Overview of the KSTAR Research Progress and Future Plan toward ITER and K-DEMO

Hyeon K. Park
UNIST, Ulsan, Korea

On behalf of the co-authors and KSTAR Team

at 27th IAEA FEC, Gandhinagar, India, 2018


a Ulsan National Institute of Science and Technology, Ulsan, Korea
b National Fusion Research Institute, Daejeon, Korea
c Seoul National University, Seoul, Korea
d CEA, St. Paul Lez Durance, France
e ITER Organization, Route de Vinon-sur Verdon. 13067 St. Paul Lez Durance, France
f Princeton Plasma Physics Laboratory, Princeton, NJ, USA
g Columbia University, NY, USA
h Oak Ridge National Laboratory, TN, USA
i Korea Advanced Institute of Science and Technology, Daejeon, Korea
j General Atomics, CA, USA
k Pohang University of Science and Technology, Pohang, Korea
Topics to be addressed

- Mission and role of the KSTAR research for ITER and K-DEMO
- Advantages of tokamak plasma research on KSTAR
- Progress of the KSTAR research program
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
  - Progress and understanding of the ELM-crash control with RMP
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary
Mission and role of KSTAR for ITER and K-DEMO

**KSTAR Mission is:**
- to explore science and technology for **high performance steady-state operation**, that are essential for fusion reactors

**Role of KSTAR for ITER & K-DEMO**
- Expansion of operating regimes, validation of tokamak physics and advanced control for SC device like ITER using the KSTAR unique tools
  - to expand the KSTAR operation boundaries of the conventional modes of operation and new mode of operation for minimum harmful instabilities (avoid NTM and ELM-crash)
  - to explore physics and preemptive control of the harmful instabilities in high beta operation (ELM-crash, NTM, disruptions, etc.)
  - to assist optimum operation of ITER: H-mode threshold power control, rotation control via NTV, heat dispersion with RMP, etc.
- Exploration of the limit of high beta steady state operation and R&D of key engineering and technology for K-DEMO
  - Exploration of higher beta operation with the KSTAR upgrade
  - Alternative current drive for steady-state operation
  - New start-up for high duty cycle with long pulse

- Stationary High beta ($\beta_n \sim 4$) with high bootstrap
- Optional new mode of operation including auto start-up with high duty cycle
- CD and divertor heat flux control

- Steady-state H-mode ($\beta_n \sim 2$)
- Rotation by NTV, and new start-up, H-mode access
- Suppression of ELM-crash, disruption

**KSTAR**

**ITER**

**K-DEMO**
View of KSTAR with new NBI-2 system

- ECH & Helicon & LHCD
- KSTAR
- NBI-1
- Advanced Microwave Imaging Diagnostics
- Carbon wall
- NBI-2 (New)
Collaborating domestic and international Institutes and Universities on the KSTAR program

**Domestic Collaborating Universities and Institutes**

- EU & Russia:
  - Heating & CD (CEA)
  - Diagnostics (ENEA, TU/e, Wigner)
  - PWI, fueling (ITER, PELIN)
  - Theory & analysis (York U)
  - Experiments (JET, AUP, WEST)
  - ELM, PSI, CODAC (ITER)
  - ETC

- Asia & Australia:
  - Heating & CD (QST)
  - Diagnostics (NIFS, QST, Nagoya U, Kyushu U, ASIPP, HUST, ANU)
  - PWI, fueling (ASIPP, SWIP)
  - MHD physics & simulation (NCKU)
  - Joint workshop (A3 project)
  - ETC

- USA:
  - Heating & CD (PPPL, GA, SLAC)
  - Diagnostics (ORNL, MIT)
  - 3D physics (GA, PPPL, Columbia U)
  - Plasma control & CODAC (GA, PPPL, ORNL, FNAL)
  - ETC

**Domestic Collaborating Universities and Institutes**

- EU & Russia:
  - Heating & CD (CEA)
  - Diagnostics (ENEA, TU/e, Wigner)
  - PWI, fueling (ITER, PELIN)
  - Theory & analysis (York U)
  - Experiments (JET, AUP, WEST)
  - ELM, PSI, CODAC (ITER)
  - ETC

- Asia & Australia:
  - Heating & CD (QST)
  - Diagnostics (NIFS, QST, Nagoya U, Kyushu U, ASIPP, HUST, ANU)
  - PWI, fueling (ASIPP, SWIP)
  - MHD physics & simulation (NCKU)
  - Joint workshop (A3 project)
  - ETC

