Overview of KSTAR diagnostics and experiments

Sang Gon Lee
on behalf of KSTAR Team
National Fusion Research Institute (NFRI), Daejeon, Korea
Contents

- KSTAR machine status and unique features
- KSTAR Diagnostics
  - Overview
  - Current status
- Research highlights in 2013 experimental campaign
  - Long-pulse H-mode operation
  - Extension of operation boundary
  - ELM control & H-mode physics
  - Rotation & MHD/Transport Physics
- Future plan
Machine status of KSTAR

NBI-1 (PNB, co-tangential) (3 beams, 5 MW/95keV)

110 GHz ECH (0.7 MW/2 s)

30 MHz ICRF (0.5 MW/3 s)

5 GHz LHCD (0.5 MW/2 s)

170 GHz ECH (1 MW/10 s)

Full Graphite PFCs (Water cooling pipe is installed, however, no active cooling up to now)

Ad-hoc Invessel Cryopump (etc. cryo-cooling tube was installed, Helium circulator is not ready, but temporal operation is possible by flowing from He dewar tank)
Unique features of KSTAR: Ideal machine for 3D & rotation physics

- **Intrinsically low toroidal ripple and low error field also**
  - Error field: very low value was detected ($\delta B_{m,1}/B_0 \sim 10^{-5}$)

- **Modular 3D field coils (3 polidal rows / 4 toroidal column of coils)**
  - Provide flexible poloidal spectra of low n magnetic perturbations

**Preliminary:** The intrinsic error field in KSTAR appears an order of magnitude smaller than in any other tokamaks

- Among the planned 3 single row scans, only the mid-RMP coil scan was completed in 2013

- Excluding an outlier, a simple circle fitting led to a low level of error field in KSTAR (10 A) *(could be the world record!)*

Full angle scan shows that the error field would be lower than sub Gauss *(resonant field at q=2/1 based on IPEC calculations)*
High toroidal rotation at pedestal top (might be due to low ripple)

- **Mach number** \((\equiv \frac{v_\phi}{v_{\text{thermal}}})\) **is also found to be very high** \((\text{Mach}_D \sim 0.6, \text{when } v_{\phi,D} = v_{\phi,C})\)
- The clear observation of the toroidal rotation velocity pedestal seems **to come from a low toroidal field ripple** of the KSTAR tokamak \((\sim 0.05\%)\)
- NB: It has been observed that the toroidal rotation velocity at the pedestal is significantly changed by the toroidal field ripple whereas the plasma pressure is not changed [P. C. de Vries NF (2008), H. Urano NF (2011), M. F. F. Nave PRL (2010)], In JET, Mach number is 0.5 for \(\delta_{TF} \sim 0.08\%\) whereas 0.2 for \(\delta_{TF} \sim 1\%\) (Mach number in KSTAR is \sim 0.6)

Suggesting the advantage of high energetic ptl confinement
### Overview of diagnostic systems

- **Magnetic diagnostics** *(NFRI, ASIPP)*
- **Edge probe sensors** *(NFRI, HYU)*
- **Recip. Langmuir Probe** *(NFRI)*
  - **Visible TV** *(3 sets)* *(NFRI)*
  - **Survey IRTV** *(NFRI)*
  - **D-alpha Monitor** *(NFRI)*
  - **Visible Spectrometer** *(NFRI)*
  - **Visible Filterscope** *(ORNL)*
  - **VUV Survey Spec.** *(ITER KO, KAIST)*
  - **Resistive Bolometer** *(NFRI, NIFS)*
  - **Imaging Bolometer** *(NIFS)*

- **mm-Interferometer** *(NFRI)*
- **Thomson Scat.** *(NFRI, JAEA, NIFS)*
- **ECE** *(NFRI, KAERI, NIFS, Kyushu U.)*
- **Reflectometer** *(NFRI)*
  - **Hard X-ray** *(NFRI)*
  - **Ellipsometry** *(NFRI)*
  - **Deposition** *(NFRI, HYU)*
  - **Neutron** *(NFRI, HYU, ITER KO)*
  - **Fast-ion loss** *(NFRI)*
  - **NPA** *(KAERI)*

