Present State and Future Plan of MCF Research in China

Jiangang LI
Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
Outline

HL-2A Tokamak

EAST Tokamak
- Physical engineering capability
- Main experimental results
- Research Plan in next 2-5 years

ITER-CN Activities

Future Plan of CN-MCF program

Summary
**HL-2A Tokamak — Present Status**

- **R:** 1.65 m
- **a:** 0.40 m
- **Bt:** 1.2~2.8 T
- **Configuration:** Limiter, LSN divertor
- **Ip:** 150 ~ 480 kA
- **ne:** 1.0 ~ 6.0 x 10^{19} m^{-3}
- **Te:** 1.5 ~ 5.0 keV
- **Ti:** 0.5 ~ 1.5 keV

**Auxiliary Heating:**

- ECRH/ECCD: (3+2) MW
  - (6/68 GHz/500 kW/1 s)
  - Modulation: 10~30 Hz; 10~100 %
- NBI (tangential): 1.5 MW
- LHCD: 1 MW
  - (2/2.45 GHz/500 kW/1 s)

**Fueling System (H\textsubscript{2}/D\textsubscript{2}):**

- Gas puffing (LFS, HFS, divertor)
- Pellet injection (LFS, HFS)
- SMBI (LFS, HFS)
  - LFS: f =1~80 Hz, pulse duration > 0.5 ms
gas pressure < 3 MPa
ELMy H-mode discharges were achieved on HL-2A tokamak.
HL-2A Tokamak

EAST Tokamak

- Physical engineering capability
- Main experimental results
- Research Plan in next 2-5 years

ITER-CN Activities

Future Plan of CN-MCF program

Summary
EAST: 5.5 years, 30M$ (TPX)

- CICC & magnet design and fabrication
- Control system
- ICRH & LHCD system
- Vacuum pumping system
- SC magnet test
- 2kW/4.5K Cryogenic & refrigerator system
- 210MW Power supply system
2006-9-26, 1st Plasma

Vloop=5.7 V

disruption
Key elements in-vessel

- Actively-cooled PFC (~9000 tiles)
- Internal Cryo-Pump
- LHCD: 2.45GHz, 2MW
- ICRF: 30-110MHz, 1.5MW
- Magnetic sensors
- 2 Removable limiter

75,600L/S for D2 With DIII-D

High heat flux region 2MW/m²

Total 37 flux loop
Main diagnostics (~50, IFS, GA, PPPL, ORNL)

Key Profiles
Te, Ti, ne, Zeff, Prad, Ha

Advance diagnostics
Thomson scattering (25)
TXCS,
PXCS,
ECEI (384)
Dual-polarization reflectometer
ECE (32)
Fast Moving LP
GPI, CO2 scattering
Edge diagnostics
New Method: HF_GDC

- **Power Supply:** $U=1.0$KV, $f=100$KHz, $I\sim 0.5-1.0$A
- **Work Gas:** Ar, He, H2
- **GDC electrode**
- **HT-7:** $5\times 10^{-4}$Pa-0.5Pa, $B_t=0.5-2$

HF-GDC is routinely used in HT-7 for wall conditioning, siliconization and recycling control between shots which shows almost the same effects with RFWC.

**Recovery from 10Pa leakage**

- Proceed with Bt
- Without Bt

**B-Field**

Vertical view window @Top

- $P=5.0E-2$Pa, IGD=1.0A, $B_t=1.0$T, He
- $P=5.0E-4$Pa, IGD=1.0A, $B_t=1.0$T, H2
Li Wall Conditioning (PPPL)

• Li Oven: RF coating (10-60g) Evaporating
• Li power dropper
• Main Results:
  • Very good and quick technique
  • $Z \sim 1.5-2.5$
  • More broad Te and radiation profile
  • Low recycling
Fueling Effect of Gas Puff Locations

DOME D$_2$ puffing has highest fuelling efficiency, less from inner target plate, lowest from outer target plate. Compared to SN configuration, DN is more sensitive to gas puffing location.
Effect of Ar:D2 mixture gas injection into upper and lower outer divertors

EAST adopted ITER-like vertical target configuration, which promotes detachment near strike point. However, this scenario by density ramping is not fully compatible with LHCD and high confinement scenario, radiative divertor is required.

