Fusion Energy Research and Development in “ITER Era”
- A Korean Perspective

Gyung-Su LEE
National Fusion Research Institute
Past and Present : KSTAR
Initiation of KSTAR Project based on “Mid-Entry Strategy”
Establishment of National Fusion Research Center

Opening Ceremony of National Fusion Research Center in January 1996
KSTAR Mission

• To achieve the superconducting tokamak construction and operation experiences

• To develop high performance steady-state operation physics and technologies that are essential for ITER and fusion reactor development

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>Designed</th>
<th>2010 Op</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius, $R_0$</td>
<td>1.8 m</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Minor radius, $a$</td>
<td>0.5 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Elongation, $\kappa$</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Triangularity, $\delta$</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>17.8 m$^3$</td>
<td>17.8 m$^3$</td>
</tr>
<tr>
<td>Bootstrap Current, $f_{bs}$</td>
<td>&gt; 0.7</td>
<td>-</td>
</tr>
<tr>
<td>PFC Materials</td>
<td>C, CFC (W)</td>
<td>DN, SN</td>
</tr>
<tr>
<td>Plasma shape</td>
<td>DN, SN</td>
<td>DN, SN</td>
</tr>
<tr>
<td>Plasma current, $I_p$</td>
<td>2.0 MA</td>
<td>0.5 MA</td>
</tr>
<tr>
<td>Toroidal field, $B_0$</td>
<td>3.5 T</td>
<td>3.5 T</td>
</tr>
<tr>
<td>Pulse length</td>
<td>300 s</td>
<td>5 s</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Plasma fuel</td>
<td>H, D</td>
<td>D</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb$_3$Sn, NbTi</td>
<td>Nb$_3$Sn, NbTi</td>
</tr>
<tr>
<td>Auxiliary heating /CD</td>
<td>$\sim$ 28 MW</td>
<td>2.0 MW</td>
</tr>
</tbody>
</table>
Technology Development of entire process of KSTAR from Concept Design to Commissioning!

- **1995**: Launch of KSTAR Project
- **1996 - 1997**: Basic Design and R&D
- **1998 - 2001**: Engineering Design and Facility Construction
- **2002 - 2007**: Construction of KSTAR
- **June 2008**: First Plasma
Success of KSTAR is based on dedication and Technological Advancements of Korean Industries!

1,510 Participants from 69 Companies
Ancillary Systems of KSTAR in 2010 & Upgrade

- **Neutral Beam Injector (NBI-1)**
  - 120 keV, 2.5 ~ 8 MW, 300s

- **NBI-2**
  - 120 keV, 6 MW, 300s

- **Electron Cyclotron Heating (ECH)**
  - 84 GHz / 110 GHz

- **Ion Cyclotron Heating (ICRH)**
  - 30 ~ 60 MHz, 2 MW, 300 s

- **LHCD**
  - 5 GHz, 2 MW, 300s

- **Cryogenic Helium Supply for Superconductor**
  - 4.5 K, 600 g/s

- **Vacuum Pumping System**

- **Diagnostic Systems**
  - ECH/ECCD
    - 170 GHz, 3 MW, 300s
Whole in-vessel components were installed in 2010, including Divertors, In-vessel Coils, In-vessel Cryopumps, Passive Stabilizers, and In-board & Poloidal Limiters.
KSTAR In-Vessel System Design

1. Divertor
2. Inboard Limiter
3. Passive Stabilizer
4. NB Armor
5. Poloidal Limiter
6. In-Vessel Control Coils
Segmented Coil Design of IVCC

- Upper Vertical Control Coil
- Upper Radial Control Coil
- Top FEC/RWM
- Middle FEC/RWM
- Bottom FEC/RWM

- Upper IVC
- Upper IRC
- Middle FEC/RWM
- Lower IVC
- Lower IRC

- Upper Vertical Control Coil
- Upper Radial Control Coil
- Middle FEC/RWM
- Lower Radial Control Coil
- Bottom FEC/RWM

- Bottom Vertical Control Coil
KSTAR In-Vessel System Installation

In-Vessel Cryopump

Top IVCC

Upper IVCC

Lower IVCC

Bottom IVCC

Coolant Manifold for PFCs
KSTAR In-Vessel Systems in 2010 Campaign

- Passive Stabilizer
- In-vessel Coil
KSTAR D-shape Diverted Plasma

KSTAR #3754

Diverting

KSTAR #3766

KSTAR_003754.png
KSTAR Diverted H-mode Plasma

- Shaping Capability: Plasma Shaping with vertical instability control
- Heating: 1.2 MW NBI, 0.4 MW 110GHz ECH

- Wall Conditioning with full carbon PFC: Baking @ 200 C,
- Intensive He Glow Discharge Cleaning, Boronization with Carborane

Shot #4333
kappa~1.7
delta~0.4
Rgap~3cm

- Slightly shifted to the lower divertor
- Ion $\nabla B$ is at lower divertor
Typical H-mode Discharge in KSTAR