- **XICS** *(NFRI, PPPL, ASIPP)*
- **Charge Exch. Spec.** *(NFRI, NIFS)*
- **ECEI (2 sets)** *(POSTECH, UCD)*
- **MIR** *(POSTECH, UCD)*
  - **X-ray Pinhole** *(KAIST, KAERI, NFRI)*
- **SXR** *(KAIST, Far-Tech, JET, ENEA)*
  - **BES** *(Wigner)*
  - **Li-beam** *(Wigner)*
  - **Coherence Image, iMSE** *(NFRI, ANU)*
  - **Divertor IR TV** *(NFRI)*
  - **FIR Interferometer** *(NFRI, SNU)*
  - **DBS** *(NFRI, SWIP)*
  - **MSE** *(NFRI, TU/e)*

*Black: installed  Blue: plan for 2015*
Magnetic diagnostics
Electric probe diagnostics

EPDs were used to measure $n_e$, $T_e$, $J_{sat}$ for evaluation of particle and heat fluxes in the SOL and divertor regions.

- Poloidal probe array at poloidal limiter (far SOL region)
- FRLPA at mid-plane (SOL region)
- Poloidal probe array at lower divertor region
- FRLPA at the middle port of KSTAR machine: max. scan speed of 1.5 m/s
- Previous probe head
- New probe head
- Poloidal probe array at divertor (57 ea)
- Fixed probes
- Poloidal probe array at poloidal limiter (8 ea)
Divertor IRTV

To be presented by Dr. H. H. Lee

<table>
<thead>
<tr>
<th>Model</th>
<th>FLIR SC6101</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector type</td>
<td>InSb (Indium Antimonide)</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>3.0 ~ 5.0 μm</td>
</tr>
<tr>
<td>Resolution</td>
<td>640 × 512</td>
</tr>
<tr>
<td>Detector Pitch</td>
<td>25 μm</td>
</tr>
<tr>
<td>Integration time</td>
<td>10 μsec to 687 sec</td>
</tr>
<tr>
<td>Max Frame Rate  (@ Min Window)</td>
<td>35.112 kHz (64 × 4)</td>
</tr>
<tr>
<td>Full frame rate</td>
<td>125 Hz</td>
</tr>
<tr>
<td>Temperature range</td>
<td>up to 1500 °C</td>
</tr>
</tbody>
</table>
Microwave diagnostics

- 0-Dimensional (spatial averaged)
  - Interferometer (280 GHz, 1 ch, NFRI)

- 1-Dimensional (Radial distribution)
  - Radiometer (110-196 GHz, 76 ch, NFRI)
  - Reflectometer (33-50, 50-75, and 75-108 GHz, 3 ch, NFRI)

- 2 and 3-Dimensional (advanced imaging)
  - ECEI (POSTEC)
  - MIR (POSTEC)

ECE radiometer

Reflectometer

To be presented by Dr. S. H. Seo

To be presented by Dr. G. Yun
Microwave imaging diagnostics

(2) MIR
Fast imaging system for $n_e$ fluctuations

(1) Two ECEI systems
Fast & high-resolution imaging system for $T_e$ fluctuations

(3) Fast RF Spectrometer for plasma waves (ion cyclotron, Alfven, whistler, etc)
3D ECE imaging

- Space resolution ~ 1x1—2x3 cm²
- $T_e$ resolution (real-time), $\delta T_e/\langle T_e \rangle \approx 2\%$
- Time resolution ~ 2 µs

e.g. Observation of ECH-induced flux tubes in the sawtoothing core
Microwave imaging reflectometry