- USA:
  - Heating & CD (PPPL, GA, SLAC)
  - Diagnostics (ORNL, MIT)
  - 3D physics (GA, PPPL, Columbia U)
  - Plasma control & CODAC (GA, PPPL, ORNL, FNAL)
  - ETC

- NRC, KI, JINR, Gyeong, PELIN
- NCKU
- ANU
- DOE, PPPL, ORNL, General Atomics, Columbia U, MIT, UCSD, UC Davis, LBNL, Princeton U, Wisconsin U, SLAC, FNAL

---

**Fusion Plasma Stability and Confinement Research Center**

- UNIST (POSTECH, PUS)

**Impurity and Edge Plasma Research Center (IEPR)**

- KAIST (HNU, SNU)

**Center for Advanced Tokamak Study (CATS)**

- SNU (KAERI)

**Universities & Research Institutes**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>KSTAR (achieved)</th>
<th>KSTAR (Goals)</th>
<th>ITER (Baseline/SS)</th>
<th>K-DEMO (Option II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius, R₀ [m]</td>
<td>1.8</td>
<td>1.8</td>
<td>6.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Minor radius, a [m]</td>
<td>0.5</td>
<td>0.5</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Elongation, κ</td>
<td>2.16*</td>
<td>2.0</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Triangularity, δ</td>
<td>0.8</td>
<td>0.8</td>
<td>0.33</td>
<td>0.63</td>
</tr>
<tr>
<td>Plasma shape</td>
<td>DN, SN</td>
<td>DN, SN</td>
<td>SN</td>
<td>DN (SN)</td>
</tr>
<tr>
<td>Plasma current, I_p [MA]</td>
<td>1.0</td>
<td>2.0</td>
<td>15/ ~10</td>
<td>~12</td>
</tr>
<tr>
<td>Toroidal field, B₀ [T]</td>
<td>3.5</td>
<td>3.5</td>
<td>5.3</td>
<td>7.4</td>
</tr>
<tr>
<td>H-mode duration [sec]</td>
<td>73</td>
<td>300</td>
<td>400 / 1000</td>
<td>SS</td>
</tr>
<tr>
<td>β_N</td>
<td>3.0 (4.3, transient)</td>
<td>5.0</td>
<td>~3.0</td>
<td>~ 4.2</td>
</tr>
<tr>
<td>Bootstrap current, f_bs</td>
<td>~0.5</td>
<td>~0.5</td>
<td>~0.6</td>
<td>~ 0.6</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb₃Sn, NbTi</td>
<td>Nb₃Sn, NbTi</td>
<td>Nb₃Sn, NbTi</td>
<td>Nb₃Sn, NbTi</td>
</tr>
<tr>
<td>Heating /CD [MW]</td>
<td>~10</td>
<td>~ 28</td>
<td>~ 73</td>
<td>120</td>
</tr>
<tr>
<td>PFC / Divertor</td>
<td>C, W</td>
<td>C, W</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>Fusion power, P_th [GW]</td>
<td></td>
<td></td>
<td>~0.5</td>
<td>~ 3.0</td>
</tr>
</tbody>
</table>

* exceeded
Topics to be addressed

- Mission and role of KSTAR research
- Advantages of tokamak plasma research on KSTAR
- Progress of the KSTAR research program
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
  - Progress and understanding of the ELM-crash control with RMP
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary
Uniqueness-1: nearly perfect symmetry of the tokamak plasmas

- Extremely low magnetic ripple for minimum ripple loss. ($\delta B/B \sim 0.05\%$)
- Extremely low error field configuration ($\delta B/B_0 \sim 1 \times 10^{-5}$)
  - Manufacturing and assembly of the magnets with high accuracy
  - Robust structures to sustain the TF coil shape uniform
- Designed with strong shaping capability for high beta operation stability
  - Double & single null capable and passive stabilizer for stabilizing VDE & RWM
  - Control flexibility using four pairs of CS coils and high elongation ($\kappa \sim 2.16$) & triangularity ($\delta \sim 0.8$)

SC magnets manufactured without internal joints to minimize error field
Uniqueness-2: Versatile in-vessel control coils for perturbation study and advanced imaging diagnostics

- Unique in-vessel control coils with 3 poloidal rows (top, middle and bottom; e.g., ITER)
  - Flexible 3D field perturbation with n=1, 2 and mixed
  - Broad band power supply (~10 kHz) and patch panel for fast control for position, ELM-crash, rotation control & RWM control