Discharge #4333

$I_p \sim 0.6$ MA, $N_e \sim 2 \times 10^{19}$ m$^{-3}$
Double null, $\kappa \sim 1.8$
$B_T = 2$ T, $R \sim 1.8$ m, $a \sim 0.5$ m
Boronization with carborane

$P_{NBI} \sim 1$ MW (80 keV, co-NBI)
$P_{ECW} \sim 0.25$ MW (cntr - Ip)
$P_{OH} \sim 0.2$ MW

$P_{thres} \sim 1.1$ MW
*(ITER Physics Basis, 1999)*

Type-I ELMs
sharp increase of edge ECE
80% increase of $\beta_p$
Phased Operational and Experimental Plans for KSTAR

<table>
<thead>
<tr>
<th>Year</th>
<th>Main Goal</th>
<th>Research Subjects</th>
<th>Operation Phase 1</th>
<th>Operation Phase 2</th>
<th>Operation Phase 3</th>
<th>Research for Commercialization</th>
</tr>
</thead>
<tbody>
<tr>
<td>08</td>
<td></td>
<td></td>
<td>Operational Technology for Superconducting Tokamak</td>
<td>Technology for Long Pulse Operation</td>
<td>High-performance AT Operational Technology</td>
<td>Demo Advanced Technology Test</td>
</tr>
<tr>
<td>09</td>
<td></td>
<td></td>
<td>Achieve Target Operational Performance (D type, H-mode, D-D Plasma)</td>
<td>Role of Pilot prior to Completion of ITER</td>
<td>Role of a ITER Satellite and Leading AT Operational Technology</td>
<td>Optimization of AT-mode Operation</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>0.1 sec.</td>
<td>10 sec. (world-class)</td>
<td>300 sec.</td>
<td>Over 300 sec.</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td>1.5 T</td>
<td>3.5 T (world-class)</td>
<td>300 sec.</td>
<td>Over 3.5 T</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>0.1 MA</td>
<td>1 MA (world-class)</td>
<td>2 MA</td>
<td>Over 2 MA</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>ECH, ICRH</td>
<td>NBI-I, LHCD</td>
<td>NBI-II</td>
<td>Over 20 MW</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>0.5 MW</td>
<td>9 MW level (world-class)</td>
<td>Over 20 MW</td>
<td>Over 30 MW</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
*Goal: Large-scale Fusion Simulation and Fusion Informatics*
Present and Future : ITER
ITER Facility Design and Construction Site
## Overview of Construction Schedule

### ITER Construction

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TF Coils (EU)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case Winding Mockups Complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TF10</td>
<td>TF15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Solenoid (US)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS Final Design Approved</td>
<td>CS3L</td>
<td>CS3U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS Ready for Machine Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum Vessel (EU)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VV Fabrication Contract Award</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VV05</td>
<td>VV09</td>
<td>VV07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buildings &amp; Site</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction Contract Award</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tokamak Bldg 11 RFE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tokamak Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start Machine Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tokamak Basic Machine Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start Install CS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start Cryostat Closure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ex Vessel Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly Phase 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly Phase 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITER Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump Down &amp; Integrated Commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated Commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Participation of KSTAR Industrial Partners in ITER Procurement
Challenges and Risk Management thru KSTAR

- In-cryostat welding of He lines > 8,500+ points
- In-situ joints of SC Magnets
- Composite material based Insulation Breakers to maintain
- He System Operation in AC System

- SC Installation Accuracy for reducing Magnetic Field Error
- CS Pre-load Assembly for anti-parallel Current Operation
- Thermal Shield Assembly for maximal Maintainability

>>> Not by TEST, but by Quality Assurance! Engineering!
Overview of Operation Schedule

ITER Construction

<table>
<thead>
<tr>
<th>Year</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
<th>2032</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Assembly Phases II and III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ITER Operations

- Assembly Phase 2
- Assembly Phase 3

Integrated Commissioning

- Start Torus
- Pump Down
- Pump Down & Integrated Commissioning
- Magnet Commissioning

Hydrogen-Helium Operations Campaign

- Commission, Cool & Vacuum
- Plasma Development & H&CD Commissioning
- Full H&CD, TBM & Diagnostics Commissioning
- Pre-Nuclear Shutdown & Divertor Change

Deuterium Operations Campaign

- Deuterium Operations
- Start DT
- Planned Shutdown
- Q=10 Short Pulse

Deuterium-Tritium Operations Campaign

- Q=10 Long Pulse Achieved
In-Vessel Control Coil System (IVCC)

- Coil Case
- Filler
- Ground Insulation
- Section Insulation
- Corner Roving Filler
- Turn Insulation
- Conductor

Top IVCC
Upper IVCC
Lower IVCC
Bottom IVCC

* IVCC: Vertical & Radial Position Control, ELM & RWM Control
Visualization of physics via 2-D real time imaging

