EXL Fusion Power Technology R&D
ENN Energy Research Institute
Hebei Key Laboratory of Compact Fusion

March 26, 2021
ENN Fusion R&D Mission — Compact Clean Commercial (Low Unit Cost) Power. But How?

**Compact Simplified**

**Fusion ENN**

**Low Unit Cost**
Mass Produced
~6c/kW-hr
(310 USD)

**Protect Environ’t**
Aneutronic
Tritium-free
### Main design parameters of EXL-50

- **No CS coil**
- **No divertor**
- **No first wall**
- **Fully welded vacuum vessel**
- **Drive plasma current with ECRH**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current</td>
<td>( \leq 0.5 \text{ MA} )</td>
</tr>
<tr>
<td>Thermal ions major radius ( R_i )</td>
<td>0.48 m</td>
</tr>
<tr>
<td>Energetic electron cloud radius</td>
<td>0.7 m</td>
</tr>
<tr>
<td>Thermal ions aspect ratio (LCFS)</td>
<td>1.5</td>
</tr>
<tr>
<td>Energetic electron cloud aspect ratio</td>
<td>1.3</td>
</tr>
<tr>
<td>Toroidal magnetic field (at ( R_i ))</td>
<td>( \leq 0.5 \text{T} )</td>
</tr>
<tr>
<td>Elongation</td>
<td>( \approx 2 )</td>
</tr>
<tr>
<td>Thermal ions temperature</td>
<td>( \leq 1 \text{ keV} )</td>
</tr>
<tr>
<td>Energetic electron temperature</td>
<td>0.23 MeV</td>
</tr>
<tr>
<td>Electron density</td>
<td>( 2 \times 10^{19}/\text{m}^3 )</td>
</tr>
<tr>
<td>ECRH power (28GHz)</td>
<td>1.6 MW</td>
</tr>
<tr>
<td>LHCD power</td>
<td>1 MW</td>
</tr>
<tr>
<td>ICRH power</td>
<td>1 MW</td>
</tr>
<tr>
<td>NBI power</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Discharge TF flattop duration</td>
<td>( \leq 5 \text{ s} )</td>
</tr>
</tbody>
</table>
Tungsten-coated copper limiters

- Central column limiters (4)
- Vertical limiters: 12
- Upper and lower limiters: 8

Tungsten coating has been shown to survive incident heat fluxes of 10 MW/m² for 1,000 cycles in testing at SWIP, showing shallow surface cracks.
Magnet coils

Parameter | Value
---|---
Turn | 12
Current | 100 kA
Magnetic field | 0.41 T (at R=0.58m)
Materials | CuZr, CuAg
Weight | 13 t
Cooling | water
Ripple | <1.6% (at R=1.51m)
Temperature rise | 70 ℃
Pulse flattop time | 5 s

Central column flexible joint

Poloidal field coils

<table>
<thead>
<tr>
<th>Coils</th>
<th>R,m</th>
<th>Z,m</th>
<th>dR,m</th>
<th>dZ,m</th>
<th>Turns</th>
<th>Current,kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF1</td>
<td>1.908</td>
<td>± 0.963</td>
<td>0.147</td>
<td>0.224</td>
<td>22</td>
<td>17.3</td>
</tr>
<tr>
<td>PF2</td>
<td>1.335</td>
<td>± 2.107</td>
<td>0.147</td>
<td>0.224</td>
<td>22</td>
<td>17.3</td>
</tr>
<tr>
<td>PF3</td>
<td>0.445</td>
<td>± 2.107</td>
<td>0.147</td>
<td>0.224</td>
<td>22</td>
<td>17.3</td>
</tr>
</tbody>
</table>
2 X 2.45-GHz/15kW/CW systems

- Produced first plasma in 2019.
- ECRH startup to ~7kA plasma current at low field.
- Used for discharge cleaning, ECR boronization, and pre-ionization at full field.
1 X 28-GHz/50kW/30s, 2 X 28-GHz/400kW/5s systems