- D2+5.7% Ar mixture puffing was initiated at 5s led to detachment at both upper and lower outer divertor targets
- Significantly reducing the peak heat fluxes, $q_{\text{peak}}$, near outer strike points
- $Z_{\text{eff}}$ is reduced

Ar puffing in divertors promote partial detachment and reduce peak heat flux
A minimum (dip) $V_{\phi}$ at ~1 cm inside the separatrix.

Collisionality > 4, in the Pfirsch-Schlüter regime.

It is situated at the same location of a dip of $E_r(r)$.

But a dip of $V_{\phi}(r)$ not observed in the discharges that the plasma edge touches the outer limiter.
Long Pulse Discharges (With GA)

In 2008

Ip~0.25MA, DN, elongation~1.8, triangurity~0.5,
It=9000A, Ne~1.2, Te~1.3keV, PLHCD~0.8MW

In 2009

In 2010
First H mode by Li coating either by oven or by lithium powder injection
6.5s H-mode by RF+LH (MIT,PPPL)

H-mode during ramp-up, flat-top and ramp-down phases, very important for ITER
Lithized wall on HT-7

Recent HT-7 experiments demonstrated the feasibility of Lithized full-metal wall for recycling/impurity control and effective ICRF heating
EAST 2012 capabilities

PF power supply upgrade
SMBI, SS Pellet injector
1/2 C tiles change to Mo tiles
PFC modification for 250°C and longer pulse with different puffing (place and gases)

• 4 MW LHCD @ 2.45GHz ✓
• 1.5MW ICRF @ 30-110MHz ✓
• 4.5MW ICRF @ 25-75MHz ~✓

• Diagnostics (61) → all key profiles and some of specific measurements for physics understanding

0.6-1MA operation

H-mode operation

For ITER
Safe start-up & termination
VDI
PWI
Fueling
Wall conditioning
ELM control

30s H-mode
200-400s DN
CN-MCF Near Term Plan (2020)

**ITER construction**
- ASIPP: Feeders (100%), Correction Coils (100%), TF Conductors (7%), PF Conductors (69%), Transfer Cask System (50%), HV Substation Materials (100%), AC-DC Converter (62%)
- SWIP: Blanket FW (10%), Shield (40%), Gas Injection Valve Boxes, GDC Conditioning System (88%), Magnetic Supports (100%)
- Diagnostics (3.3%)

**Enhance Domestic MCF**
Upgrade EAST, HL-2M ITER technology
TBM (Two options)
T-Plant
University program
DEMO design (Wan)
DEMO Material
Education program (2000)
70-80% of ITER-CN budget

Can start construct CN pilot power plant before 2020
<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ip(MA)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>LHCD(MW, CW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.45GHz</td>
<td>4.0</td>
<td>4.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>4.6GHz</td>
<td></td>
<td></td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>ICRF(MW,CW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-75MHz</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>30-100MHz</td>
<td>1.5</td>
<td>4.5</td>
<td>4.5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>NBI(80keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECRH(140GHz,cw)</td>
<td>1.0</td>
<td>2.0</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Diagnostics</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Duration(s)</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>t-Hmode(s)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>100</td>
<td>400</td>
</tr>
</tbody>
</table>

With over 20MW CW power and 50 diagnostics, EAST could play a key role for long pulse advanced high performance plasma for ITER within next 5 years.
Efforts Made - EAST ATSSO

NBI(2013) 4MW(80KeV)

LHCD(2013) 6MW(4.6GHz)

RF(2014) 6 MW 30-100MHz

NBI(2015) 4MW(80KeV)

ECR(2014) 6MW

LHCD 4MW(2.45)

1MA, 100s, 3.0T
6.5s H, 3MW @ 2010

1.5MA, 1000s, 4.0T
400s H, 36MW @ 2015
PFC Strategy for ATSSO

- **Initial phase** (2006-2007)
  PFM \(\Rightarrow\) SS plates bolted directly to the support without active cooling

- **First phase** (2008-2012)
  PFM \(\Rightarrow\) SiC-coated doped C tiles bolted to Cu heat sink \(\sim 2\text{MW/m}^2\)

- **Second phase** (2013-2016)
  Full W, Actively-cooled ITER W/Cu divertor, 10MW/m\(^2\).