- Detection channels: 2 by 16 (radial and poloidal)
- Detection poloidal wavenumber: kp < 3 cm\(^{-1}\)
- Radial coverage: 0 < r/a < 0.8
- Time resolution: 1 or 2 us

e.g. Apparent flow of density turbulence measured by MR
X-ray diagnostics

- **Soft X-ray array (SXRA)**
  - 2 arrays, 32 ch (64 ch)
  - $\Delta t = 2 \mu s$, $\Delta r = 5$ cm
  - Ar Ross filters (Cl & Ca K-edge): 2.8 – 4.0 keV
  - Be filters (10, 50 μm: 0.5, 1.0 keV): 2 color

- **2-D Tangential X-ray pinhole camera (TXPC)**
  - Duplex (2 color), 50x50 ch
  - $\Delta t = 0.1$ ms, $\Delta r = 2$ cm

- **GEM detector for 2-D X-ray camera**
  - 12x12 pixels, 128 ch
  - $\Delta t = 1$ ms, $\Delta r = 2 - 6$ cm
  - 3 – 30 keV

- **X-ray imaging crystal spectrometer (XICS)**
  - Advanced imaging detector
  - $\Delta t = 2$ ms

To be presented by Dr. S. H. Lee
LOS of SXR tomography system

2013 (D-port)
- 2 array, 64 ch
- Ar injection
- HU
- HD

• Be filters (10, 50 μm)
• Ar Ross filters (Ar impurity transport)
• Bolometer (No filter)

2014 (D-port)
- 4 array, 256 channels
- Total 6 arrays, 320 ch
- Magnetics-free reconstruction
- High time & spatial resolution (2 cm, 2 μs)
- Transient impurity & energy transport physics
2-D Tangential X-ray pinhole camera

*In collaboration with KAERI (M. Moon)*

- *Duplex (2-color)* Multi-Wire Proportional Counter (MWPC) detector
X-ray imaging crystal spectrometer

2013 Campaign
- Overall size: 105 mm x 85 mm
- Pixel size: 0.172 mm x 0.172 mm
- Maximum count rate: 10 MHz per pixel
- Time resolution: > 2 ms

2011-12 Campaign
- Overall size: 35 mm x 85 mm/module
- Pixel size: 0.172 mm x 0.172 mm
- Maximum count rate: 1 MHz per pixel
- Time resolution: > 10 ms
Energetic particle diagnostics

• Fast ion loss:
  – FILD (scintillator-based)

• Fast ion confinement / mode:
  – Compact NPA (solid-state detector)
  – FIDA (feasibility test using MSE optics)
  – FIR, SXR (AEs, fishbone, LLM, ...)

• Runaway electron:
  – Hard X-ray detector (30 – 500 keV)
  – IR camera (synchrotron rad.) (~MeV)

To be presented by Dr. J. H. Kim
Fast Ion Loss Detector (FILD)

Plan in 2014 (2\textsuperscript{nd} FILD @ I-port)

Prompt beam-ion losses from single / double beams

MHD-induced fast-ion loss (example)

Ultra-fast camera (JAEA)
Thomson scattering system
- Core APDs were saturated in 2013
  (no meaningful core data)
  => 1. collection optics modification
  2. APD/Amp array replacement
  3. stray light reduction
  4. using back-up Nd:YAG laser
- 2013: 17 spatial points (core 5, edge 12)
  => 2014: 17+7 spatial points

T.S. comparison with interferometer, ECE and CES

- need to improve Thomson data accuracy

To be presented by Dr. K. C. Lee
- Achieved first line integrated $n_e$ measurement vertical 1-Ch(2013) by improvements;

  1. reduction of beam path from ~50 m to ~20 m
  2. securing of mirror holders
  3. increase of wave guide diameter
  4. modification of beam propagation optics
  5. improved pre-amp (doubled gain)
  6. humidity control down to ~10%.

