Superconducting Tokamak Program in China

HT-7U Team Presented by Weng Peide

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Introduction

• The steady state operation is one of the basic requirements for future fusion reactor. In order to explore this issue, ASIPP started superconducting tokamak project in 1991.

• The project includes two steps: the first step is to build **HT-7 tokamak**; second step is to construct an upgrade device **HT-7U**.
Two Steps

**First Step:** ASIPP Received T-7 tokamak from Kurchatov Institute in 1991 and modified it to HT-7 in end of 1994. The experiment on it mainly concentrated on the topic related with long pulse operation, ICRH and LHCD. The operation and experiment on HT-7 accumulated experience in both physics and technology, provide a basis for Chinese Superconducting tokamak project.

**Second Step:** A new superconducting tokamak project HT-7U, aiming at steady state advanced tokamak operation, was proposed in the year of 1994, and approved as one of key national science project in 1998 by Chinese government. The HT-7U project is on progress now, the construction will be completed in 2005.
HT-7 Superconducting Tokamak
The main parameters of HT-7

R = 1.22m    a = 0.285m (C Limiter)    B_T = 1~2.5T (2.5)
Ip = 100~250 kA (250)    ne = 1~8x10^{13} cm^{-3} (6.5)
Te = 1~2 KeV (2.9)    Ti = 0.2~0.6KeV (0.8)
t = 1~5s (20s)
ICRF: f = 15~45MHz,    P = 0.35MW, CW (0.35, 10s)
LHCD: f = 2.45GHz,    P = 1.2MW, 10s (0.85MW)
Pellet injector: up to 8 pellets /per shot
Supersonic beam injection: <1.0 km/s
Pump limiter (Mo head)
New vacuum vessel was made & 34 new larger ports were increased to improve the accessibility satisfying requirement of diagnostics, auxiliary heating & current drive.
TF coils of HT-7. Two TF coils of T-7 were merged into one coil of HT-7.

Number of TF coils reduced from 48 to 24 to get more space between two coils to provide the possibility of increasing new larger ports on the vacuum vessel.
HT-7 Progresses in 2001

- **Technical improvements:**
  Ripple reduction, CW PFP system, C limiter and exhaust system, new wave systems, new diagnostics

- **RF wall conditioning:**
  Boronization, Li coating, Li+Si coating

- **IBW experiments**

- **LHCD experiments**

- **Synergy of IBW and LHCD**

- **Long pulse operation**

- **Steady-state H-mode**
Significant Results in HT7 during 2001

- Several technical improvement have established the base for steady-state operation.
- Quasi-state operation of 1000 times of energy confinement time hot plasma has been obtained.
- RF wall conditioning techniques have been developed which is very useful for future large superconducting devices.
- IBW has been carried out which might be used in controlling profile and the shear flow and H-mode has been obtained.
- SS H-mode with more than 53 energy confinement time has been achieved by combining LHCD and IBW.
- Long pulse operation
Long pulse discharge with plasma duration longer than $1000 \tau_E$
Good confinement with $H_{93} > 1$ for 1.1 seconds
Steady-state H-mode

\[ I_p = 215 \text{kA}, \quad n_e = 2.6 \times 10^{19} \text{m}^{-3}, \quad B_T = 2.0 \text{T}, \quad P_{\text{LHCD}} = 250 \text{kW}, \quad P_{\text{IBW}} = 130 \text{kW}, \quad T_e = 2.9 \text{keV}, \quad T_i = 1.6 \text{keV}, \quad H_{89} = 1.6, \quad t_H/\tau_E = 53 \]
RF siliconization-SiH₄:He=90:10, 1 hour

