ITER Participation and Possible Fusion Energy Development Path of Korea

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CS Kim, S Cho, DI Choi
ITER Korea TFT
Korea Basic Science Institute
52 Yeoeun-dong, Yusong-ku, Daejeon
305-806, Korea
Outlook

- Korean Energy Program
- Korean Fusion Research Program
- ITER Participation
- We Need Tritium
- Korean Fusion Energy Development Path
Korean Energy Program

- Energy Situation in Korea
- Nuclear Power Program
Energy Situation in Korea

• Energy Import in Korea
  – Lack of domestic natural resources: 97% of energy is imported.
  – 80% of energy import is crude oil from Middle East
  – Anticipated average annual growth rate of energy demand through 2035 is 2.3%

• Rapid Increase of Electricity Demand
  – About 7 times in 20 years from 1980 to 1999 with an average annual growth rate of 10.3%
  – Anticipated average annual growth rate of electricity demand through 2015 is 4.9%.
Energy Situation in Korea

• CO₂ Emission
  – Total emission amount ranks 10th in the world.
  – Emission per unit area is the highest in the world.
  – Export expected to lose price competitiveness due to CO₂ Tax.

• Need to Prepare Future Social Demand
  – Unification of Korea
Nuclear Power Program

• First commercial nuclear power plant Kori Unit 1 started operation in 1978.

• Currently there are 16 PWRs and 4 CANDUs in operation
  – 8 out of 16 PWRs are KSNP (Korea Standard Nuclear Plant)
  – 6 in preparation
  – Total of 28 units by 2015
Nuclear Power Program

• Nuclear Power Share (as of Dec. 2003)
  – 28% of total installed capacity (6th in the world)
  – 40% of total electricity generation

• KO has a substantial infrastructure on nuclear technology
  – Shares the key technologies with fusion reactor
  – Design of various fission reactors
  – Experiences with Tritium recovery and storage from CANDUs
  – Relatively young and experienced staff
Korean Fusion Research Program

- SNUT-79 and KAIST Tokamaks
- KT-1 Tokamak and HANBIT Mirror
- KSTAR
- ITER Participation
SNUT-79 and KAIST Tokamaks

- Korea has been involved in plasma and fusion research in a modest way since the mid-1970s.
- Most activities were small in scale and housed within various universities.
- Based on basic plasma and fusion researches at Universities in 1970’s, Seoul National University developed a small scale fusion research device named SNUT-79.
- And, KAIST (Korea Advanced Institute for Science and Technology) developed another device named KAIST Tokamak.
- These programs have valuable meanings to launch real tokamak projects in Korea, and to develop human resources in Korean fusion program up to now.
SNUT-79 and KAIST Tokamaks

SNUT-79 (Seoul National University)  KAIST Tokamak
KT-1 Tokamak and HANBIT Mirror

• In the mean time, KAERI (Korea Atomic Energy Research Institute) developed KT-1 tokamak in a research institutional territory.

• In 1995, Korea Basic Science Institute installed a medium-sized device called HANBIT, which is now fully operational. HANBIT is devoted to basic plasma research such as basic plasma diagnostics and radio frequency/microwave heating method development.

• It is operating as a national-user facility and drawing more than 20 research work groups from universities and research institutes throughout the nation.
KT-1 Tokamak and HANBIT Mirror

KT-1 Tokamak (KAERI)  HANBIT Tandem Mirror (KBSI)
KSTAR (will be constructed by 2007)

• Korea Superconducting Tokamak Advanced Research

• Mission
  – To extend present stability and performance boundaries of tokamak operation through active control of profiles and transport
  – To explore methods to achieve steady state operation for tokamak fusion reactors using non-inductive current drive
  – To integrate optimized plasma performance and continuous operation as a step toward an attractive tokamak fusion reactor

• Design Features
  – Fully superconducting magnets
  – Long pulse operation capability
  – Flexible pressure and current profile control
  – Flexible plasma shape and position control
  – Advanced profile and control diagnostics
KSTAR Main Hall (March 9, 2005)
KSTAR Tokamak
Vacuum Vessel Fabrication
Cryostat Fabrication Highlights

- Base Plate Assembly
- Bearing Plate
- Connection Ring
- BV Port Stub
- Circular Port of Base
KSTAR TF Magnet Structure Fabrication

- Inner Intercoil Str.
- Outer Intercoil Str. (OIS)
- Outboard Leg
- Inboard Leg
- Connection Plate
TF Structure Fabrication Highlights

- Formed Inter-coil Structure
- Machined Inter-coil Structure
- Welded with Connection Plate
- Cover Structure
KSTAR SC TF Magnet Fabrication
Superconducting Magnet Test
TF Superconducting Test

