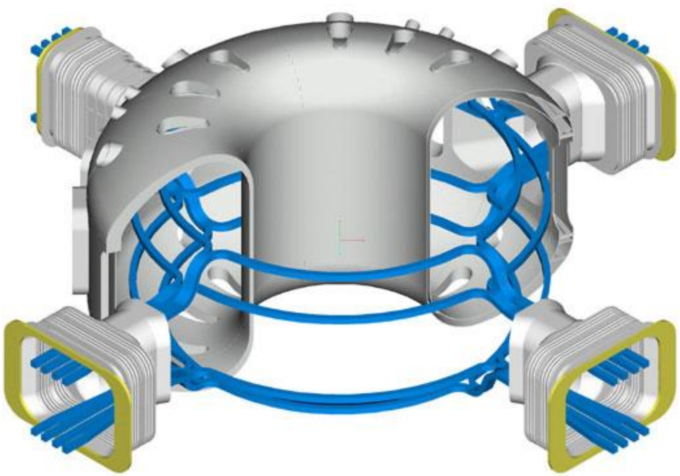
- **Participating in the KSTAR experiments**
  - on-site or remote participation on experiments
  - experimental proposals
- **Participating in the system development**
  - heating & current drive system development
  - control and data analysis system development
  - diagnostics
  - etc.
- **Experimental data access and analysis**
  - high speed data access
  - data analysis tools implementation
  - networking hardware upgrade and security issues to be solved
- **Human resource exchange**
  - on-site participation and co-experiments
  - training and lecture

These items are draft and not final official version.

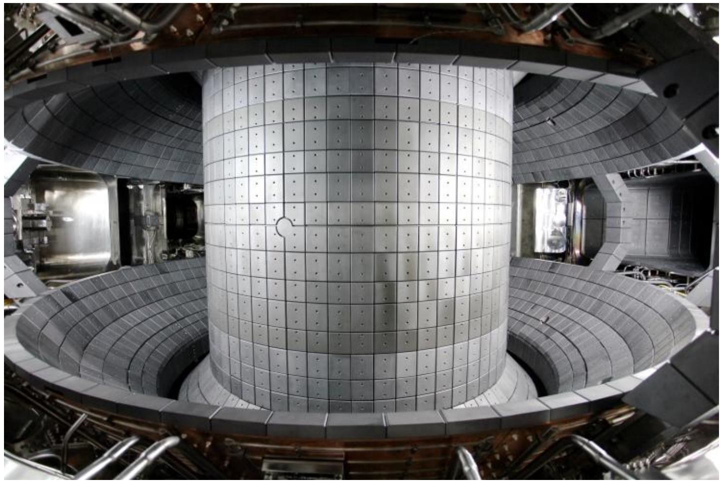
2010 experimental results

In-vessel components upgrade

- All in-vessel components have been installed and baking system for the components were implemented for the 2010 operation.
  - In-vessel control coils (IVCCs) were installed in 16 modules for multi-functional plasma control as IVC/IRC/RMP/FEC/RWM.
  - The in-vessel vertical controls (IVCs) were in operation in 2010.
  - Passive stabilizers made of copper alloy were installed after the design modification by eliminating current bridge between stabilizers.
  - Divertors were installed to have double null operation capability. In-vessel cryopump for the particle control was installed for the operation afterward.
  - All plasma facing components were covered with graphite tiles.



Schematic drawing of the In-vessel control coils



In-vessel components after assembly finish

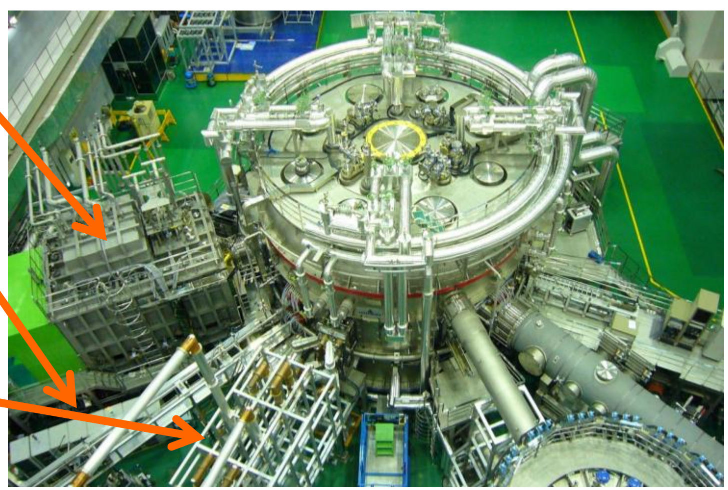
Heating system upgrade

- For the plasma heating and current drive, heating system has been upgraded including a newly fabricated NBI system.
  - The ECH system for startup and electron heating has been prepared for two frequency selective operation at 84 or 110 GHz. 110 GHz system was loaned from GA.
  - ICRF system had a frequency adjustment to 30 MHz for the H minority heating at 2 T. It is available for the RF discharge cleaning between shots.
  - First NBI system has been commissioned and operated up to 1.3 MW at 85 keV with one ion source. The NBI system was developed under collaboration with KAERI and JAEA.