- Different edge plasma property due to the different profiles
- Si is not only O capturer but also a radiator, which has higher boundary ne and lower edge Te for the same line-average ne;
- It is very easy to control density
No impurity problem with boronized wall and the new antenna;
P_{\text{max}}=350\text{kW}, T_e=3.3\text{keV};
B_T=1.8\text{T}, \Omega_H=-10\text{cm},
\Omega_{5/2D}=12\text{cm};
Maximum \Delta n_e T_e/P_{\text{IBW}} = 9.2\times 10^{19}\text{m}^{-3}\text{eV/kW}

- Off-axis heating was observed
- Very broad ne profile was obtained
- An ITB-like ne profile at r/a=0.8
- $\tau_E$ and $\tau_p$ are increased
MHD suppressing by IBW

- A power threshold of 100kW is required
- $\Omega_{5/2D}$ is setting at the $q=2$ surface.
- The ponderomotive stabilization or current profile is modified
20s reproducible hot plasma discharge

Ip=50kA, n_e0=1.0x10^{19} m^{-3}, B_T=1.9T, P_{LHCD}=135kW
The main mission of the project is to develop an advanced full superconducting tokamak and explore the science and technological bases for fusion reactor.

- **Demonstrate of steady-state operation with high plasma performance.**
- **Investigate of advanced tokamak physics and demonstration of stationary H-mode operation** by strong shaping, current profile control and auxiliary heating.
- **Investigate of particle and heat fluxes handling** on a time scale much longer than the wall equilibration time.
Main Parameters of the HT-7U

- Major Radius $R_o$: 1.75 m
- Minor Radius $a$: 0.4 m
- Toroidal Field $B_o$: 3.5 T
- Plasma Current $I_p$: 1 MA
- Elongation $K_x$: 1.6 - 2
- Triangularity $\delta_x$: 0.4 - 0.8
- Pulse length: 1000 s

Heating and Driving: (first phase)
- ICRF: 3 MW
- LHCD: 3.5 MW
- ECRH: 0.5 MW

Configuration:
- Single null divertor
- Double-null divertor
- Pump limiter
Design feature of HT-7U

• Full superconducting magnets;
• CW inductive current driven system and heating systems;
• Large operation space for the advanced operation flexibility;
• Real-time plasma position and shaping controls
• Standard PFC with changeable tile structure
• Divertor for power and particle handling
• Advanced diagnostics
TF & PF Magnets

- The TF Magnet System consists of 16 D shape coils, each coil has 130 turn, Maximal field at coil 5.8T, Operating current 14.3 kA, Total storage energy 300 MJ.
- The PF magnet system consists of three pair of Central Solenoid coils and four pair of PF coils. Maximal field at coil 4.5T, Maximal operating current is 14.5kA Maximal field change rate is less than 6.8T/s The flux swing of the PF magnets will be 10 VS
- NbTi Cable in Conduit Conductor with large quantity of segregated copper is chosen for both TF & PF magnet. Vacuum pressure impregnation will be adopted.
- The TF & PF magnets will be cooled by 3.8 K supercritical helium.
Vacuum Vessel & in vessel components

- Full welded **double wall structure**.
- **Sixteen horizontal ports and thirty two vertical ports** for Diagnostic, auxiliary heating and current drive
- **Divertor and limit armed by graphite and CFC tiles**
- **Passive stabilizers and fast feed back control coils.**
- **Armor electrical heater back up the vessel and first wall up to 200 ° C and 350 ° C respectively.**
- **Active cooling for first wall components and vessel wall.**
- **Flexible gravity supports.**
Status of HT-7U

- The engineering design of Tokamak is completed already.
- Most of R& D work including Conductor development, Model coil and related technology is completed last year. First wall material R&D is on the way.
- CIC conductor jacketing line, two winding machines, a set of VPI equipment and a test facility for the TF and PF coils are ready in ASIPP, the manufacture of TF CIC conductor and TF coils has begun already.
- One prototype TF coil is wound and one prototype of PF coil will be fabricated soon, both TF and PF prototype coils will be tested this year.
- Prototype of 1/16 vacuum vessel, prototype of 1/16 thermal shield and cryostat are in manufacture in industrial now, they will be delivered in beginning of next year.
Large proportion of segregated cooper in conductor (68%) 
Different surface coating for TF and PF respectively 