- **Last phase** (2017--)
  High Tw operation (>400C) by hot He Gas 15MW/m\(^2\).

**Edge Simulation under H-mode**
With LLNL, ENEA, TS, ITER-IO
Outline

HL-2A Tokamak

EAST Tokamak
- Physical engineering capability
- Main experimental results
- Research Plan in next 2-5 years

ITER-CN Activities

Future Plan of CN-MCF program

Summary
ITER-Conductor: Ready for deliver

Wire: NICNC, Oxford  
Coating: Shenghai Ltd  
Wire testing: ASIPP  
Central tube: Tai Steel,

Cabling: Basheng Ltd,  
316LN Tube:  
Integration: ASIPP

1000m jacketing line  
In ASIPP
I. **Current Scope of CN procurement**
   - Current: 10%FW and 40%SB.
   - New proposal: 12.6%FW and 50.2%SB.

II. **First wall (FW) qualification**
   Two phases towards manufacturing.
   (1) Qualification of Be/Cu/SS joining technology by fabrication & testing qualification mock-ups;
   (2) Semi-prototype qualification.

III. **Shielding block (SB) analysis and technology**
   - Modeling, hydraulic, thermal stress, EM analysis;
   - 316L(N), deep EB welding and hole drilling.

IV. **Materials research and qualification**
   - Qualification of Chinese VHP-Be for ITER FW;
   - Post-fabrication property of CuCrZr alloy.
Feeders: Start Construction
ITER Power Supply: Start Construction

ITER power supply Package in CN
⭐ AC/DC converter (share with KO)
  Tested on EAST
⭐ Reactive power compensation
⭐ HV substation

Local control R&D
DC inductor R&D

AC/DC Converter structure R&D
Converter arm displacement in EM force
Outline

HL-2A Tokamak

EAST Tokamak

- Physical engineering capability
- Main experimental results
- Research Plan in next 2-5 years

ITER-CN Activities

Future Plan of CN-MCF program

Summary
Planning for Next Step

- **CN-Design team (18)**
  - Y.Wan, J.Li, Y.Liu, X.Wang
  - Phy. Design, 13 sub-groups
  - 2 options within 3 years (ECD1)

- **Eng. Design (4-6 Y)**

- **Key R&D (3-10 Y)**
  - Diagnostic
  - Blanket (TBM, FFHM)
  - Magnet
  - T-plant
  - RH

- **Education (10 years)**

---

2016-2025 Construction

Rank No.1 in 2016-5Y plan

Operation:

- 5-years, H2, He (D2)
- 6-8 Y DT-1 operation
- 6-8 Y DT-2 operation

ITER

2019: 1st Plasma

2027: DT-1, Q=10, 400s

2037: DT-2, Q=5, 3000s
Efforts Made-Education

Present state:
- ASIPP: HT-7/EAST (150 students), ITER (80 students)
- SWIP (60)
- School of Physics (USTC, 25)
- School of Nuclear Science (USTC-ASIPP, >50)
- CN-MOE-MCF center (10 top universities) 50

Total about 450 students, 150/y, 20-30% remain in fusion

Targets and efforts
- 2000 fusion talents in 2020
- MOST, MOE, CAS, CNNC have lunched a national fusion training program for next 10 years.
  - Basic training in 10 top univ.
  - Join EAST/HL-2A experiments
  - Small facilities in Univ.
  - Foreign Labs & Univ.
  - Annual summer school, workshop
<table>
<thead>
<tr>
<th>Year</th>
<th>Efforts Made</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>Present state</td>
</tr>
<tr>
<td></td>
<td>• 5 year-MCF plan</td>
</tr>
<tr>
<td></td>
<td>• 10-year MCF plan</td>
</tr>
<tr>
<td></td>
<td>2010 Hybrid concept design</td>
</tr>
<tr>
<td></td>
<td>• 10-year MCF plan</td>
</tr>
<tr>
<td></td>
<td>2011 CN-MCF Reactor design</td>
</tr>
<tr>
<td></td>
<td>Solid TBM concept design</td>
</tr>
<tr>
<td></td>
<td>DCLL TBM concept design</td>
</tr>
<tr>
<td></td>
<td>PWI</td>
</tr>
<tr>
<td></td>
<td>ITER design</td>
</tr>
<tr>
<td></td>
<td>ITER-ICRF</td>
</tr>
<tr>
<td></td>
<td>MCF-talent (8, exp.)</td>
</tr>
<tr>
<td></td>
<td>T-plant design</td>
</tr>
<tr>
<td></td>
<td>MCF-talent (5, simulation)</td>
</tr>
<tr>
<td></td>
<td>MCF-talent (11, material)</td>
</tr>
</tbody>
</table>
R&D Plans for CN HCSB TBMs