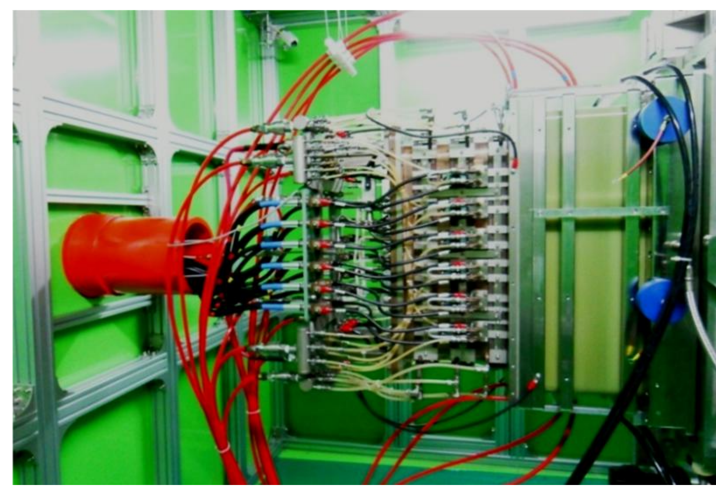
NBI-1 (85 keV)
1.3 MW, 5 s

ECH (84 / 110 GHz)
0.5 MW, 2 s

ICRH (30 ~ 60 MHz)
2 MW, 300 s



Heating systems available for 2010 operation

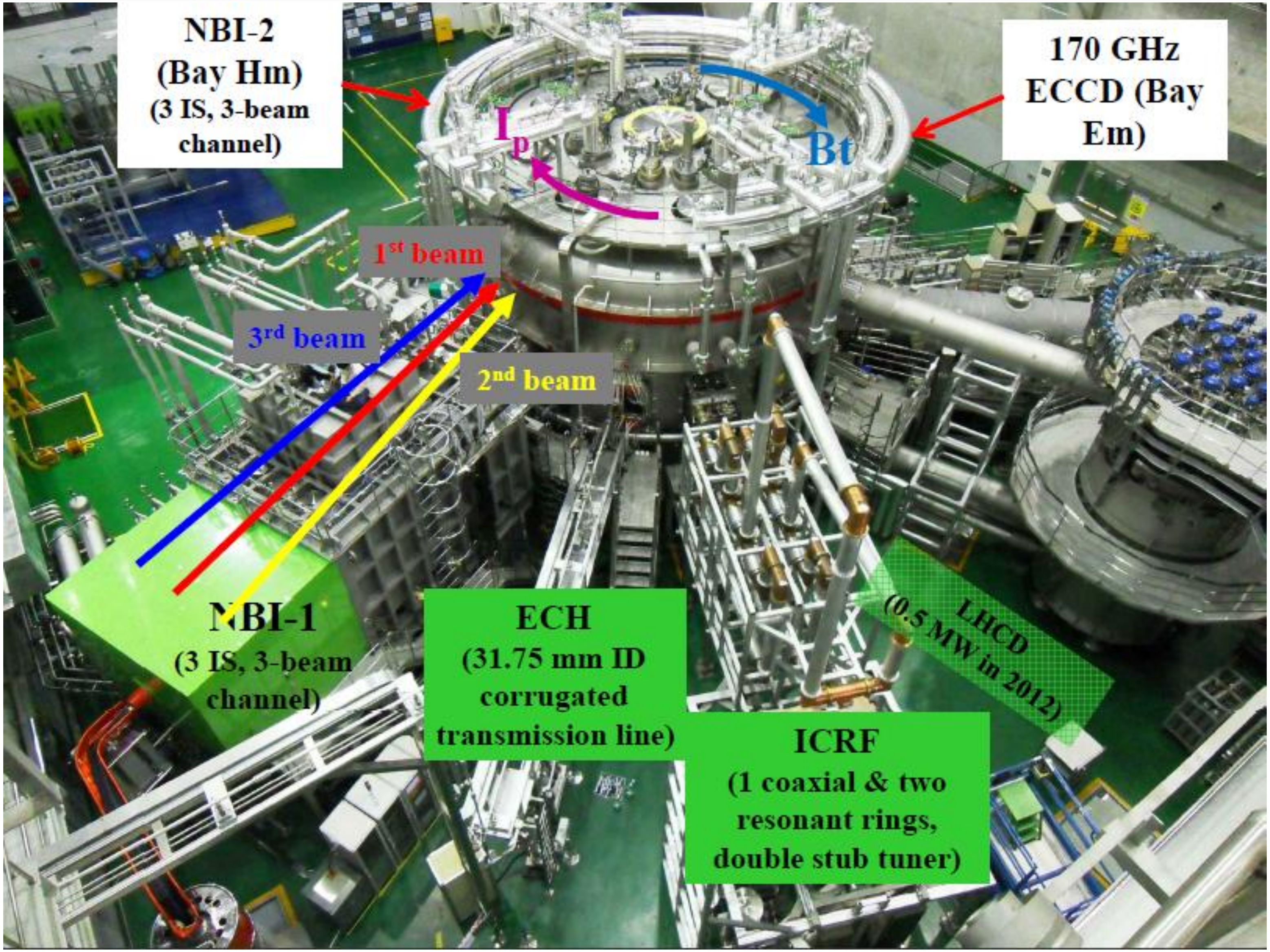


Positive ion source

Heating & current drive system plan

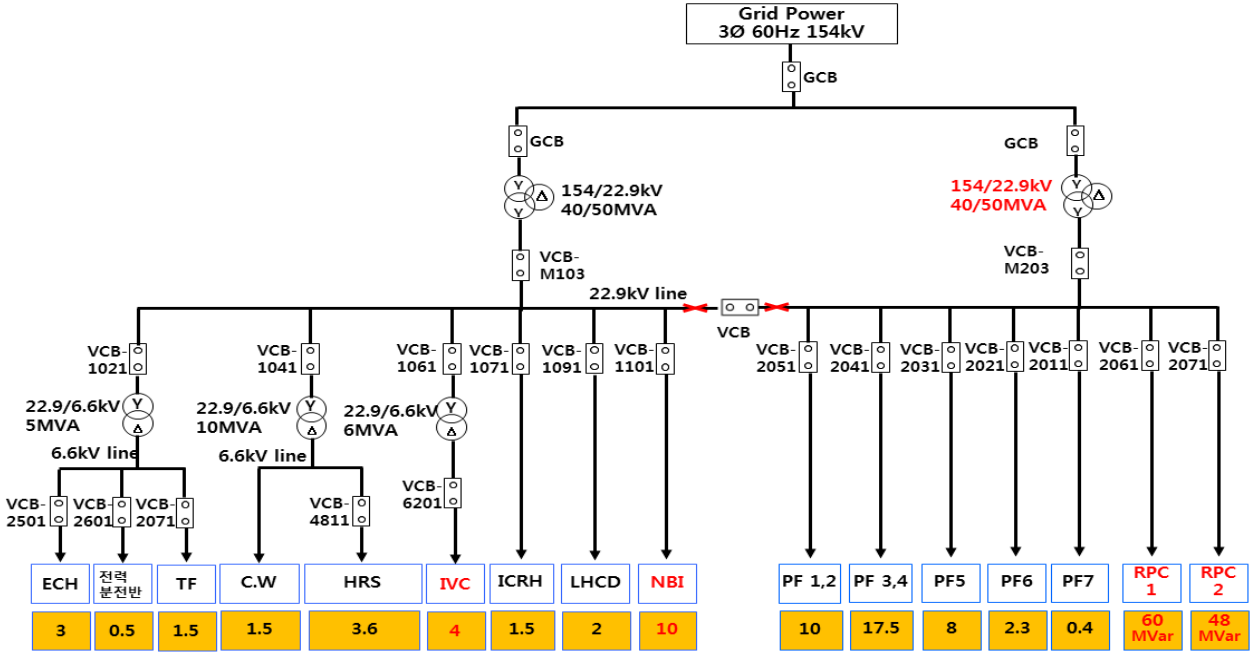
	Specification	Role	in 2010
NBI	14 MW, 300 s D0/H0 -Two beam lines -Three ion sources per each beam line -Positive based ion source at 120 keV	-Ion heating & CD -H-mode in initial phase	1 MW D0 - One beam lines - One ion source - Beam energy : max. 80 keV - Beam pulse : less than 2 s
ICRF	30 – 60 MHz, 8 MW(source), 300 s -Sources: Four 2MW transmitter	-Ion & electron heating in high density -On- and off-axis CD -Wall cleaning by RF discharge between shot	Frequency : 30 MHz Source power : < 1 MW Pulse : <5 s Use 2 straps in the antenna
LHCD	5 GHz, 2 MW(source), 300 s - 4 x 500 kW CW klystrons	-Electron heating -Off-axis CD for plasma current profile control -RS-mode	-
ECH/CD	84/110 GHz, 0.5 MW(source), 2 s -84 GHz, 0.5 MW gyrotron 170 GHz, 3 MW(source), 300 s - 3 x 1 MW CW gyrotrons	• 84 (or 110) GHz ECH Startup system -Assisted startup using pre-ionization •170 GHz ECCD system -2nd harmonic heating & CD -NTM stabilization leading to high beta -Sawteeth mode control (heating around q=1 surface)	ECH-assisted start up with 110 (and 84) GHz, 0.5 MW (5 s) Gyrotron

Heating & CD systems layout

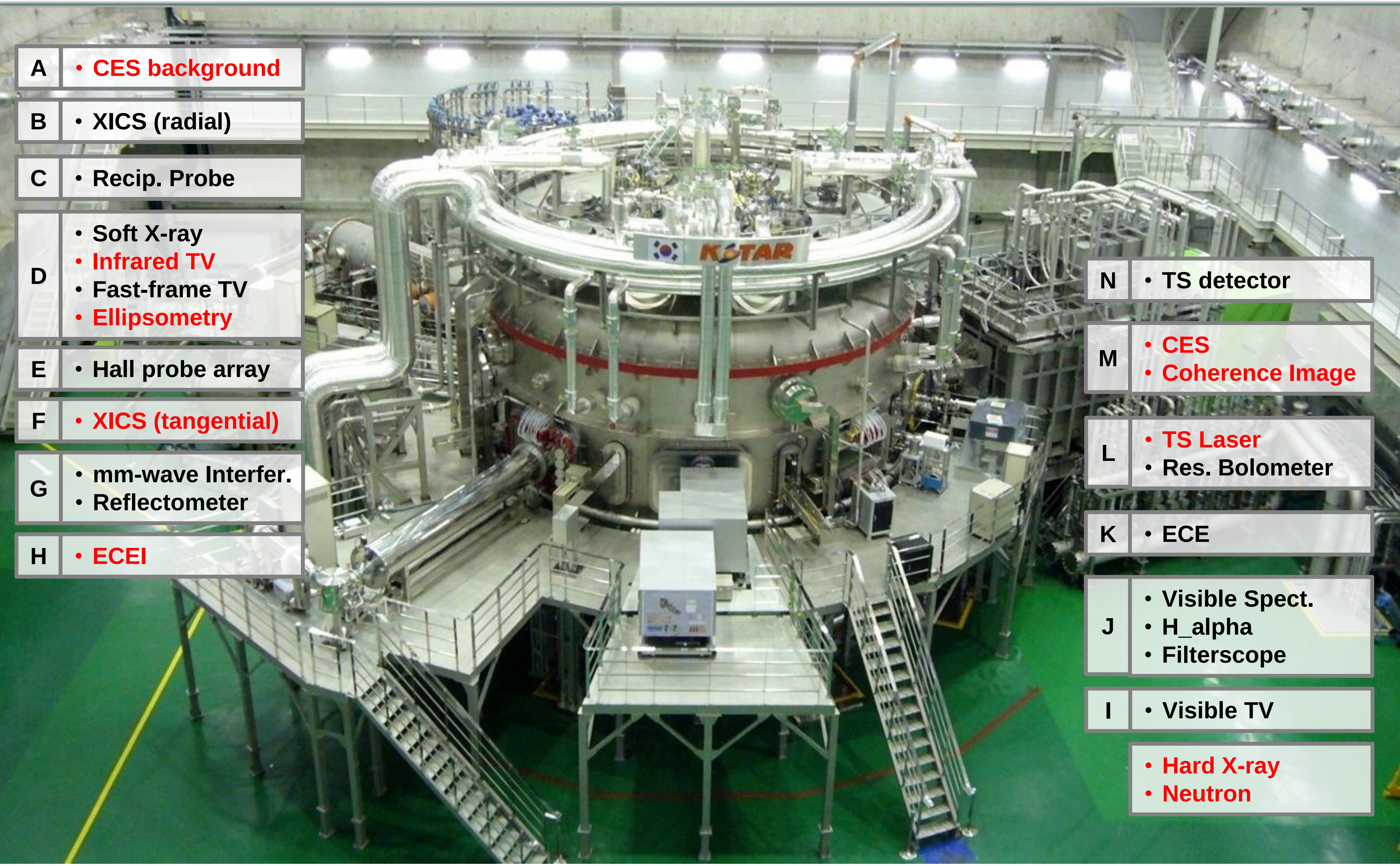


Magnet power supply system upgrade

- Magnet power supplies were upgraded to get the higher flux and faster controllability.
  - Separate power supplies were prepared for the upper and lower PF coils (PF3,4,5,6) to supply asymmetric coil current in PF coils.
  - Reactive power compensator for the operation of PF coils was installed and commissioned with capacity of 108 Mvar.
  - IVC power supply prepared (10 kA, 1 kV) with 4 kHz control frequency.



Diagnostic system upgrade



Joint experiments : Most of the experimental proposals were implemented (49 out of 55).