- Simultaneous imaging of the Edge and Core T_e fluctuations in KSTAR

- Flexible zooming capability for high resolution and global image

System Capability

- Time resolution ~2 ms
- Spatial resolution ~ 1 cm x 1 cm
- Signal resolution ~ \( dT/<T> \sim 2\% \)
- Pixels ~ 400 channels
KSTAR ELM Study by ECE Imaging

Filamentary nature of the ELM

Nonlinear crash process of the ELM

4 ms Frame View of the ELMs
KSTAR 5 GHz Klystron for LHCD (ITER Test-bed)

- Dummy Loads (250 kW CW each)
- Ion pumps (2 ea.)
- Arc detector (4-ch)
- Water cooling manifold

- Toshiba prototype Klystron (E3762 RD0)
- Output RF power (Toshiba factory test results)
  - 510 kW, 0.5 s
  - 460 kW, 10 s
  - 300 kW, 10 min.
- Single beam 68 kV, 15 A
- Modulated anode (triode gun)
- Total 6 cavities: 3 input & 3 output cavities, 48 dB gain
- 250 kW double windows (BeO) output on VSWR<1.4 any phase
- Collector dissipation: 800 kW
- Body loss < 5 kW
- Window loss < 3.2 kW

- Test at KSTAR: 20 s @460 kW, 800 s @300 kW
- Utilization for test-bed for ITER waveguide components development
Enhance Operational Readiness for ITER by Joint Operation

- High Performance SS Plasma Operation
- Advanced Scenario for ITER and beyond
- Remote Collaboration Prep for ITER

KO-US Collaboration in KSTAR

ITER TBM Collaboration
- Solid TBM R&D
- DCLL/DFLL TBM

Synergetic DEMO Consortium
- Open Innovation for DEMO R&D

Savings on Substantial Capital Investment for DEMO R&D
New ITER Korea Advanced Research Building
To establish a long-term and sustainable legal framework for fusion energy development phases.

To promote industries and institutes which participating the fusion energy development by supports and benefit.

The first country in the world prepared a legal foundation in fusion energy development.

**History of the FEDPL**

- **1995. 12**: National Fusion R&D Master Plan
- **2005. 12**: National Fusion Energy Development Master Plan
- **2007. 3**: Fusion Energy Development Promotion Law
- **2007. 4**: Ratification of ITER Implementation Agreement
- **2007. 8**: Framework Plan of Fusion Energy Development (The First 5-Year Plan)
Strategy for Mid to Long-term R&D for Commercialization of Fusion Power

Mid-Term Plan (‘09 - ‘14) NFRI 2020 (‘15 - ‘20)
- Establishment of foundation to promote fusion energy development
- Becoming one of the world’s top 5 countries in fusion energy
- Securing capacity to build fusion reactor

Design - Construction - Operation - Decommissioning

Milestone for domestic fusion energy research
- KSTAR
- ITER
- Fusion Demo Reactor
- Science Projects involving Fusion Plasma
- Development and Construction of R&D Infrastructure

Milestone for R&D reactor
- Fast Track Approach
- BA: Broader Approach

Fusion Energy Development Promotion Act and Enforcement Decree
Plans for Headquarters Campus

Overview

- Development Duration: 2012-2026 (Construction in three Phases)

Planned Site and Budget

- Site: 330,000m² (with total floor area of 86,800m²)
- Project Budget: about 489 Billion KRW
  - HQ Building, Test Facility Building, Basic Research Building, Development Research Building, Mega Science Infrastructures, etc.
Campus Plan for Headquarters
Phased Development Program for K-DEMO

Strategic Plan of the Program

- Program Definition / Gap Study
- Environmental Analysis for Licensing
- SWOT Analysis for Open Innovation
- Key Strategies & Strategic Initiatives
- Portfolio Management/Cross-Cutting Ideas

Preparatory Sub-Program (07~11)

DEMO R&D Sub-Program (12~21)

DEMO Design & Construction Sub-Program (22~36)

Commercial FPP Construction Sub-Program (37~50)
Korean Demonstration Fusion Reactor (K-DEMO) aimed for another Success following KSTAR and ITER

Perfect Location for DEMO

- Heavy water reactor producing a large supply of tritium
- Low to intermediate-level radioactive waste repository site nearby
- Equipped with large-capacity power transmission facilities for test
Conceptual Layout Study of K-DEMO Plant
R&D Plan toward DEMO (Proposal)

Fusion DEMO R&D

GAP Study

Present Fusion R&D

<KSTAR> <ITER>

DEMO R&D Plan

Open Innovation

KO-US, … Collaboration and Post-ITER Coordination

Broader Approach JA-EU

Other collaboration scheme
Epilogue
Dr. Syngman Rhee, the founding president of Korea, at the groundbreaking ceremony of the first nuclear research reactor in 1959. (TRIGA)
KEPCO UAE Task Force Team is rejoicing for winning Nuclear Power Plant contract on constructing 4 APR-1400 units in Abu Dhabi, UAE (December 2009)