- Advanced 2D/3D imaging diagnostics
  - ECEI, MIR, BES, imaging bolometer, FILD, SXR, etc.
  - Enable us to access the dynamics of fundamental physics of MHD/turbulence that were not available
Topics to be addressed

- Mission and role of KSTAR research
- Advantages of tokamak plasma research on KSTAR
- Progress of the KSTAR research program
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
  - Progress and understanding of the ELM-crash control with RMP
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary
Effect of high toroidal rotation (or high edge rotation shear) on energy confinement in KSTAR

- High toroidal rotation speed in KSTAR may be due to nearly perfect tokamak plasma symmetry (low error field)
- Beam torque is linear with the Mach number (record high $M_i \sim 0.8$)
- Edge rotation shear and $E_r$ are well correlated with core rotation speed

**Toroidal rotation ($M_i$ or torque) is a hidden parameter in energy confinement scaling??**

- Excellent correlation between the energy confinement time ($\tau_{th}$) and Mach number ($M_i$) or torque
- L-mode and H-mode data can be combined with the rotation related parameter (turbulence physics basis?)
- Further study on edge shear, counter rotation, role of intrinsic rotation, etc. is in progress

---

**Off-set value:**

- Intrinsic rotation

---

**Beam torque is linear with Mach number**

**MAST, $M_i \sim 1.$**

---

**S.G. Lee, EX/P7-4**

---

**J.S. Kang, NFRI**

---

**KSTAR, DIII-D, ASDEX-U**

---

**Beam Power (MW)**

---

**Beam Torque (Nm)**

---

**T[MeV]**

---

**V[MeV]**

---

E'[keV, $10^{-3}$]

---

Normalized $\tau_{th}$ to the ITER H93-P scaling (AU)
NBI-heated long pulse H-mode operation (> 1 min)

- Long pulse H-mode discharge with NBI & ECH
  - Fully non-inductive advanced operation with high beta ($\beta_N \sim 2.0$, $\beta_P \sim 2.5$) was up to 20s.
  - H-mode was sustained over 70 s, BUT gradual performance degradation due to the heated limiter

In 2018 campaign, longer steady-state, fully non-inductive operation over ~100s will be attempted with upgraded:

- Active water cooling into PFC/Divertor
- Boron powder dropper (PPPL / ORNL collaboration)
- Additional heating (NBI, ECCD)
Exploring conventional and new operation modes for optimal scenarios applicable to ITER and K-DEMO

- Broad ITB provides good confinement in the core
- Low $q_{95}$ avoids harmful MHDs (e.g. NTM and ELMs)
- Sawtooth can be used for particle control and $q \approx 1$ surface can be controlled with CD.
- Expense for MHD control (ELM and NTM) can be used for additional CD due to reduced $P_{bs}$ from H-mode
Topics to be addressed

- Mission and role of KSTAR research
- Advantages of tokamak plasma research on KSTAR
- **Progress of the KSTAR research program**
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
  - Progress and understanding of the ELM-crash control with RMP
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary
Theoretical model for Sawtooth instability (Full or Partial)?

- Direct $q_0$ measurements (2015, 2016) alone cannot validate the model
  - During nearly four decades, there are two groups of measurement; $<q_0>\sim 1.0$ and $<q_0>\sim 0.8$ with $\delta q_0 \sim 0.07$

- Supplementary experiment is essential
  - Excitation of double tearing modes inside the $q\sim 1$ surface is consistent with the growth rates calculated by M3DC1 with $q_0>1.0$ in MHD quiescent time right after the crash
  - Time evolution of $3/3 \rightarrow 2/2 \rightarrow 1/1$ further supports $q_0>1.0$

- “Full reconnection model” by Kadomtsev is supported by the validation experiments

Y. Nam, NF 2018
Magnetic island (2/1) can alter the electron heat transport by the flow and turbulence

- Measured $T_e$ turbulence and apparent rotation around the 2/1 island
  - Merging of turbulence near X-point and penetration to the island can cause “minor and major” disruption

- Magnetic island modifies the poloidal flow and the $T_e$ turbulence around itself
  - Global XGC1 simulation shows that magnetic island makes an 2/1 electrostatic potential structure $\rightarrow$ non-axisymmetric $E \times B$ flow perturbation (a)
  - gKPSP Micro-stability analysis shows that the $E \times B$ shear flow at near O-point is strong enough to suppress a significant portion of micro-instabilities (c)