- FIR data compared with mm wave interferometer
- FIR data at ELM crashes showed density flow
- Influence from mechanical vibration
  
  => will be improved (2014)

MM wave Interferometer will be presented by K. C. Lee
Active beam-based diagnostics

CES* / MSE** (Middle window) – NBI
BES (Bottom window) – NBI, Li beam

*Toroidal
**Spectrum measurements only till 2014
**Polarimetric MSE in 2015

Li Zeeman (Slanted) – Li beam (2016)
Poloidal CES (Top/Bottom) – NBI (2014)

<table>
<thead>
<tr>
<th>Beam Specifications</th>
<th>Deuterium (Heating)*</th>
<th>Lithium (Diagnostics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>24 x 60 cm (W x H)</td>
<td>2 – 5 cm (dia.)</td>
</tr>
<tr>
<td>Shape</td>
<td>Rectangular</td>
<td>Circular</td>
</tr>
<tr>
<td>Current</td>
<td>~ 20 A</td>
<td>~ 2 mA</td>
</tr>
<tr>
<td>Energy</td>
<td>80 – 100 keV</td>
<td>&lt; 60 keV</td>
</tr>
<tr>
<td>Modulation</td>
<td>2 ~ 5 Hz</td>
<td>~ 250 kHz</td>
</tr>
</tbody>
</table>

To be presented by Dr. J. Ko
• DS-spectrometer (400 mm, F/2.8) lent from NIFS (Japan) for KSTAR toroidal CES was installed in 2011.
• \( \Delta r \) & \( \Delta t = 0.5 \) (edge) – 2 (core) cm & 100 Hz
• Have routinely and reliably provided Ti and Vt profiles to study various fast dynamics - L-H transitions, rotation damping, pedestal structures during ELM cycles and ELM suppression.
• Feasibility test for a new poloidal CES system will be performed in the 2014 campaign.
Beam Emission Spectroscopy (BES)

- Collaboration with Wigner Research Centre for Physics (Hungary)
- Flexible optics allow various modes of operations (horizontal & vertical, D & Li, APD & CCD etc)
- 4 x 8 channels that can move radially and vertically ($\Delta r \& \Delta t = 1 \text{ cm} \& 2 \text{ MHz}$)

Example: Electron density profile evolution during ELM cycle
• Polarimetric (conventional) MSE will commission in 2015. Procurement and installation in 2014.
• Partial collaboration with Eindhoven University of Technology (The Netherlands)
• $\Delta r \& \Delta t = 1 \text{ - } 2 \text{ cm} \& 100 \text{ Hz}$

• Spectral approach is also pursued – ITER-relevant

- First-time-ever spectral approach for multi-ion source NBI to obtain pitch angles
- Stark-split base: free from mirror coating (promising for ITER)

• Clear Li-beam Zeeman spectra were observed during the 2013 campaign. Feasibility study underway.

Mirror and dichroic beam splitter are dielectric-coated:
- S/P reflectance ratio: $1.000 \pm 0.01\%$
- S/P phase difference: $\pm 5^\circ$ in the range of operation
KSTAR machine status and unique features

KSTAR Diagnostics

Overview
Current status

- Research highlights in 2013 experimental campaign
  - Long-pulse H-mode operation
  - Extension of operation boundary
  - ELM control & H-mode physics
  - Rotation & MHD/Transport Physics

- Future plan
Objectives of 2013 campaign in Broader Perspective

**Operation Phase I**
2008 ~ 2012
Superconducting Tokamak Operation
- Integrated control of SC tokamak
- First plasma
- H-mode discharge
- Experimental collaboration

**Operation Phase II**
2013 ~ 2017
Long-pulse H-mode and ITER pilot
- ITER priority research (ELM, Disruption, NTM)
- High performance plasma study using KSTAR intrinsic tools (intermediate heating power, low density)

**Operation Phase III**
2018 ~ 2022
High-performance Scenario related to DEMO
- Demonstrate advanced operation scenario (high power, high density)
- Integrated control of profile and stability
- Research applicable to DEMO

**Operation Phase IV**
2023 ~
DEMO Advanced Technology
- Stabilization and optimization of advanced scenario
- Technologies at extreme environments

---

Long-pulse discharges & ITER urgent issues was the main thrusts for 2013
Effort for long-pulse operation: Longer phase of H-mode flattop ($t_{\text{H-mode}} \sim 20\text{s}$)