- **Experimental proposals are classified into 6 Tasks**
  - Plasma commissioning (7/7) : Shaping, Ip, Position
  - Diagnostics (7/9) : Ti, Te, Rotation, ECEi, (FIDA, Fast CCD)
  - Heating and current drive (7/10) : NBI 1.3 MW, ICRH~500 kW, ECH (110 GHz)350 kW (2 ICRH Heating, NBI Start-up)
  - Plasma wall interaction (6/7) : Boronization, He GDC, ECWC, (ICWC)
  - MHD (15/15) : Sawtooth, RE, TAE, LM, ETC
  - Transport and confinement (7/7) : H-mode / Slide away/ RE

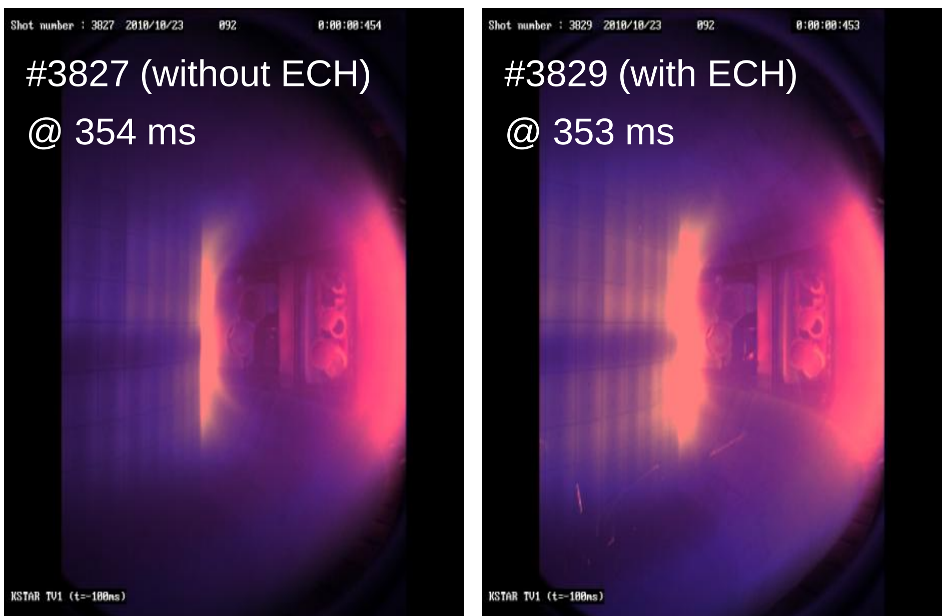
- **41 proposals from domestic collaborators**
  - NFRI (19/21) * KAERI (7/11)
  - POSTECH (6/6) SNU (2/2)
  - Sungsil U. (1)

  ** It includes the proposals from the int'l post-doc at NFRI*

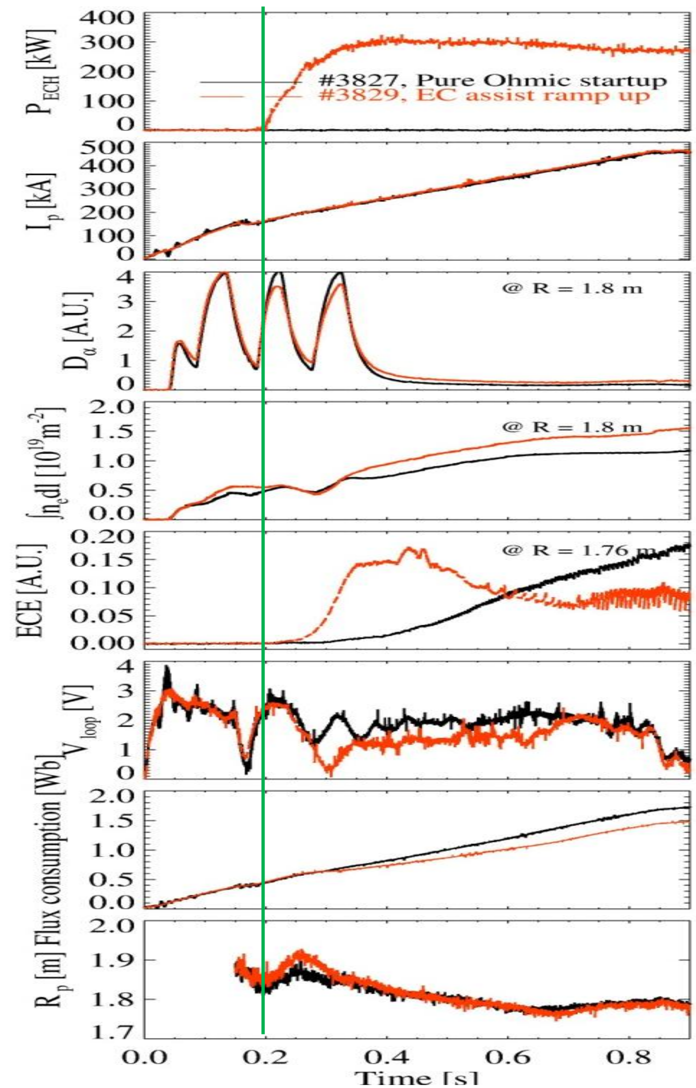
- **14 proposals from international collaborators**
  - GA (6) PPPL (2)
  - ANU (2) JAEA (2)
  - ORNL (1) Far-Tech (1)

Reliable startup : Reliable Ohmic breakdown with ECH-assisted ramp up could be achieved.

- Reliable Ohmic breakdown and current ramp up could be achieved.
  - Pure ohmic ramp up without ECH (#3827)
  - ECH assisted ramp up (#3829)
  - Reduction of flux consumption = 0.23 Wb (14 %)
  - Startup was reliable for the TF field of 1 ~ 3.5 T.



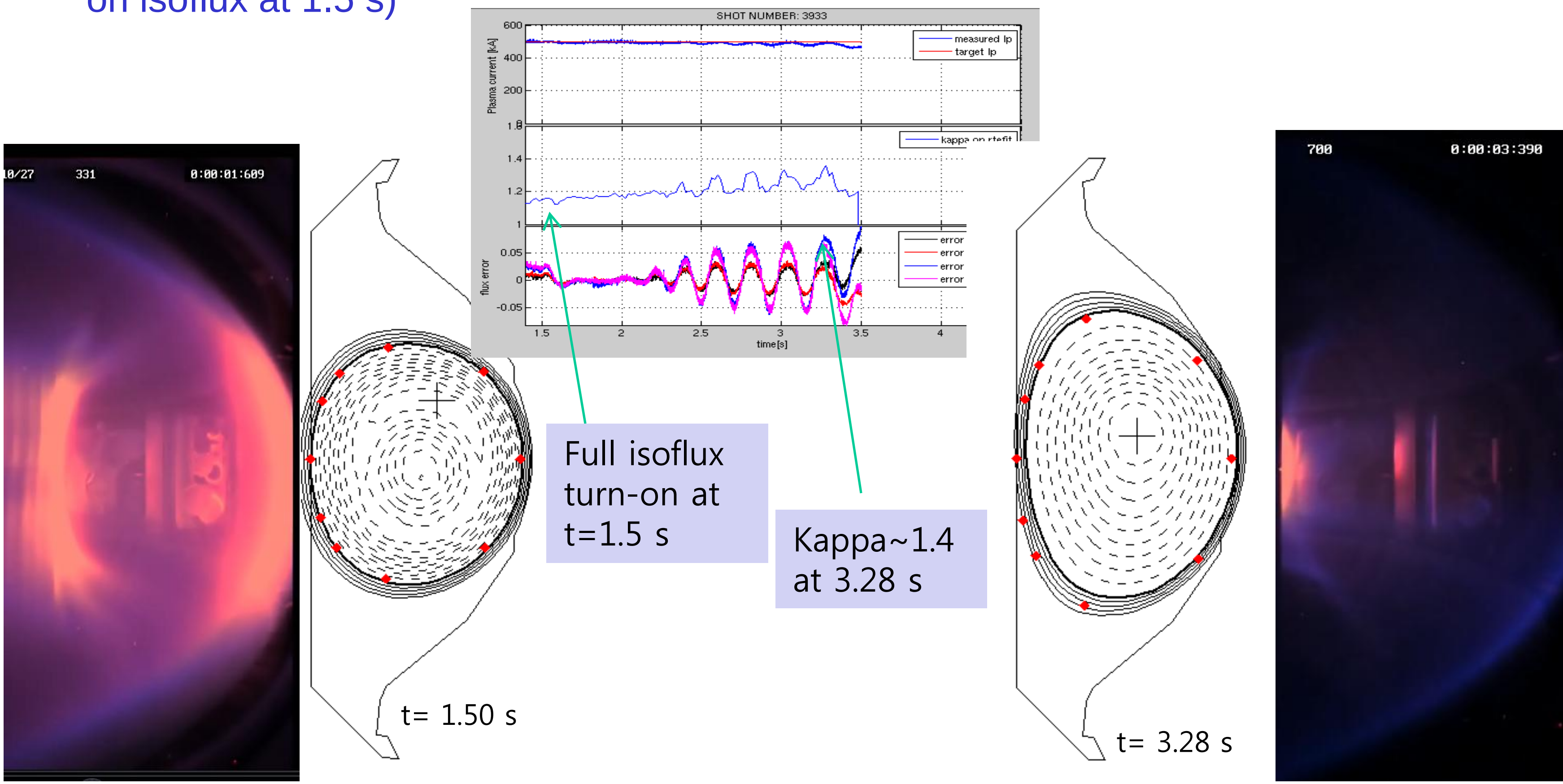
Plasma images during current ramp w/ and w/o ECH