- **Fabrication Technology**
  - Mockup of U-shape first wall (2010)
  - Mockup of sub-module (2012)
  - Small-size (1:3) Mockup of HCSB TBM (2013)

- **Helium Cooling System**
  - Design of Test facility for FW
  - Test facility of mockup (2013)
  - Prototype HCS for ITER TBM (2016)

- **Breeder Materials**
  - Li$_4$SiO$_4$ pebble (in-pile 2014-2016)
  - Be pebble in lab. level (2013)
  - Be-irradiation test (2017)

- **Structure Materials**
  - RAFM join by laser solid forming and by diffusion bonding (2010);
  - RAFM HIP join (ongoing);
## Development of DRAGON Series LiPb Loops

<table>
<thead>
<tr>
<th>Loop name</th>
<th>Type</th>
<th>Function</th>
<th>Temperature</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAGON-I</td>
<td>TC*</td>
<td>Material Compatibility</td>
<td>420–480°C</td>
<td>2001-2005</td>
</tr>
<tr>
<td>DRAGON-II</td>
<td>TC</td>
<td>Compatibility</td>
<td>550–700°C</td>
<td>2004-2006</td>
</tr>
<tr>
<td>DRAGON-III</td>
<td>TC</td>
<td>Compatibility</td>
<td>800–1000°C</td>
<td>2007-2009</td>
</tr>
<tr>
<td>DRAGON-S*</td>
<td>Static</td>
<td>Compatibility</td>
<td>250–1000°C</td>
<td>2008-2009</td>
</tr>
<tr>
<td>DRAGON-R*</td>
<td>Flowing</td>
<td>Compatibility</td>
<td>450–600°C</td>
<td>2009</td>
</tr>
<tr>
<td>DRAGON-IV</td>
<td>FC*</td>
<td>Material Compatibility, Thermal-hydraulics, MHD, Purification of LiPb, etc.</td>
<td>480–800°C</td>
<td>2007-2009</td>
</tr>
<tr>
<td>DRAGON-V</td>
<td>FC</td>
<td>Dual-coolant test for TBM, MHD test for the complex ducts</td>
<td>300–700°C</td>
<td>2010-2012</td>
</tr>
<tr>
<td>DRAGON-VI</td>
<td>FC</td>
<td>Auxiliary system for EAST-TBM</td>
<td>-</td>
<td>2012-2015</td>
</tr>
<tr>
<td>DRAGON-VII</td>
<td>FC</td>
<td>Auxiliary system for ITER-TBM</td>
<td>-</td>
<td>2015-2018</td>
</tr>
<tr>
<td>DRAGON-VIII</td>
<td>FC</td>
<td>Auxiliary system for DEMO blanket</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*TC: Thermal Compatibility, FC: Flowing Compatibility, FC*: Dual-coolant test

![Diagram of DRAGON Series LiPb Loops](image)
Choice 1: Smaller machine
R=5m; a=1.5m; k=1.75;
T=4.5K, BT=5T; Ip=8MA;
ne=1-4x10^{20} m^{-3};
Step 1: Beta N = 2.5
Pth: 150MW-300MW
Step 2: AT H-mode, Beta N = 3-4
Pth: 1-1.5GW
Q=2-5, t> 8 hour, SSO
Material & Component testing,
T breeding (TBR>1),
T fuel recycling, RH validation
RAMI validation
FFH blanket testing (SFB, TM)