Better shape control in 2013 without strong $n_e$ rise (due to better X-point control)

Shut-down at $t=21.4\text{ s}$ due to limit of electricity of grid (VAr limit) **not due toVs limit**

With better PF control logics and motor-generator(2 GJ), longer pulse will be available in next campaign

- Based on experiments, Ohmic flux is available for more than 50 sec flattop at $I_p=1\text{ MA}$ even with $P_{\text{NBI}} \sim 3\text{ MW}$

  $3.8\text{ Wb (up to 1 MA ramp-up)} + 0.15\text{ Wb/s*50 s} = 11.3\text{ Wb} < 12\text{ Wb limit}$

Reliable shaping control is essential for sustainment of longer-pulse discharge without confinement degradation
KSTAR is approaching and exceeding no-wall MHD stability limit by optimizing scenario

- By Early heating for low \( l_i \)
  (Better \( I_p \) ramp-up scenario)

- Optimizing \( B_T \) & \( I_p \)
  \( B_T \) in range 1.3-1.5 T
  \( I_p \) in range 0.5-0.7 MA

- Max \( \frac{\beta_N}{l_i} \sim 4.1 \)
  \( \beta_N \sim 2.5, l_i \sim 0.7 \)
  100% increase from 2011

- Rotating \( n=1, 2 \) mode activities observed in core

S. Sabbagh & Y. Park

Columbia University
In the City of New York
ELM-suppressions have been demonstrated both for n=1 or n=2 RMP with each $q_{95}$ window.

n=1 (+90 phase) RMP at $q_{95} \sim 6.0$

n=2 RMP (mid-FEC only) at $q_{95} \sim 4.1$
ELM suppression is even extended to intermediate $q_{95}$ with using the combination of $n=1$ & $2$ RMP.

- $r=1$ (middle) NOR $r=2$ (top/bottom) NA field ALONE has not shown the ELM suppression yet.
- The $q$-window (4.3~4.5) in ELM suppression is observed during $I_p$ scan ($q$-scan).
- NB : $q\sim6$ at $n=1$, $q\sim3.7$ at $n=2$, $q\sim4.5$ at $n=1+2$ (wide $q$ window)

**Results in 2012 campaign**

Extending $q_{95}$ window for ELM suppression
ELM mitigation effect observed by injecting ECCD at pedestal

Poloidal angle scan

<table>
<thead>
<tr>
<th>$\rho_{\text{pol}}$</th>
<th>$P_{\text{tot}}$ [MJ]</th>
<th>$n_e$ [$10^{19}$ m$^{-3}$]</th>
<th>$H_a$ [a.u.]</th>
<th>$W_{\text{tot}}$ [MJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.86$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.90$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.94$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.98$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mitigation stronger at larger $\rho_{\text{pol}}$

No ECH

$\rho_{\text{pol}} \sim 0.86$

- $f_{\text{ELM}} \sim 30$ [Hz]
- $\Delta W_{\text{ELM}} \sim 20$ [kJ]
- $\Delta N_e L \sim 0.16 \times 10^{19}$/m$^3$
- $\Delta T_{e,\text{ped}} \sim 0.4$ [keV]

$\rho_{\text{pol}} \sim 0.98$

- $f_{\text{ELM}} \sim 90$ [Hz]
- $\Delta W_{\text{ELM}} \sim 2$ [kJ]
- $\Delta N_e L \sim 0.16 \times 10^{19}$/m$^3$
- $\Delta T_{e,\text{ped}} \sim 0.4$ [keV]

Strong coherent oscillation ($\sim 10$ kHz) during ECH injection
ECH effects on heat and momentum transport

($B_T$; 3 T)