Plasma parameters at ohmic startup

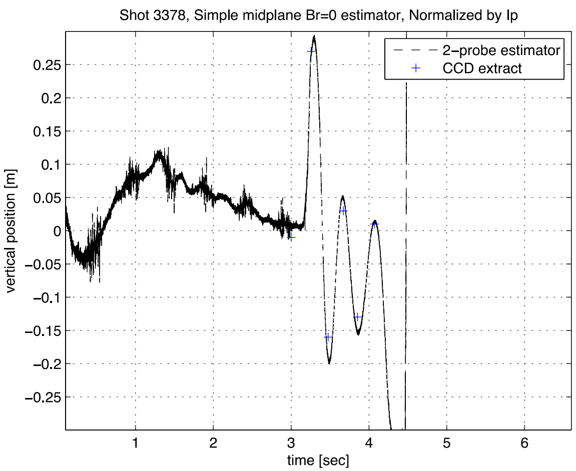
Plasma commissioning : First attempts on 2D isoflux shape feedback control

- Attempts to maintain kappa with isoflux were successful under Ip ~ 500 kA
  - The outboard coils (PF6/7) were used to keep the plasma position at the center
  - PF5U/L was used to pull the plasma according to the last closed flux points
  - Plasma's sustained until the CS reached to system limits (~2.4 seconds after turning on isoflux at 1.5 s)

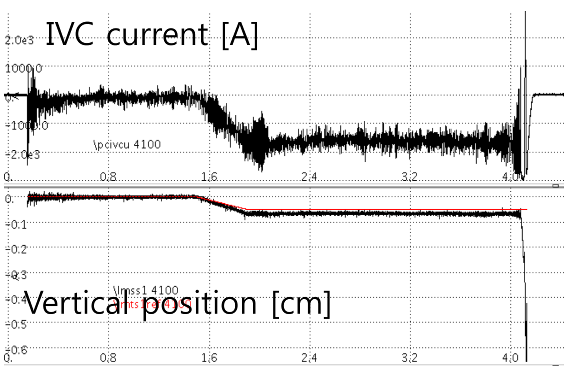


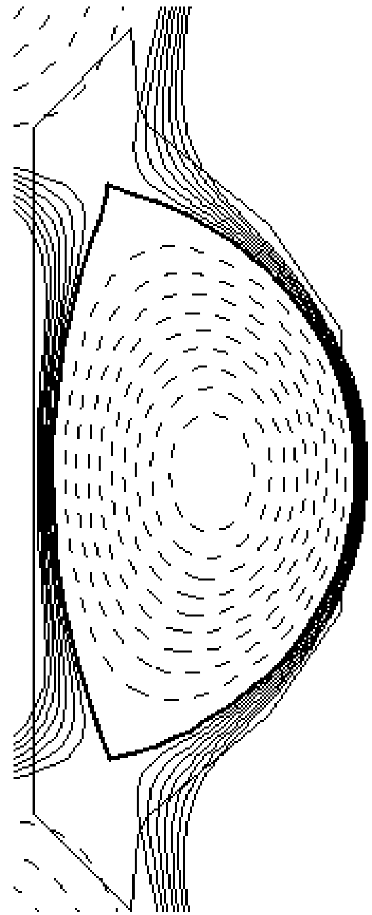
Stable diverted plasma was achieved with vertical stabilization feedback.

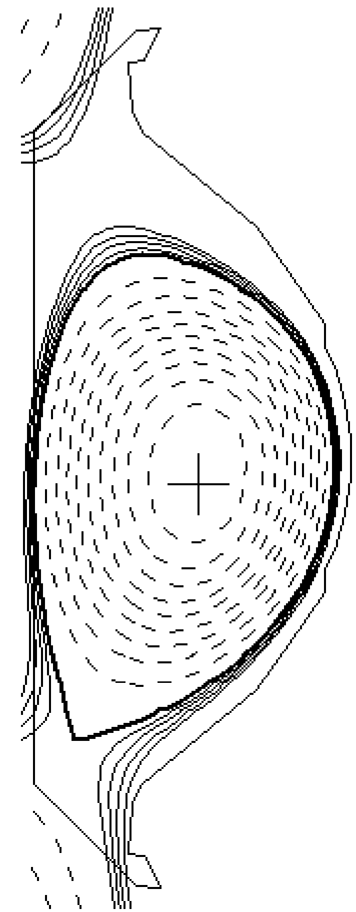
A fast Z estimator was verified up to +-15 cm with TV image estimates (denoted as +)



IVC is capable to maintain vertical bias ~ -7 cm by itself [#4100]





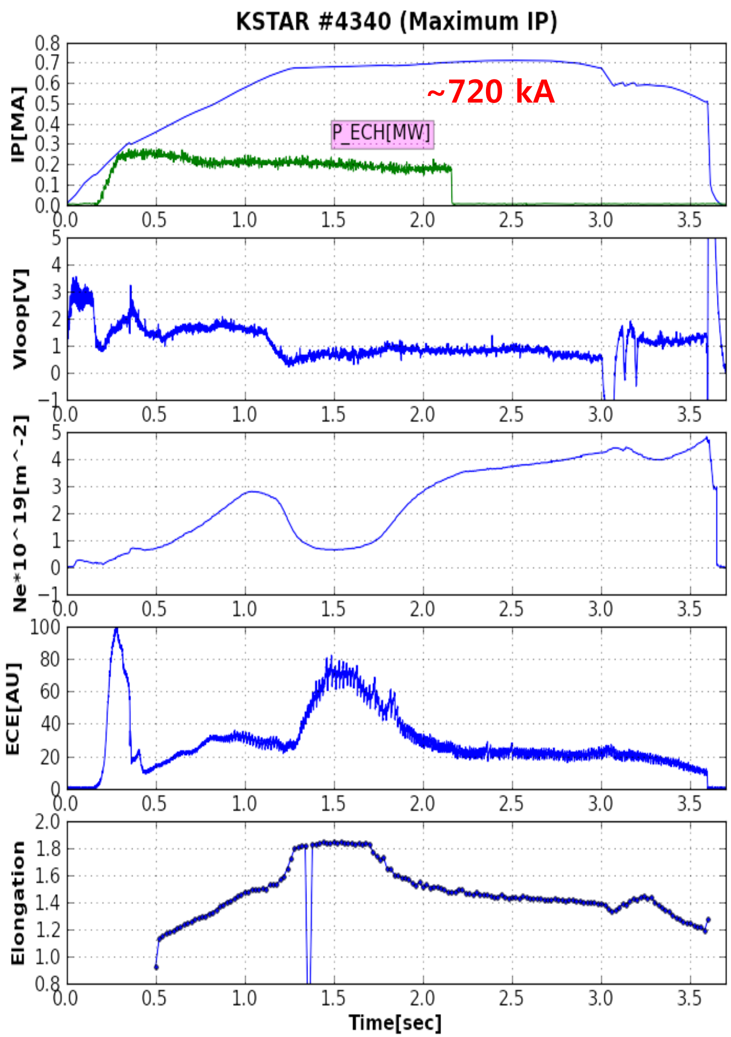


#3791 : Double null divertor (DND) shaped plasma with highest elongation (k~1.9)

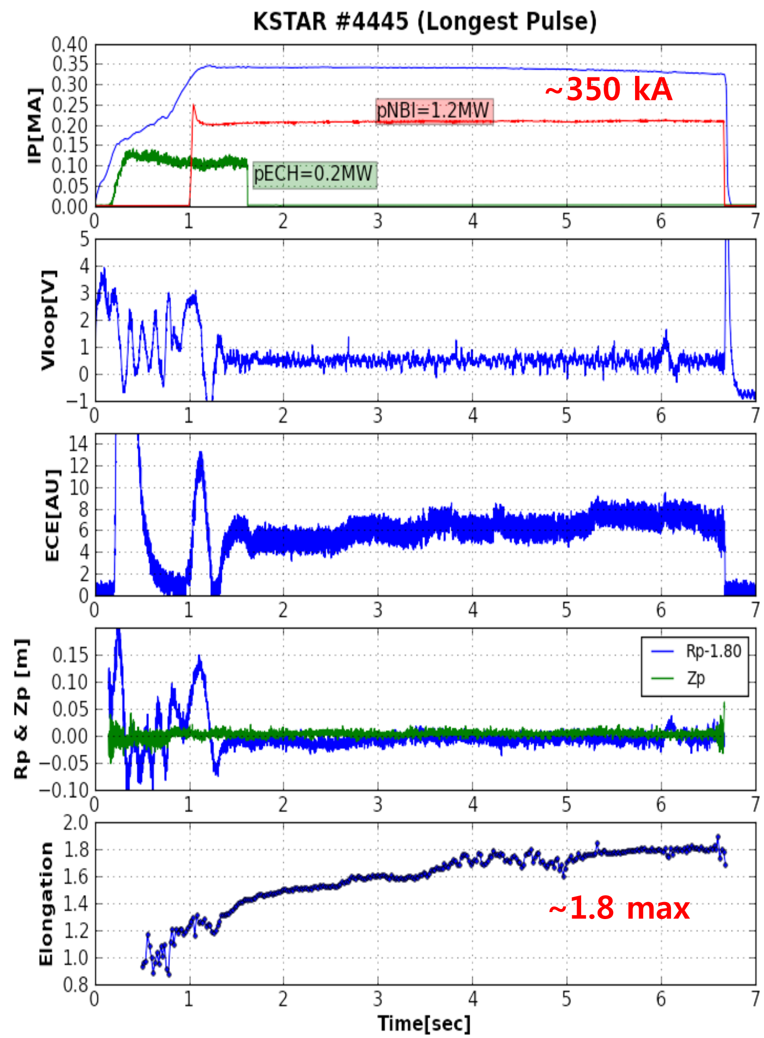
#4100 : Lower single null (LSN) shaped plasma with vertical bias ~ -7 cm at 3.0 s

Plasma current ramp : Current level over 500 kA and pulse length over 5 s were achieved.