- Electron Cyclotron Resonance Heating (ECRH) alone is used for plasma start-up, heating and current drive during 2020.
- Consist of gyrotron, S/C magnet, MOU, transmission line, antenna, high-voltage power supplies, control and protection system, vacuum, monitor and protection, water cooling systems.
- Installed systems delivered up to ~300kW/4.5s.
- Three antenna systems: toroidal injection angle from -44° to 48° (midplane). Upper antenna injection angle from 0° to 30° (vertical), and from 15° to -30° (toroidal).
- A total gyrotron power of 2.4 MW is planned.
Main Parameters of 1.5MW NBI for EXL-50 Tokamak

- Ion source type: Multi-cusp bucket ion source;
- Number of grids: 3;
- Number of ion sources: 2;
- Acceleration parameters: 50kV/40A/5s;
- Beam Convergence angle: $2 \times 3.2^\circ$;
- Grid convergence angle: $178^\circ$;
- Beam focal length: 5366mm;
- Neutralization efficiency: $> 55\%$;
- Proton ratio: $> 70\%$;
- Pumping speed: $1 \times 10^6$ l/s;
- Residual ion deflection: magnetic deflection;
- Injection angle: $55.3^\circ$;
- Number of filaments: 16
Present and planned diagnostics on EXL-50

- **Black**:已安装(Installed)
- **Blue**:建设中(Under Construction)

### Present Diagnostics

- 120°-S2-500
  - 高速相机1号(Fast Camera #1)
  - 杂散功率测量点2(Stray ECW Power Measurement, #2)
- **红外相机(Infrared Camera)**
- 120°-U2-150
  - 可见光谱仪阵列2(Visible Spectrometer, Array #2)
- 120°-U1-400
  - Hα阵列(Hα Arrays)
- 120°-S1-400
  - VUV谱仪(VUV Spectrometer)

### Planned Diagnostics

- **150°-S2-500**
  - 静电探针(Langmuir probe)
  - 多通道干涉仪(Multi-channel Interferometer)
- **180°-S3-400**
  - 杂散功率测量点3(Stray ECW Power Measurement, #3)
  - 激光离子束轨迹探测器(Laser-driven Ion-beam Trace Probe)
  - 210°-L1-400
  - 硬X射线阵列3(Hard X-ray Array #3)

### Additional Diagnostics

- **90°-S2-500**
  - 软X射线阵列(Soft X-ray Array)
- **60°-S2-500**
  - 可见光谱仪阵列1(Visible Spectrometer, Array #1)
  - 杂散功率测量点1(Stray ECW Power Measurement, #1)
  - 彩色相机(Color Camera)
  - Hα测量(Hα Measurement)
  - EUV谱仪(EUV Spectrometers)
- **30°-S2-500**
  - 单通道微波干涉仪接收端(Single-channel Microwave Interferometer, Receiver)
  - 杂散功率测量点5(Stray ECW Power Measurement, #5)
- **30°-S3-400&U1-400**
  - AXUV阵列征(AXUV Arrays)
- **270°-S2-500**
  - 硬X射线阵列1(Hard X-ray Array #1)
  - 硬X射线阵列2(Hard X-ray Array #2)
2020 progress in driven current

- Transient 172kA, quasi-stationary 140-150kA
- A new record, as far as we know
- Power absorbed by the plasma unknown
<table>
<thead>
<tr>
<th>Founding time</th>
<th>Our people</th>
<th>Honor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 2018</td>
<td>Around 100 researchers with 40% holding PhD degree</td>
<td>Authorized as Hebei Key Laboratory of Compact Fusion</td>
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</tbody>
</table>
Promote an efficient and agile p-B fusion R&D effort, be a member of fusion community

Learning by doing, drawing from expertise in fusion, high-energy particles, laser, materials

Engage experts from schools, laboratories, industries, power companies, private enterprises
“Develop Fusion Energy, Benefit Mankind for Generations!”