M.J. Choi, NF (2017), EX/11-2 (oral)
Exploring the physics of transport and transient instability using ECEI and MIR systems

- Interaction of the ELMs and Solitary perturbation (SP: partial n=1 mode)
  - SP appears ~ 100 $\mu$s prior to crash
  - Opposite rotation due to $E_r \times B$ drift

- Observation of long range non-diffusive “avalanche” event
  - Voids and bumps in spatial $T_e$ fluctuations is shown in (a)
  - Symmetric corrugations in $T_e$ profile are shown in (b) and (c)

- Quasi-coherent modes (QCMs) were observed in low-collisionality regime of KSTAR ECH and ohmic discharges.
  - In ECH discharge, the increased $T_e/T_i$ by ECH injection seems to drive the QCM.

JE Lee, Scientific Report 2017
M. Choi, 4th UNIST-Kyoto Workshop (2018)
Topics to be addressed

- Mission and role of KSTAR research
- Advantages of tokamak plasma research on KSTAR
- Progress of the KSTAR research program
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
  - Progress and understanding of the ELM-crash control with RMP
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary
Stable and robust ELM-crash control at ITER baseline operation conditions

- ELM-crash suppression state sustained with n=1, and RMPs (record ~34 s with n=1)

- ELM-crash suppression is close to the ITER baseline conditions ($q_{95} \sim 3.4$, and $\beta_N \sim 1.8$)

- ELM-crash suppressed condition is sustained under $360^\circ$ rotation at n=1 RMP: owing to the low error fields in KSTAR?

- Middle coils are very important to get better and reliable ELM-crash suppression in KSTAR
  - Additional mid-RMP coil could provide more flexibility in control of the ELMs and rotation in ITER

Lowest $q_{95}$ ELM-suppression by n=2 RMP

KSTAR stable and robust ELM-crash control at ITER baseline operation conditions

- Middle coils are very important to get better and reliable ELM-crash suppression in KSTAR
  - Additional mid-RMP coil could provide more flexibility in control of the ELMs and rotation in ITER
Offering excellent guidance to optimize new RMPs — such as “off-mid-plane” only n=1 RMP ELM suppression in KSTAR

Various ELM suppression windows were successfully validated with dynamic RMPs

Prediction and validation of the n=1 RMP operating window for the ELM-crash suppression in complex KSTAR coil configuration space

\[ I_M = 0 \text{kA subspace (off-mid-plane only)} \]

J.K. Park, Nature Physics 2018
Role of turbulence induced by RMP and rotation \( (v_{\perp,\text{ped}}) \) in the ELM-crash suppression experiment

- Change of the turbulence amplitude (red box) and \( v_{\perp,\text{ped}} \) (blue box) as the RMP current ramp up and down (green) during ELM-crash suppression experiment:
  - Turbulence amplitude: Gradual increase and gradual decrease with a clear time delay with the RMP current ramp up and down – slow magnetic diffusion?
  - Rotation \( (v_{\perp,\text{ped}}) \): Bifurcation?

- Poloidal coherence: Gradual increase in turbulence level along the field line through the ELM-crash phase, -mitigation, and -suppression phases

- Radial coherence: only at ELM-crash suppression phase – turbulence spread?

- In early study, amplitude of the ELM (blue) during ELM-crash suppressed period is decreasing as the amplitude of turbulence (red) induced by the ramping RMP current (gold)
Topics to be addressed

- Mission and role of KSTAR research
- Advantages of tokamak plasma research on KSTAR
- **Progress of the KSTAR research program**
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
  - Progress and understanding of the ELM-crash control with RMP
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary
The effect of error fields on L-H transition threshold (Resonant $\delta B$ is more critical)

Misaligned RMP configurations could be an alternative way to disperse the localized divertor heat flux

- No electromagnetic cycling of the coils for misaligned RMPs.