Highest plasma current : 720 kA (#4340)

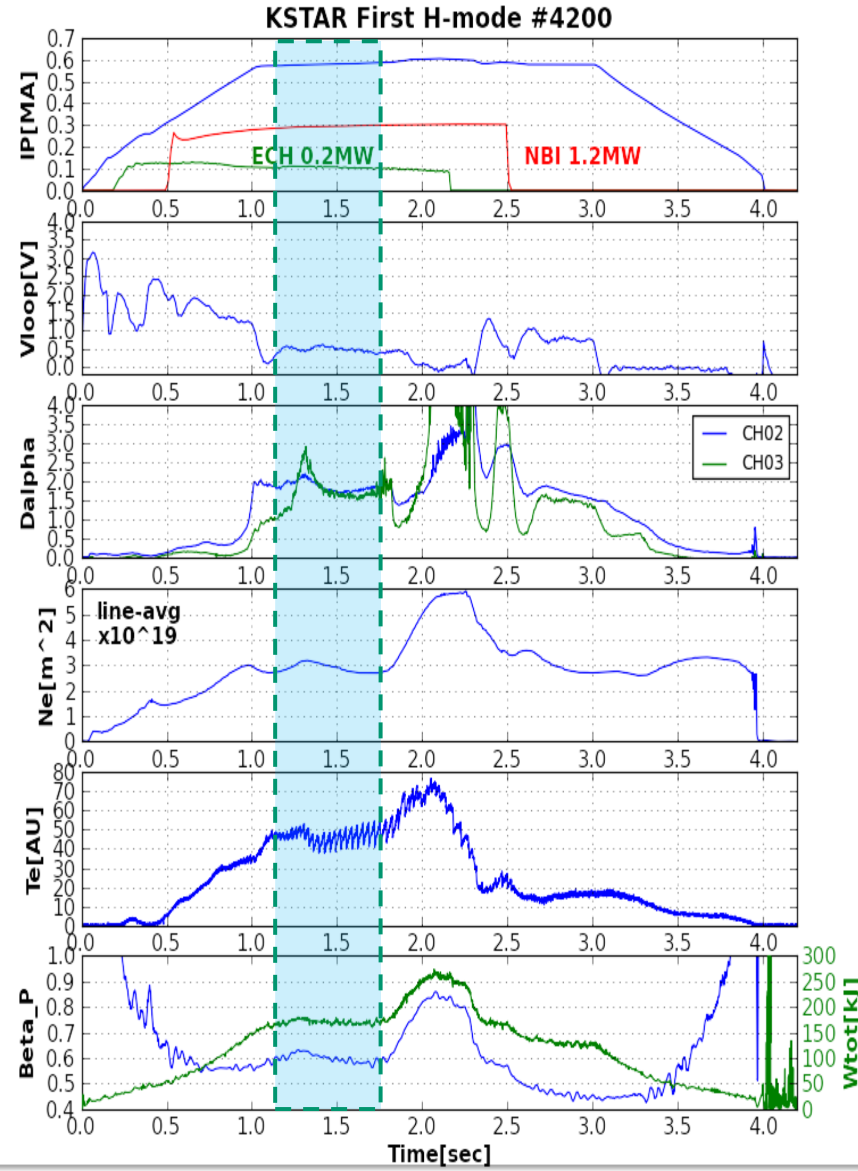


Longest pulse : 6.7 s (#4445) NBI heating for 5.6 s



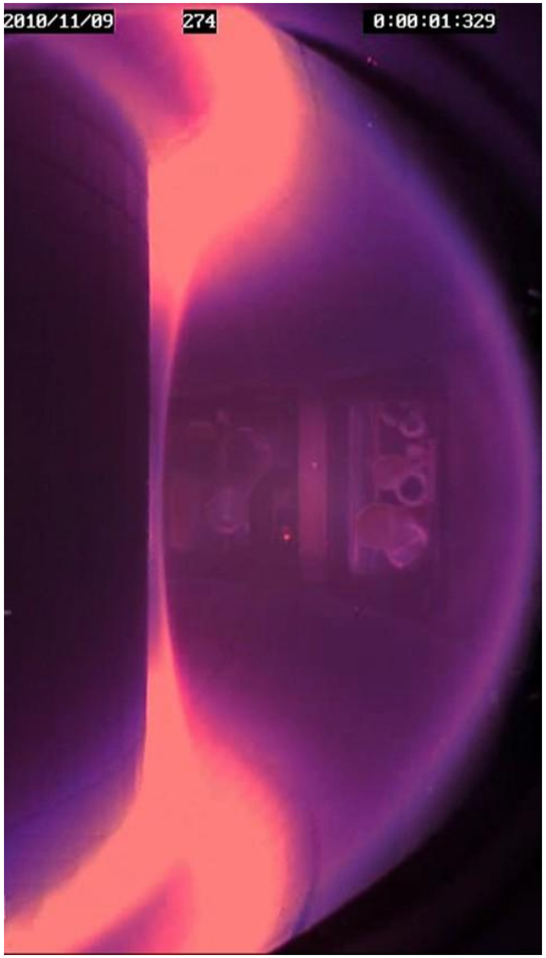
H-mode achievement : First ELMy H-mode in KSTAR

- First ELMy H-mode obtained with
  - Boronization with carborane
  - 1.2MW NBI (80keV, co-)
  - 0.2MW ECRH (counter Ip)
  - 0.2MW Ohmic
  - P_{th} ~1.1MW (ITER Physics Basis,1999)
- on the condition
  - Ip~0.6MA, Rp~1.8m, a~0.5m
  - <ne>~1.5x1019m-3
  - B_T~2.0T
  - double null (κ =1.8)
- Improvement is
  - <ne> by a factor of 2.0
  - β_p by a factor of 1.5
  - W_{tot} by a factor of 1.3

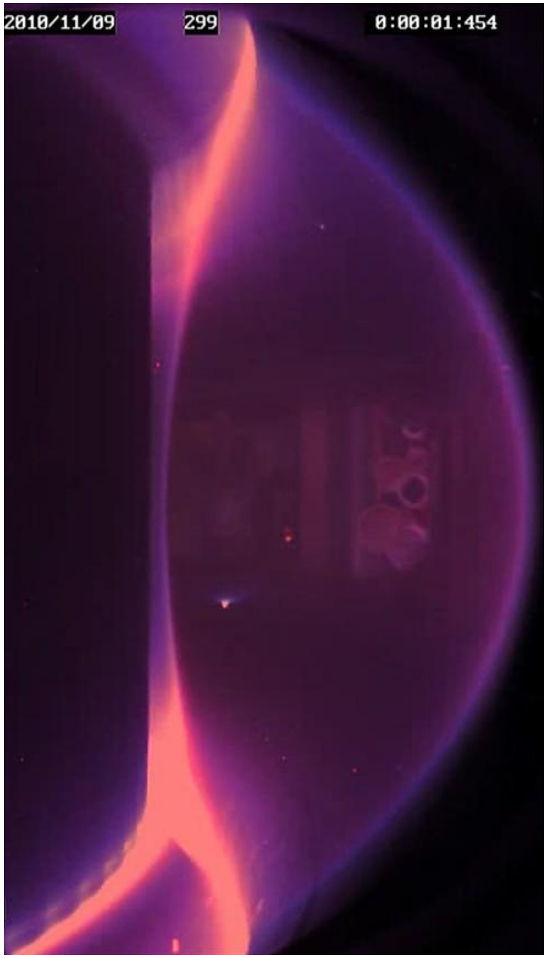


H-mode achievement : Fast framing camera images show clear L/H transition.

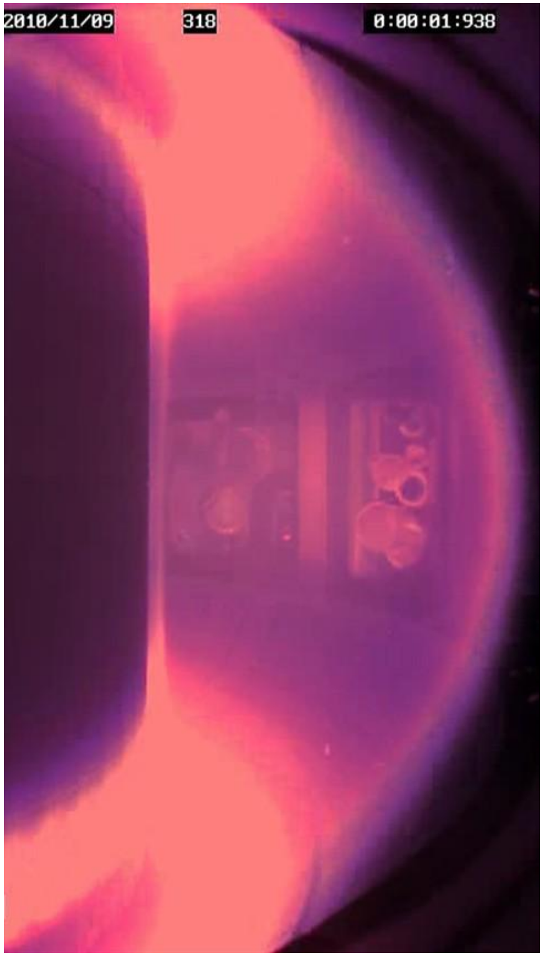
KSTAR #4232



D-shape diverted plasma
(L-mode)