- More than 30kA achieved

Superconducting Transition @18 K

Coil Resistance vs. Temperature

TF08 SC Coil Test : Current
Heating System Development (KAERI)

NBI Heating System

RF Heating System

MW Heating System
Diagnostics (KBSI, KAERI, KAIST, Univ.)
Power Supply Fabrication (POSCON, PAL)
Industries Participating Fusion Program
KSTAR Construction Progress

<table>
<thead>
<tr>
<th>Component</th>
<th>2003.12</th>
<th>2005.7</th>
<th>Finish</th>
</tr>
</thead>
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<tr>
<td>VV</td>
<td>72%</td>
<td>100%</td>
<td>2004.6</td>
</tr>
<tr>
<td>VVTS</td>
<td></td>
<td>100%</td>
<td>2004.12</td>
</tr>
<tr>
<td>Cryostat</td>
<td>89%</td>
<td>100%</td>
<td>2004.6</td>
</tr>
<tr>
<td>Cryo TS</td>
<td></td>
<td></td>
<td>'05.10.100% 2006.8</td>
</tr>
<tr>
<td>TF Coil</td>
<td>14%</td>
<td>54%</td>
<td>100% 2005.12</td>
</tr>
<tr>
<td>PF Coil</td>
<td>8%</td>
<td>35%</td>
<td>100% 2006.8</td>
</tr>
<tr>
<td>TF Structure</td>
<td></td>
<td>23%</td>
<td>100% 2005.12</td>
</tr>
<tr>
<td>PF Structure</td>
<td></td>
<td></td>
<td>100% 2006.6</td>
</tr>
<tr>
<td>Assembly Finish</td>
<td>22%</td>
<td>100%</td>
<td>2007.8</td>
</tr>
</tbody>
</table>

Note: The progress percentages are approximate and may vary.
Fusion Research Activities in Korea

• Basic Plasma and Fusion Research at Universities : 1970’s

• Construction of Small-scale Fusion Research Device : 1980-1990’s
  – SNUT-79 Tokamak (SNU)
  – KT-1 Tokamak (KAERI)
  – KAIST Tokamak (KAIST)
  – HANBIT Tandem Mirror Device (KBSI)

• KSTAR Tokamak Project (KBSI)
  – Will be constructed by 2007. 8
  – Operate as International Fusion Collaboratory

• ITER
  – KO Participation in June 2003
ITER Participation

• KO’s Mid Entry
• Parameters
• The Site
• ITER’s Opportunity
• Korean Opportunity
KO’s Fusion Research Strategy

**Fusion Energy**

- **ITER (International Plan)**
  - (2015) [Experimental Verification of Fusion Energy]

- **KSTAR (National Plan)**
  - (2007) [World Famous Tokamak Construction]
  - (1995) [National Plan]

**Institutional Programs**

- SNU
- KAIST
- KAERI
- KBSI

**National Fusion Research Plan**

- (late 70’s~1995)
- (After 2035) [Fusion Power Plant Demonstration]

**Year**
KO’s Mid Entry

Equivalent Fusion Power Output (Watts in Log Scale)

Year


10^-1 10^-2 1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9

Projected (World-Wide)
Achieved (World-Wide)
Projected (Korea)
Achieved (Korea)

ALCATOR A
ALCATOR C
ATC
TFTR
PDX
DIll-D
JET
JET/TFTR
DIII-D
PLT
SNU-T79
KAIST-T
KT-1

KO’s Mid Entry
ITER Main Features

- Central Solenoid
- Outer Intercoil Structure
- Toroidal Field Coil
- Poloidal Field Coil
- Machine Gravity Supports
- Blanket Module
- Vacuum Vessel
- Cryostat
- Port Plug
- Divertor
- Torus Cryopump
### ITER Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fusion power</td>
<td>500 MW (700MW)</td>
</tr>
<tr>
<td>Q = fusion power/auxiliary heating power</td>
<td>$\geq 10$</td>
</tr>
<tr>
<td>Average neutron wall loading</td>
<td>0.57 MW/m² (0.8 MW/m²)</td>
</tr>
<tr>
<td>Plasma inductive burn time</td>
<td>$\geq 300$ s</td>
</tr>
<tr>
<td>Plasma major radius</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Plasma minor radius</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Plasma current ($I_p$)</td>
<td>15 MA (17.4 MA)</td>
</tr>
<tr>
<td>Vertical elongation @95% flux surface/separatrix</td>
<td>1.70/1.85</td>
</tr>
<tr>
<td>Triangularity @95% flux surface/separatrix</td>
<td>0.33/0.49</td>
</tr>
<tr>
<td>Safety factor @95% flux surface</td>
<td>3.0</td>
</tr>
<tr>
<td>Toroidal field @ 6.2 m radius</td>
<td>5.3 T</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>837 m³</td>
</tr>
<tr>
<td>Plasma surface</td>
<td>678 m²</td>
</tr>
<tr>
<td>Installed auxiliary heating/current drive power</td>
<td>73 MW (100 MW)</td>
</tr>
</tbody>
</table>
ITER’s Physics Opportunities

Capability to address the science of self-heated plasmas in reactor-relevant regimes and high $\beta_N$ (plasma pressure), and with the capability of full non-inductive current drive sustained in near steady state conditions.