Rotation control with NTV

- Strong $n = 2$ field + ECH heating yields counter-$I_p$ rotation in core, co-$I_p$ rotation in outer region (first direct measurement of NTV)
- Application to the ITER initial H-modes (5 MA / 1.8 T) with ECH heating to increase edge rotation

S. Sabbagh (Columbia U)
Advanced shaping control and new start-up method for superconducting tokamak plasmas

- Improved stability - high elongation up to \( \kappa \approx 2.16 \) (design \( \approx 2.0 \)) for high \( \beta \) operation
  
  D. Mueller et al. APS 2017

- Validation of Trapped Particle Configuration (TPC) for reliable ECH-assisted startup
  
  - Robust startup method than the conventional field null method
  - Possible new automated start-up
  
  J.W. Lee, NF 2017

- ITER baseline scenario with ITER similar shape (ISS)

- Comparison of a synthetic diagnostic of the Balmer-\( \alpha \) line emission in the BREAK code simulation considering the self-generated electric fields (a) with an experimental visible camera image (b)

N. Eidietis, APS 2017

 ITER Shape
Topics to be addressed

- Mission and role of KSTAR research
- Advantages of tokamak plasma research on KSTAR
- Progress of the KSTAR research program
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
  - Progress and understanding of the ELM-crash control with RMP
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary
New NBI-2 and Helicon CD systems for KSTAR

**NBI systems (6 MW NBI-1 + 6 MW NBI-2)**
- On-and Off-axis heating to get stable high beta operation
- Co-current direction in both NBI-1 & 2 (for CD & high rotation)
- NBI-2: 6 MW, 100keV, 300 s (4MW off-axis + 2MW on-axis)
- Schedule: 1 ion source (in 2018), 3 ion sources (in 2019)

**Helicon CD experiment and modeling**
- Prototype 500 MHz: 0.1 MW (’16 ~’18)
- High power HCD (2 ~ 4 MW)
  - Klystron: 1 MW CW tube (5 units from SLAC) (’19)
  - Power supply: 2 MW ready (’19)
  - Launcher: 2 MW (’19)

---

![Diagram of NBI systems and Helicon CD experiment](image_url)

**Current drive**

**Heating**

**Prototype Helicon Antenna**

**E.H Kim, PPPL**
**IAEA FEC PARK**

**Time line of research and upgrade plan of KSTAR**

2008

- First plasma (ECH 84 GHz)

2017

- Long-pulse H-mode research
  - Long pulse H-mode (>70s)
  - Alternative modes (ITB, low q, ..)
  - ELM research & control (>30s)
  - Fundamental physics validation

2018

- Heating upgrade (NBI ~ 12 MW) (ECH ~ 6 MW)

2017 -> 2020

- Advanced scenario & MHD research
  - Stable high beta operation
    \( \beta_N > 3.0, \, f_B > 0.5, \, T_{\text{ion}} \sim 10 \text{ keV} \)
  - Advanced mode develop. (hybrid, ITB, low q)
  - MHD & disruption control

2020

- CD upgrade (LHCD~4 MW) (Helicon CD~4 MW)

2021 ~ 2023 ~

- Divertor upgrade (Tungsten divertor) (Detached divertor)

2023 ~

- Steady-state & reactor mode research
  - Tungsten divertor & active cooling
  - Advanced current drive (HFS LHCD, Helicon CD, etc.)
  - Steady-state operation (~300s)

2020

- CD upgrade (LHCD~4 MW) (Helicon CD~4 MW)
Summary

- KSTAR is well engineered superconducting tokamak with unique tools for advanced research
  - Nearly perfect tokamak symmetry, intricate IVCC (top/middle/bottom) like ITER IVCC and advanced 2D/3D microwave imaging diagnostics
- Significant progress in expansion of operation regimes, validation of fundamental physics and ITER/DEMO relevant research
  - Long pulse H-mode (with ELM-crash) over 70s and ELM-crash suppressed H-mode over 30s
  - Expansion of conventional operating regimes (hybrid, high beta-P, ISS, High poloidal beta, ITB, low edge $q_{95}$, etc.) and exploration of new alternative mode for minimum harmful instabilities
  - Validation of fundamental physics: “full reconnection model” in sawtooth (1/1), Transport modification by turbulence and MHD in TM (2/1), design of optimum window for RMP field penetration, role of turbulence induced by RMP in ELM-crash suppression and turbulence physics (Avalanche and QCM)
  - ITER relevant research results: H-mode threshold power influenced by error fields, Rotation by NTV, Divertor heat dispersion by rotating RMPs, New start-up method, etc.
- Future upgrade plan with new ancillary systems
  - NBI-2 installation (2018~) and Helicon CD installation (2019~)
  - Upgrade plan (2021~) will be followed for actively cooled divertor and in-vessel components
Thank you for your attention!