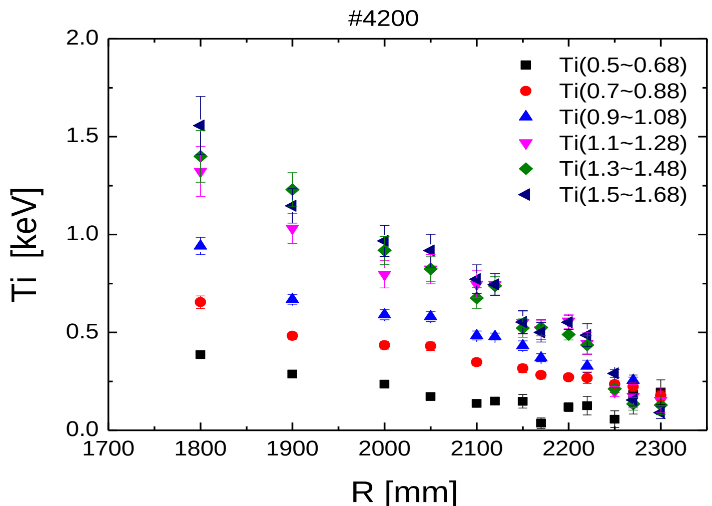
When Hα rapidly decreased
Boundary sharpening observed

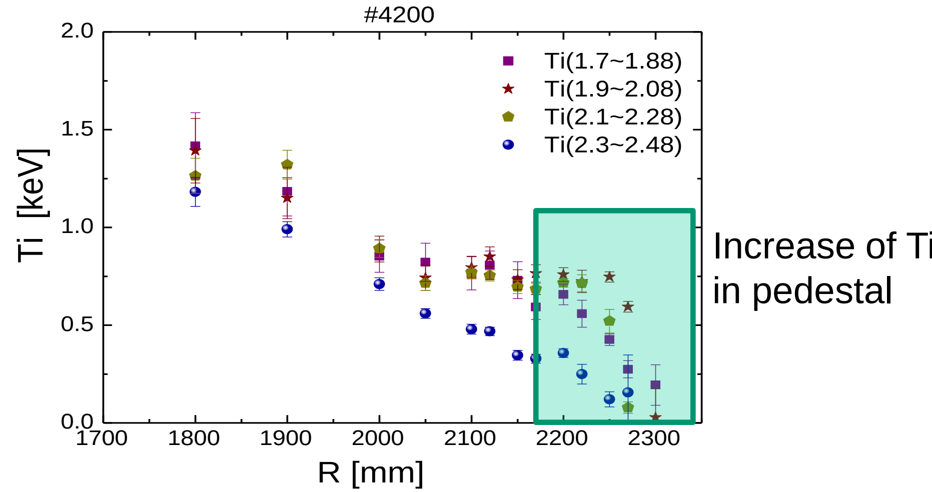


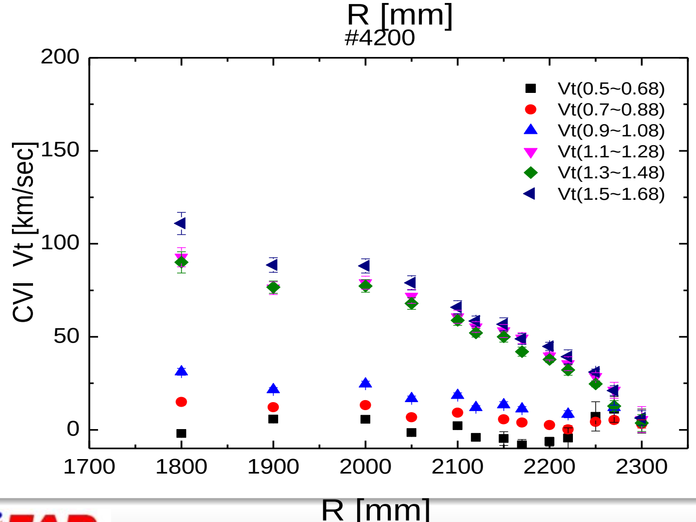
ELMy Bursts
(H-mode)

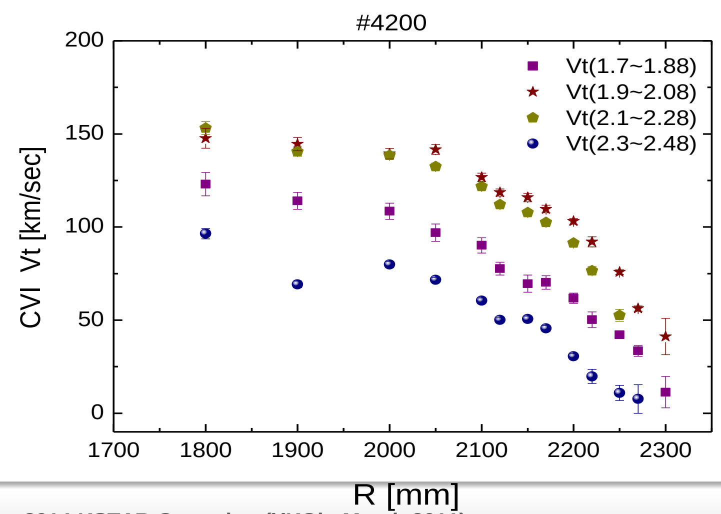
Diagnostics : Ion temperature and toroidal rotation measurement using CES

- Ti and Vt measurement for the H-mode shots (#4200)
  - Temperature profile changed after 1.7 s mainly at R=2~2.2 m (transport region).

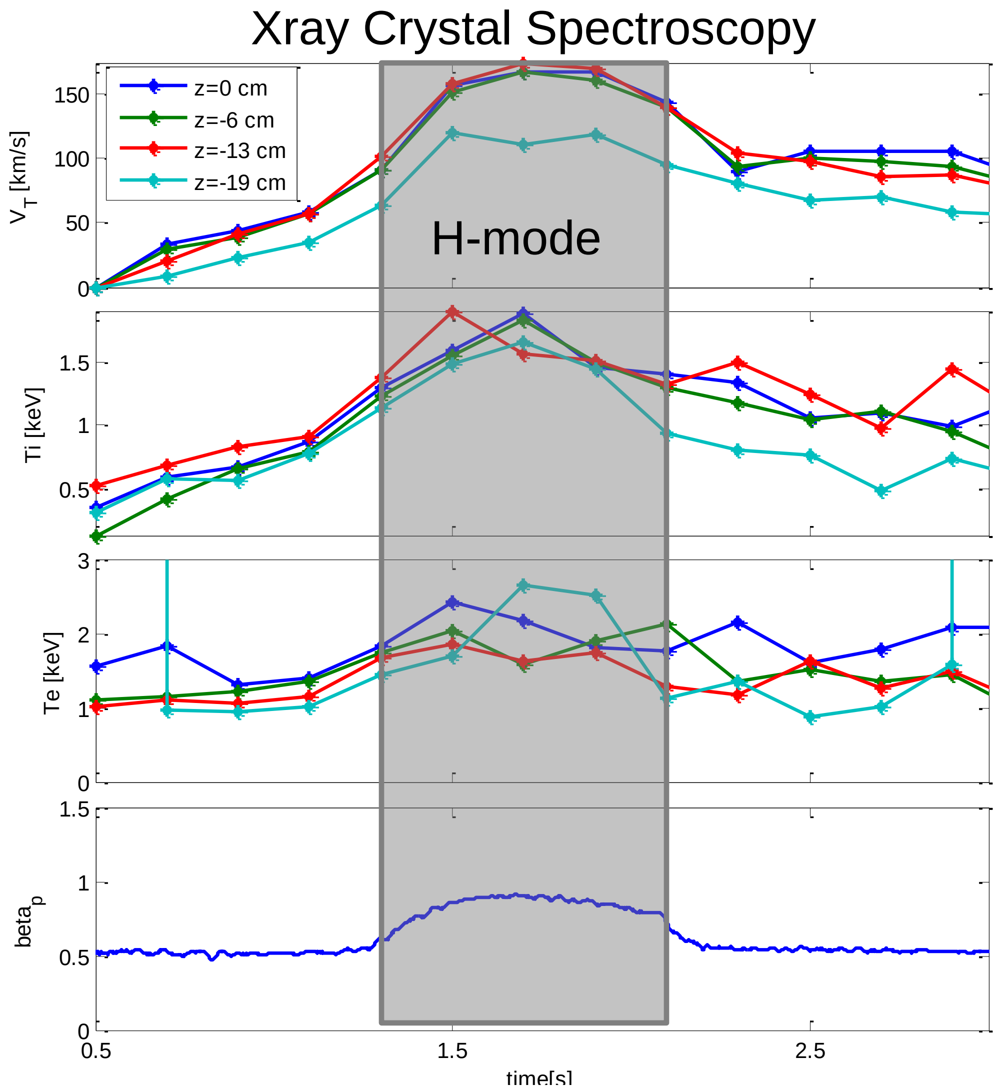








Transport : Te, Ti & V_T were increased clearly at L→ H transition



Discharge #4333

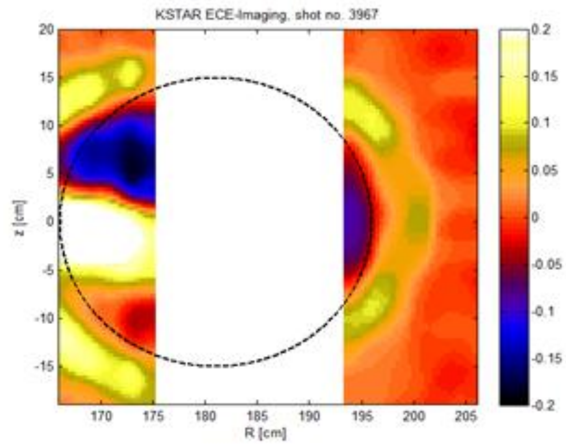
Vertical profiles from the midplane (z=0, -6, -13, 19 cm)