- Self-heated plasmas: $Q \sim 5$ (long pulse) to 10 (pulsed)
  - Exploration of alpha particle-driven instabilities in a reactor-relevant range of temperatures
- Exploration of high self-driven current regimes with a flexible array of heating, current drive, and rotational drive systems
ITER’s Technology Opportunities

• Integration of steady-state reactor-relevant fusion technology
  – large-scale high-field superconducting magnets
  – long-pulse high-heat-load plasma-facing components
  – plasma control systems (heating, current drive, fueling, …)

• Testing of blanket modules for breeding tritium
KO’s Opportunity by ITER Participation

**Tokamak**
- TF Conductor 20%
- Assembly Tooling
  - About half of Whole Tools
- Vacuum Vessel Main Body 20%
- Vacuum Vessel Port 67%
- Thermal Shield 100%

**Auxiliary**
- Tritium Storage and Delivery 88% + Cash
- Power Supply (AC/DC Converters) 65%
- Diagnostics 4%

**Other Contributions**
- ITER Organization Participation
- Cash Contribution, Test Blanket Modules (Tritium Breeding)
- Physics, Material, Safety, B/A (DEMO, Power Plant)
We Need Tritium

- We Need Tritium
- Present Tritium Supply
- More Tritium Required for the Path to Fusion Energy
We Need Tritium

• Tritium used: 55.8 kg T/yr for 1000 MW$_{fus}$ (includes alpha heat), 100% available

• Tritium bred: Fusion has never done this

• Tritium for next step:
  – ITER startup inventory estimated to be ~ 3 kg
  – DEMO startup inventory likely to be between 4-10 kg

• Tritium available: 18.5 kg (2003)

• Tritium decays at a rate of 5.47% per year.
### Generation Rate of Tritium in PHWR

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Generation Rate [Ci/MW yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^6\text{Li}(n, \alpha) \text{T})</td>
<td>1</td>
</tr>
<tr>
<td>(^7\text{Li}(n, n\alpha) \text{T})</td>
<td></td>
</tr>
<tr>
<td>(^{10}\text{B}(n, 2\alpha) \text{T})</td>
<td>0.0001</td>
</tr>
<tr>
<td>(^{10}\text{B}(n, \alpha) ^{7}\text{Li}(n, n\alpha) \text{T})</td>
<td></td>
</tr>
<tr>
<td>(^{1}\text{D}(n, \gamma) \text{T})</td>
<td>- Moderator 2,340</td>
</tr>
<tr>
<td></td>
<td>- Coolant 60</td>
</tr>
<tr>
<td>Total</td>
<td>2,400</td>
</tr>
</tbody>
</table>
Projected Canadian tritium inventory without major impact from fusion
ITER will have a big impact on tritium supply
We Need More Tritium

- Tritium available for fusion development will likely begin to diminish rapidly during the next 35 years
- Fusion should be developed expeditiously to take advantage of this unique opportunity
- Development of D-T fusion must be carefully planned worldwide taking into account available tritium
  - Experiments without breeding must be low power and/or low availability (ITER-FEAT appears okay...but barely so)
  - Sufficient tritium must be left for next steps
  - Significant losses of tritium must be carefully avoided
- ITER-FEAT may change the operation level to require more tritium.
Additional Korean Tritium Supply

- Wolsong Tritium Removal Facility (WTRF) is now under construction to remove the tritium from heavy water at CANDU reactors in Korea.
- WTRF will start its operation at the end of this year.
- That means that more than 10 kg of tritium from Korea is available additionally.
- Additional Korean tritium supply can be a marginal source to the startup inventories and the consumption in ITER and DEMO.
- Korea is to deliver the tritium storage and delivery system to ITER and this can be very good opportunity to take advantage of Korean tritium supply.
Fusion Tritium Self-Sufficiency

- For the commercial fusion power plants, the achievable tritium breeding ratio should be somewhat larger than the required tritium breeding ratio for self-sufficiency.

- The achievable tritium breeding ratio is a function of technology, material and physics.