Choice 2: ITER-like machine
R=6.5m; a=2.5m; k=1.75;
T=4.5K, BT=5T; Ip=8MA;
ne=1-4x10^{20} m^{-3};
Step 1: Beta N = 2.5
Pth: 300MW-500MW
Step 2: AT H-mode, DEMO-like
Pth: 2-3GW
T> 8 hour, SSO
Material & Component testing
T breeding (TBR>1),
Pure fusion TBM configuration
RH validation, RAMI validation
Close fuel cycle
FFH blanket testing (SFB, TM)
Possible Plan and Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Conceptual Design</td>
<td>2Y</td>
</tr>
<tr>
<td>2015</td>
<td>Physical Design</td>
<td>2-3Y</td>
</tr>
<tr>
<td>2017</td>
<td>R&amp;D</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diagnostic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Magnet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T-Plant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Blanket</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FTB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FFHB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Engineering Design</td>
<td>5-7Y</td>
</tr>
<tr>
<td></td>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Communication Phase D2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D-T 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D-T 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITER</td>
<td></td>
</tr>
</tbody>
</table>

- 2019: 1st Plasma
- 2027: D-T Q=10
- 2035: PFH Demo
- 2045: MFE Demo
International cooperation

- France, CEA, CADERACHE
- UK, UKAEA, CULHAM
- EU, JET, EFDA
- Germany: IPP, Garching, KFA, Julich
- Italy, Frascati: ENEA
- USA: UT/IFS, GA, PPPL, U Illinois, PSFC/MIT, SNL, ORNL, LLNL, UCLA, UCSD
- ITER-IO, 6—DAs
- Japan: NIFS, JAEA, JSPS, Tokyo (20M$/y)
  > 30 univ. in each side.
- India, IPR, Bhat
- Korea, KFRI, KBSI
- Russia: Kurchchatov institute
  St. Petersburg, AFIPT
  Troisk: Triniti
- Swiss: DRCP
- Holland: FOM
Cooperation with US

More than 20 years cooperation
Mutual benefits
Ken obtained 04 state reward
Cooperation with DIII-D

- Wide cooperation for experiments, theory, technology
- good internet connections
- Exchange of Hardware for 5-6M$
- Exchange of personnel 20m/y
- From DIII-D&EAST to ITER

2009 State international cooperation reward
Cooperation with PPPL

• Experiments (＞15 Scientists from PPPL)
• Technology (hardware exchange)
• Theory (joint research plan)
• Joint ITER activities
• Future: FSP (simulation EAST, ITERC, FETER)
Very Strong Support from Top Leaders
and Public (10,000 visitors to EAST)
Opportunities and mechanisms for collaboration

• Opportunities:

**EAST**: 400-1000s, full metal, 30MW, hot wall, 3rd shift by US
Joint task forces, detail planning

**ITER**: sharing resources from both country, joint teams.

**Next device**: joint teams, 2nd Option, FSP, joint facilities

• Mechanisms

**Standard operation found**
1-2% of MCF budget from each side

**5 years plan**
Review, assessment, workshop

**Based on present frame**
Administration, physics, engineering

“US and China should joint more closely for fusion research which is beneficial for whole human being. I would like to see your successes.”
## Fusion budget

**Fusion research deserve more budget**

**Contribution to ITER should based on sound demotic program**

### Joint US-CN ITER teams
- SC PA, 25-35% cheaper
- SS PS, 20% cheaper
- Blanket, 20% cheaper
- RF transmission 40%

Assign sub-contracts to CN
- $25\% \times 145M = 36M$
- ASIPP PA: 2-3 M$

**Joint Contracts from IO: 3-4M$**

**Total: 41-43M$**

### Non-ITER activities
- CN MCF TFs: 3-4M$
- Design, experiments, R&D
- US MCF TFs: 5-6 M$
- NSTX-Upgrade
- DIII-D Upgrade
- hardware exchange, sub-contracts
- Education
- FSP

**Total: 8-10M$**

40-50M$ saving per year might be possible, need careful and long term planning
**Summary**

- EAST Starts important experiments with helps from international cooperators, especially from US. EAST is fully open and EAST is also yours.

- By joining ITER project, China will work more closely with other 6 parties for a successful operation of ITER.

- China would do its best to try catching up. Your helps and suggestion are valuable.

- More close cooperation between US and CN will beneficial to us. I am sure we will have more productive outcome in future.
Thanks

Welcome to visit ASIPP