Facter of 2 increases of Ti & V_T

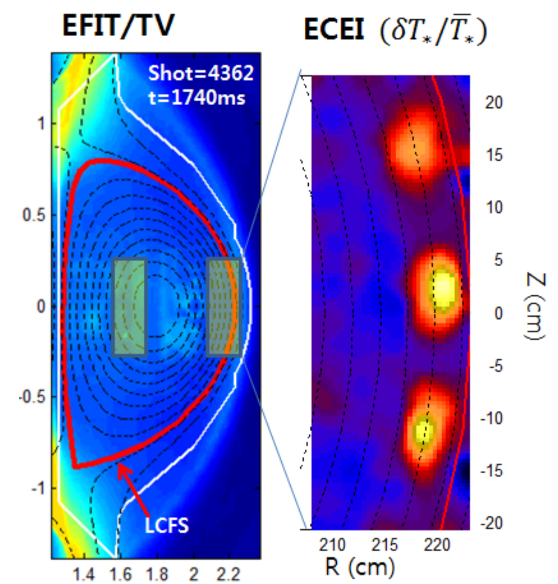
Smaller increase for Te
(Clear Te incease at edge)

Diagnostics : 2-D electron temperature fluctuation measurement using ECE Imaging

- 2-D Te fluctuation measurements
  - Simultaneous imaging of LFS and HFS (dual arrays)
  - Flexible view control
  - Vertical zooming (triplet zoom optics)
  - Independent radial translation
  - Resolution = (spatial) 1~2 cm, (time) 2 ms
- 2-D imaging of core instabilities
  - Sawtooth oscillation was observed to be similar to recent observations in other tokamaks
  - Dual filamentary hot core was observed during off-axis ECRH
- 2-D imaging of edge instabilities
  - Filamentary nature of edge localized modes was observed. Non-linear crash process was detected.



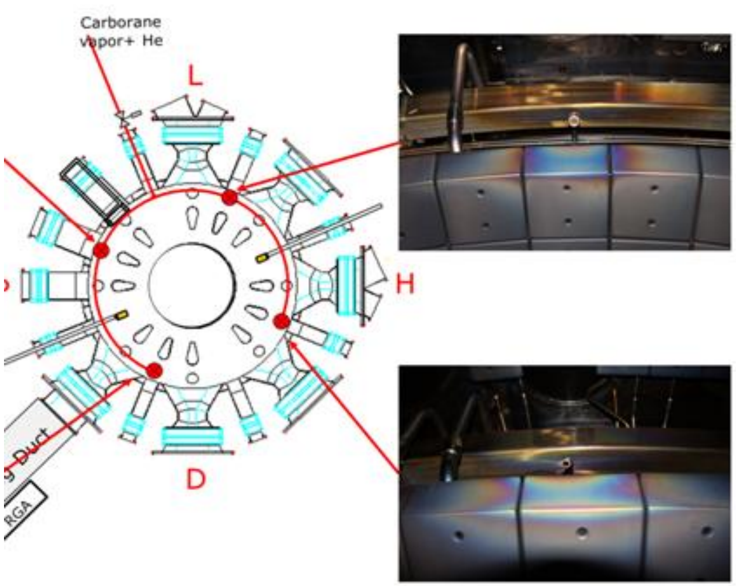
2D imaging of core instabilities



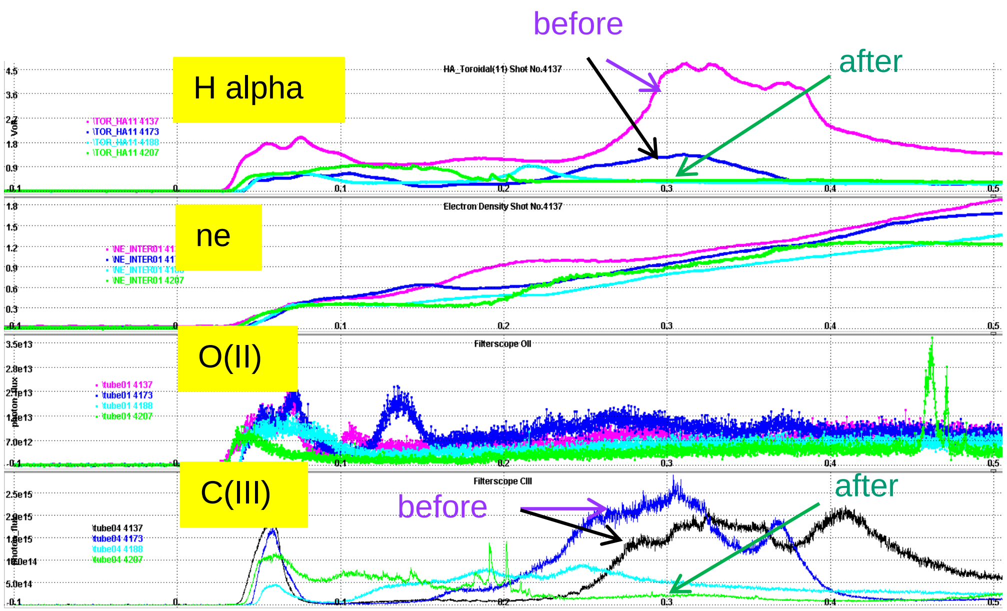
2D imaging of edge instabilities

PWI : Impurity level was reduced by wall conditioning processes

- Boroinization coating uniformity was achieved by distributing injection point at 4 toroidal places.
  - The results show that the level of impurities in the vacuum vessel is dramatically reduced due to boronization.
  - Large amount of hydrogen after the boronization in He GD (label 3) was a problem for the density control