# 9006 (left) and 9007 (right) NBI L-mode with central ECCD ($R_{res} = 1.8$ m, $\phi = 20^\circ$, $z$ scanned)

- **NTV effects due to internal kink modes** [J. Seol, S. G. Lee et al. PRL (2012)] need to be avoided through narrow $q=1$ surface to **investigate the ECCD effects on the turbulence-driven transport**
- Toroidal rotation and $T_i$ are decreased as ECH is applied regardless of the ECH resonance positions
Effect of ECH on impurity transport

- Argon gas injection through a piezo valve ($n_{Ar}/n_e < 0.1\%$)
- Different transport with varying ECH positions → Feasibility of impurity control?
- Analysis of Ar transport coefficients in L-mode (#7566, #7574) by using UTC-SANCO code with diagnostic results (SXR, VUV, XICS)

- Less core accumulation of Ar impurity with ECH
- Most effective (i.e., least core impurity concentration) with on-axis ECH
- Less effective with resonance layer position at larger radius
Demonstration of soft-landing capability at the Locked-mode triggered by n=1 external RMP

- **Tool**: n=1 RMP coils are utilized for locked mode generation
- **Detection**: PCS catches drop of $I_p$ (despite of its control effort)
- **Action**: PCS invokes async. ramp-down procedure for safe discharge termination

**Intended locked mode driven by external n=1 RMP**

- **Loop voltage**
- **RMP**
- **$R_0$, $Z_0$**
- **$\bar{n}_e$**
- **Temperature**

![Graph showing parameters over time](image)
On-going effort for NTM control: Effect of ECCD on NTM

Intensification of NTM

Partial suppression of NTM

Decrease $\beta$ due to NTM growth triggered by sawtooth crash

Spectrogram from MC signal
NTM frequency $\sim 10$ kHz

$\beta_N \sim 0.8$
$\beta_p \sim 0.8$

Mirror target $z \sim 10$ cm
$q=\sim 2$ surface

Ip = 600 kA
1.4 MW NBI1
1.2 MW NBI2
800 kW ECCD
Sawtooth locking experiments

- 170 GHz X2 at $B_T=2.9$ T
- $I_p = 700$ kA
- $\langle n_e \rangle = 2.7 \times 10^{19}$ m$^{-2}$
- $\beta_N = 0.5$
- $q_{95} = 5.43$

Sawtooth period is fully extended with $\tau_{saw}=100$ msec by CW EC beam injection outside $q=1$ surface

Sawteeth are regulated at $\tau_{saw}=43$ msec by EC modulation freq. of 23 Hz & 70 % duty
Plan for 2014 campaign

- Schedule for plasma experiments: 10 Sep – 15 Nov

- Machine milestones
  - 50/10 sec of inductive H-mode in 0.5/1.0 MA of Ip
  - $P_{\text{NBI}} \sim 5$ MW, co-/cntr- ECCD (1MW) with $\beta_p$ & better gap control
  - Long-pulse sustainment/scenario for RMP ELM suppression (~10 sec)
  - Routine profiles/fluctuations measurements at pedestal (TS, p/t-CES, Li-BES)

- Physics researches
  - Identification of error field and its impact on machine performance (lower $q_{95}$, Hugill diagram at low $n_e$)
  - Extension of operational window of RMP ELM suppression ($q_{95}$, $v^*$, ISS)
  - Rotation profile control with additional NBI torque and various damping mechanism
  - L-H transition and sustainment by SMBI at sub $P_{\text{threshold}}$
  - MHD, fast-ions, …
There are many strong points of KSTAR for advanced research capabilities

- Robust machine integrity and reliability of long-pulse SC magnet operation is demonstrated
- Low error field, TF ripple and hence strong rotation: ideal for rotation study and low q95 operation
- Similar magnetic/vessel system as ITER
- Optimized for advanced operation scenario: equipped with passive plates, in-vessel coils and capable of strong shaping
- Versatile in-vessel coils and power supplies for multi-purpose: flexible system for ELM/RWM/EF control
- Advanced diagnostics: ECEI, MIR, BES, Li-Zeeman and TS
- Mix of various heating technologies: tangential NBI, ECH/ECCD, LHCD, ICRF
Thank you!