CICC for HT-7U TF & PF magnets
**I_c measurement**

<table>
<thead>
<tr>
<th>Temperature T (K)</th>
<th>Critical current I_c (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>65</td>
</tr>
<tr>
<td>5.2</td>
<td>60</td>
</tr>
<tr>
<td>5.4</td>
<td>55</td>
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<tr>
<td>5.6</td>
<td>50</td>
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<td>5.8</td>
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<td>6.6</td>
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<td>7.6</td>
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<tr>
<td>7.8</td>
<td>-5</td>
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</table>

B=4.5 T  
dm/dt=2.8 g/s  

**Results of AC loses measurement**

<table>
<thead>
<tr>
<th>Frequency f, HZ</th>
<th>ac losses, mJ/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<tr>
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</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
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</table>

**Transient stability against Magnet field disturbance**

- TF: 5.8T, T=4.6K  
- PF1: 4.5T, T=5.8K  
- PF2: 4.5T, T=4.6K  
- PF3: 4.5T, T=4.6K  

**IC measurement**

- TF: 5.8T, T=4.6K  
- PF1: 4.5T, T=5.8K  
- PF2: 4.5T, T=4.6K  
- PF3: 4.5T, T=4.6K  

**Calculated**

- Tcs-Top (K)
  - 0.25
  - 0.30
  - 0.35
  - 0.40
  - 0.45
  - 0.50
  - 0.55
  - 0.60
  - 0.65
  - 0.70

**F/T/s**

- 0.25
- 0.30
- 0.35
- 0.40
- 0.45
- 0.50
- 0.55
- 0.60
- 0.65
- 0.70

**Integration of (dB/dt)*(dB/dt)*dt, T2/S**

- TF: 4.5T, 14.3kA  
- PF1: 4.0T, 14.5kA  
- PF2: 4.5T, 14.5kA  
- PF3: 4.5T, 14.5kA  

**Transients of (dB/dt)*(dB/dt)*dt, T2/S**

- TF: 5.8T, T=4.6K  
- PF1: 4.5T, T=5.8K  
- PF2: 4.5T, T=4.6K  
- PF3: 4.5T, T=4.6K
Stress measurement of Vacuum Vessel ports and support
Jacketing Line and 600 meters long CICC Conductor
Diameter available 3.1 m
Height available  4.7 m
Vacuum       $1 \times 10^{-5}$
Maximal current  30 kA
Refrigerator 500W/4.5 k
The prototype of TF and PF magnet will be tested in the facility this year

Superconducting magnet test facility
CS model coil installed in test facility
CS Model Coil exciting
TF prototype coil winding
TF coil case machining
The power supply system consists of power supplies for TF magnets, for PF magnets, power supply for fast plasma position control and a new 83 MW transformer substation.

New transformer substation in construction

First set of PF power supply installation
The cryogenic system:
2kW/4.4K+11kW/80K refrigerator.
Supercritical Helium pump for He circulation.
1000L-3.8K sub-cooler for TF & PF coil cooling.
10000L-4.5K liquid tank for liquid Helium storage

Compressor station & Helium gas storage system
1MW 2.45GH LHCD launcher

1.5MW/30-110MHz RF generator

2MW LHCD power supply
ASIPP

Summary

- Superconducting program is a long term national research program.
- The operation and experiment on HT-7 accumulate rich experience in both plasma physics and technology. The further experiment on HT-7 will carry over 4-5 years, the next target is to reach longer high performance plasma up to 30-60 Seconds.
- The main mission of HT-7U project is to develop an advanced full superconducting tokamak and explore the science and technological bases for fusion reactor.
- Fabrication HT-7U has begun. It is hopeful to get the first plasma around 2005.
- ASIPP hope our Superconducting program could make some contribution for world fusion community and welcome international collaboration.