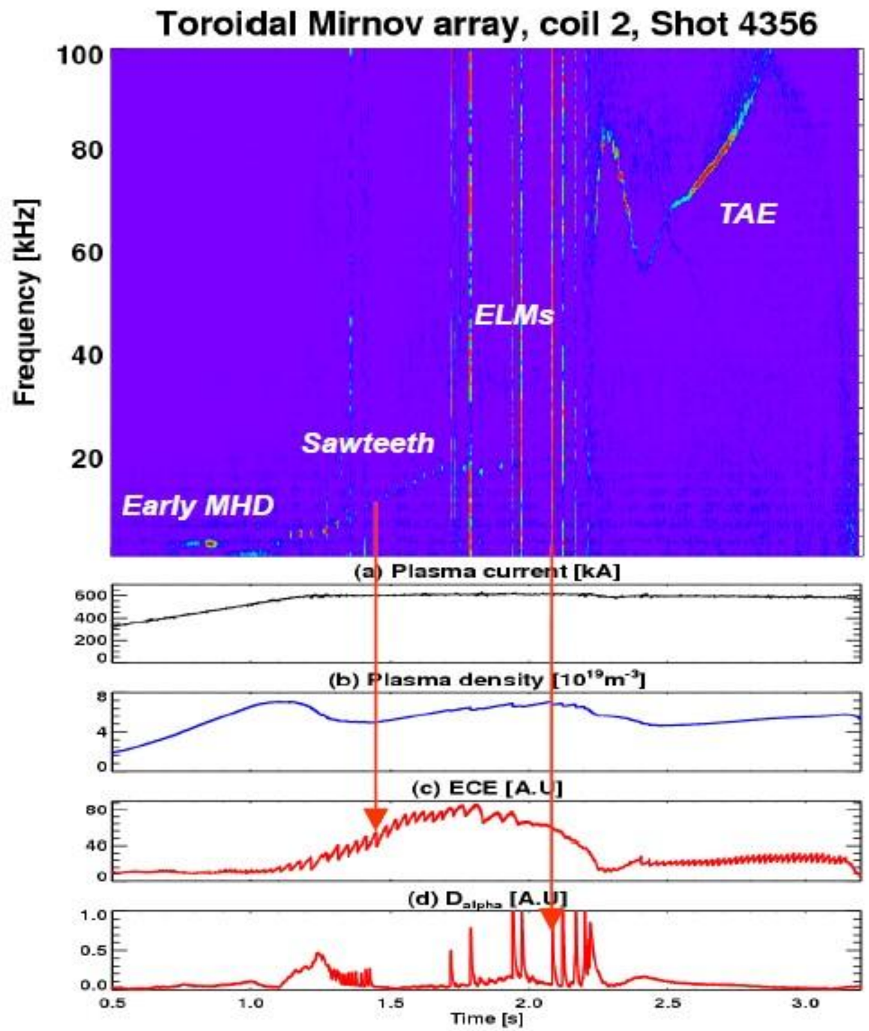


Uniform boronization coating



Impurity level reduction after boronization

MHD : Various MHD activities were observed in KSTAR 2010 operation

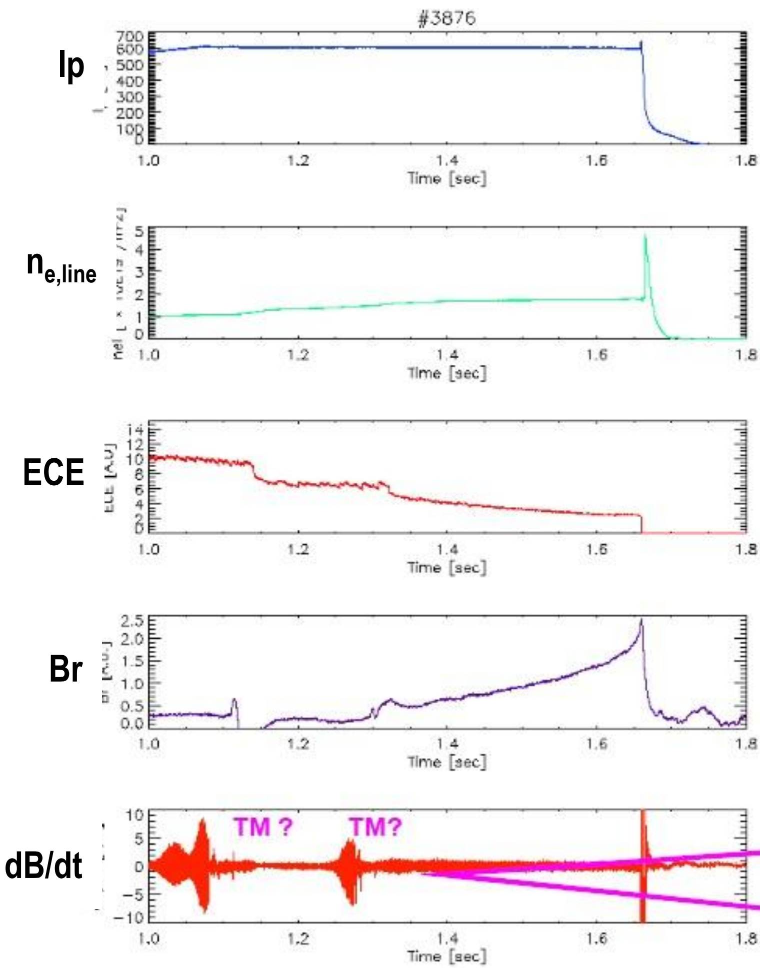


Various MHD activities observed

* J.K. Park, et.al., KSTAR H-mode meeting, Dec 17 (2010)

- 20 toroidal and 22 poloidal MC (mirnov coil) utilized for MHD analysis
- Phase-shift method with careful noise reduction used in collaboration with PPPL

MHD : Tearing mode and mode-locking were observed clearly,

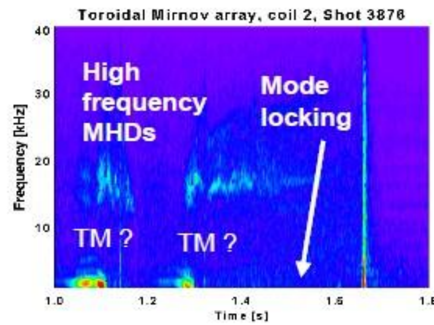


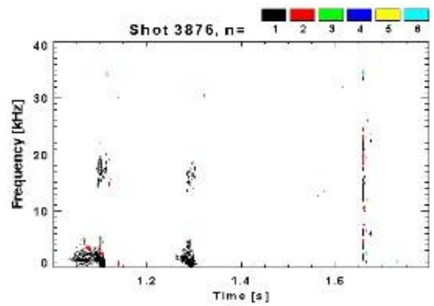
Tearing mode like activity and mode locking

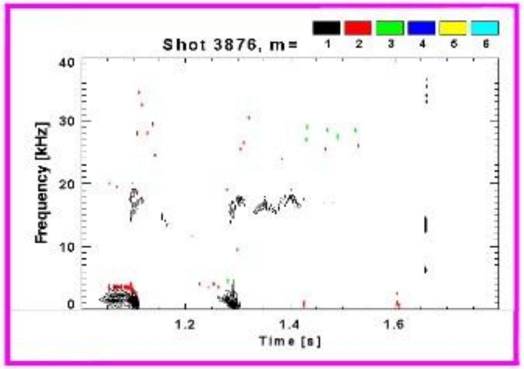
* J.G. Bak, KSTAR science meeting, Jan 24 (2011)

BT=1.96T

- *n*=1, *m*=2(?????)
- Frequency : Few kHz

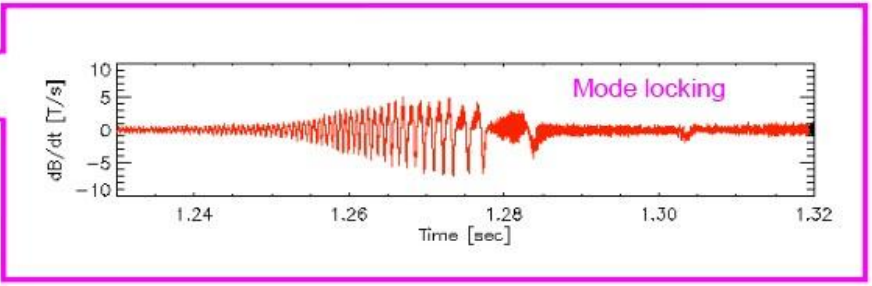




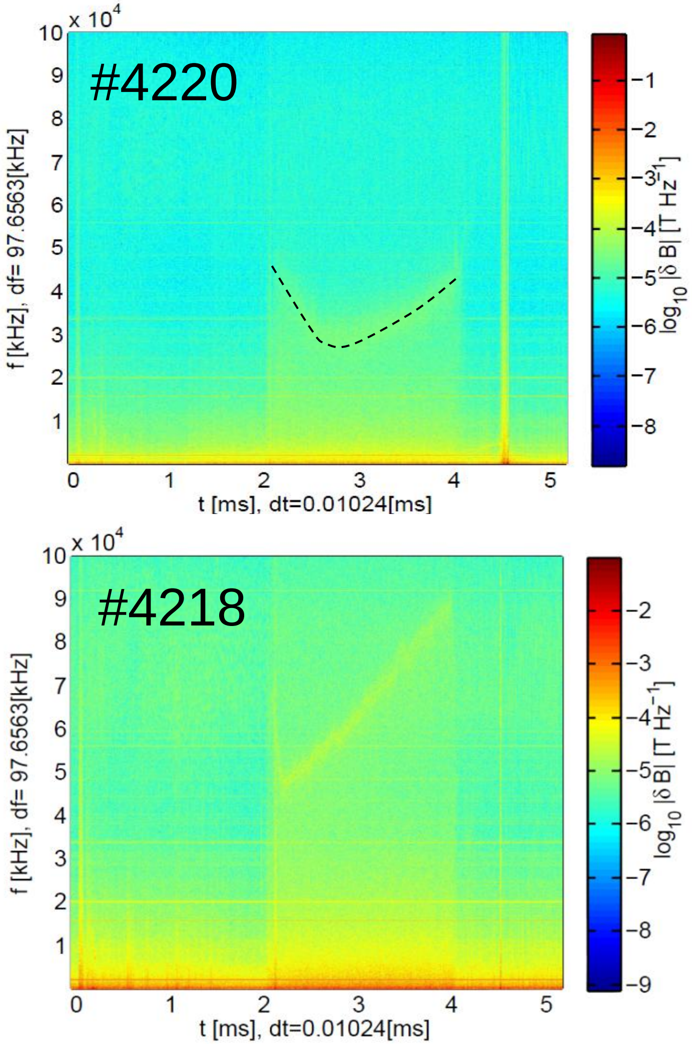


Signals from poloidal array (simple evaluation) : *m* = 1 ~ 2 ?

➔ Further study for mode identification of *m*

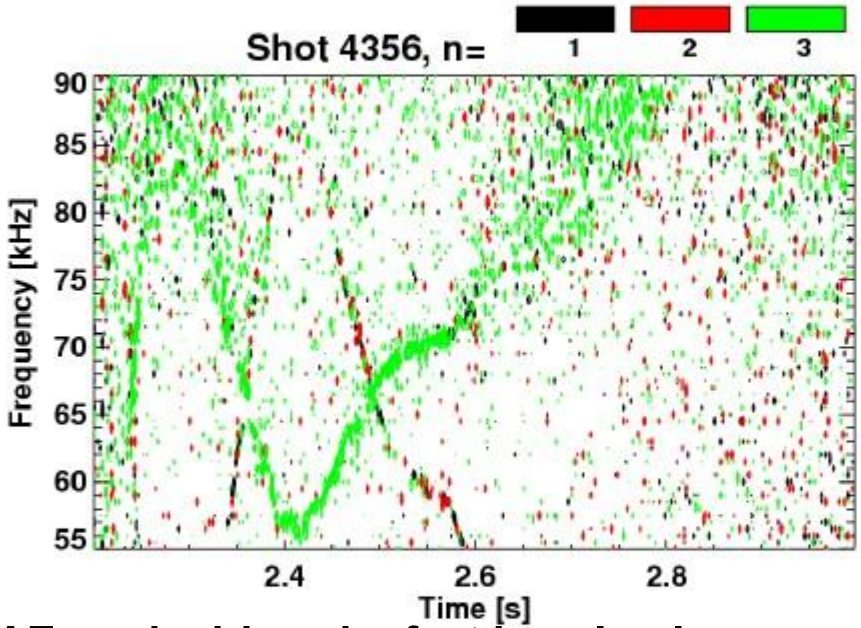


MHD : TAE by Fast Ion Clearly Observed



TAE mode on NBI heating phase

* M.J. Hole, et.al., KSTAR Exp. Report, Feb 18 (2011)



- TAE mode driven by fast ion clearly observed on NBI heating phase
- In H-modes, TAE almost always appeared after H→L back transition
- Consistent with rough estimation of TAE freq.
  - Theoretical: 120kHz for 80keV beam
  - Experiment: 50~90kHz