- Most of our works on Korean fusion energy development path should be focused on increasing the achievable tritium breeding ratio by the developments of technology, material and physics.
Korean Fusion Energy Development Path

- Fusion Power Plant Study
- Korean Fusion Energy Development Path
- DEMO Concept
- ITER Test Blanket Module
- Korean Unification
Fusion Power

- Ultimate & Clean Energy

- Tritium can be recycled in Fusion Power Plants.

- Fusion is the only known technology capable in principle of producing a large fraction of world’s electricity.

- We should burn our oil to develop Fusion Power Plants.
Fusion Power Plant General Layout

From European PPCS Report
Korean Fusion Power Plant Study

• Should be launched soon.
  – KO has a substantial nuclear infrastructure which shares technologies with nuclear fusion.
  – KO would be serious about the development of the fusion energy.

• The information accumulated in and out of Korea is being investigated.

• Systems code varies the parameters of the possible designs, subject to assigned plasma physics and technology rules and limits, to produce economic optimum.
Korean Fusion Power Plant Study

- Plasma physics concerns
- Cost concerns
- Material concerns
- Maintenance concerns
- Safety concerns

- Outputs
  - Keep the cost of electricity lower
  - Keep safety and environmental features excellent (external costs [to health, environment] ~ wind power)
  - Economically acceptable fusion power stations, with major safety and environmental advantages, seem to be accessible on a fast-track through ITER + material testing by IFMIF (but without major material advances)
Current Strategy

• The world needs major sources of (environmentally responsible) energy.

• Fusion is one of very few options.

• Korean Fusion Power Plant Studies → time to move to a project oriented approach → fast track → DEMO → KFPP
  – This will require a change in mind set, organisation and funding.
  – First steps are
    • fusion community → agree an guiding fast track model
    • government → funding to turn aspirations to reality
Korean Fusion Energy Development Path

• To be approved at National Science & Technology Council
KO DEMO

• DEMO is regarded as the last step before commercial fusion reactor.

• Requirements of DEMO
  – It should demonstrate a net electric power generation.
  – It should demonstrate a tritium self sufficiency.
  – Blanket system should have a reasonably high thermal efficiency to show an extraction of high-grade heat and positive evidence of a low COE.
  – It should demonstrate the safety aspect of a power plant and it should be licensable as a power plant.
KO DEMO

• With limited extension of the expected plasma physics and technology from the 2nd phase of the ITER operation, major technical parameters can be derived (System code analyses).
  – Fusion Power is about 2 GW for a net electricity generation
  – Neutron wall loading is above 2.0 MW/m²
  – Maximum FW heat flux is less than 1.0 MW/m²
  – Low-activation structural material is used
  – Thermal efficiency is above 30%
Korean ITER Test Blanket Module

- **Solid Breeder**
  - Technically mature and all 6 parties have interests
  - Conceptual design of HCSB with graphic reflector is underway
  - Small size sub-module will be tested from a day-one operation of ITER and independent TBM will be tested from a later phase (D-T phase) of the ITER operation.

- **Liquid Breeder**
  - Conceptual design of He-cooled Li-breeder/FS (HCML) is underway
  - HCML TBM will be tested from a day-one operation of the ITER

- **Also interests in the R&D progresses of other TBM families**
  - Will contribute to the development of TBMIs through collaboration
  - Blanket concept as well as the DEMO concept needs to be updated based on the R&D achievements
HCSB TBM

- Reduce Be multiplier by using graphite reflector
  - Optionally Pb multiplier
- Solid Breeders
  - Li$_4$SiO$_4$ (62% packing fraction)
  - Low Li-6 : 40% enrichment
- Be multiplier : 80% packing fraction
- Graphite reflectors
  - 85% packing fraction
  - Can be used as a heat sink
- Structural material : EUROFER
Design of HCSB TBM

Flow path : FW → SW → Breeding zone
HCML TBM

• Cooled by He coolant
• Molten Li is breeder (Li speed < 1 cm/sec)
  – No concern about MHD & material corrosions
  – Li-6 enrichment is 12 wt%
  – Li loop as a redundant cooling circuit in case of LOCA
• Pebble-bed type graphite reflector
  – No need for neutron multiplier
  – Reduced Li Volume (~28 Liters)
  – Maximizing TBR & minimizing neutron leakage
• Structural material: EUROFER
  – FS and Li is compatible up to 550°C
Design of HCML TBM

Flow path: FW → SW → Breeding zone
International Center for Energy Research

Proto/DEMO Fusion Reactor in “Unified Korea”!

Presented at
1992 KAPRA & KPS/DDP JOINT WORKSHOP
Proceedings on Accelerator and Plasma Research
Leading Nuclear Industry in the 21 C
July 14, 1992
Korea Atomic Energy Research Institute
Daejeon, KOREA