pB11-reactor: trends and physics issues

S.Putvinski
For TAE team
OUTLINE

- New cross section for pB\textsuperscript{11}
- Optimization of plasma and device parameters
- Physics issues for reactor
  - Gas/recycling control
  - Plasma fueling
  - Ash control requirements
  - Energy conversion
TAE goal is development of pB\textsuperscript{11} fusion

\[ {^1}\text{H} + {^{11}}\text{B} = {^4}\text{He} + {^4}\text{He} + {^4}\text{He} \]

- **Advantages:**
  - No neutrons (almost), no neutron damage of the wall
  - No Tritium breeding is required
  - Fuel is benign and widely available (\textsuperscript{11}B abundance 80%)
  - Low activation of plasma facing components

- **Difficulties:**
  - High plasma temperature is required
  - The required \( n_T \) is larger than for other fuels
  - Sensitive to He ash
pB$^{11}$ cross section and $\alpha$ spectrum has a long history

New pB$^{11}$ cross sections from TUNL

- pB$^{11}$ cross section have been re-measured at TUNL facility (uncertainty 3.5%). It is higher than previously assumed.
- $\alpha$-particle spectrum is also different from widely accepted (after H. Becker, et al., Z. Phys. A 327 (1987) 341)


pB\textsuperscript{11} fuel has good reactivity

- Maximum fuel reactivity, $\langle\sigma v\rangle^*E_{\text{fusion}}$, of pB\textsuperscript{11} is high:
  - Only 3 times less than DT,
  - Comparable with DHe\textsuperscript{3},
  - 5 times higher than DD

- pB11 fuel requires higher temperature to achieve high reactivity
pB11 can have higher Q than previously concluded

- Ignition of pB11 fuel is possible with new cross sections
- Optimum ion temperature is in the range 200-400 keV
Neutral Beam Driven Field Reversed Configuration

- FRC opens a unique pass to high temperature plasma
- Very low magnetic field -> low synchrotron radiation
- Confinement scaling predicts plasma confinement time increases with plasma temperature

\[ n \tau \sim (rB)^\alpha T^\gamma \]
Two step optimization of design point

- Optimization of plasma parameters to estimate Q
- Optimization of device parameters
0D model

- Power balance equations for ions and electrons

- Total power balance to evaluate NB power:

\[ P_{\text{fus}} + P_{\text{NB}} = P_{\text{brem}} + P_{\text{conv}} \]

- Electron power balance to evaluate \( T_e \):

\[ P_{\text{fus,e}} + P_{\text{aux,e}} + P_{\text{ie}} = P_{\text{brem}} + P_{\text{conv,e}} \]

- Convective loss:

\[ P_{\text{conv}} = n \eta T/\tau_p \text{ with } \eta_i = 1.5, \eta_e = 5.5 \]
Fusion gain, $Q$

- All powers $\sim n_i^2$ -> density drops from balance equations

- Essential plasma parameters
  - Ion temperature, $T_i$
  - Boron concentration, $C_B = n_B/n_i$
  - He ash concentration, $C_{He} = n_{He}/n_i$
  - $n_i\tau_p$

- $T_i$ and $C_B$ are optimized to maximize $Q = P_{fus}/P_{aux}$

- Optimum values: $T_i \sim 330$ keV, $C_B \sim 0.12 - 0.14$. 
Maximum Q of pB11 fuel vs $n\tau_p$ and $C_{He}$

- There is lethal He concentration, $C_{He}$, for each Q
- Ignition is possible but requires very high $n\tau_p$
Q = \frac{P_{fus}}{P_{NB}} > 3 \text{ is required for Plasma Energy Generator (PEG)}

To get net electrical power Q > 3 (at } \eta_{th} = 40\%, \eta_{NB} = 0.7, \eta_{hotel} = 0.15)
80% of fusion power in form of 100-200 keV photons from Bremstrahlung
0.1% of fusion power in form of 1-2 MeV neutron from secondary reaction \( \alpha(B^{11},n)N^{14} \)
Constrain: \( \Delta = \text{shielding} + \text{other shells} + \text{gaps} \sim 0.4-0.5 \text{ m} \)
Optimization of PEG device

- At fixed temperature $n \sim B^2$ and fusion power scales as:

\[ P_{fus} \sim V_p n^2 \sim r_s^3 n^2 E \sim B^4 r_s^3 E \]

- Increase of magnetic field improves economics

- Field is limited by SC technology

- Plasma radius, $r_s > 2\Delta$, for efficient use of magnetic field
Stability constrain $S^*/E$

- Traditional FRC’s have density limit $S^*/E < 3.5$
  
  
  $S^*/E \sim r_s / \rho_L E \sim r_s B/ET^{1/2} \sim n^{1/2}/E$

- Economics drives to higher fusion power density, $p_{\text{fus}} \sim n^2$, i.e. to density limit

- TAE confinement scaling predicts $n \tau_p \sim rTB \sim S^*T$

- The higher $S^*$ -> the larger $n \tau$, the larger power density -> the better economics

- Reactor shall operate close to the density limit. Plasmas with large elongation are preferable for the reactor
Plasma stability limit

- Tilt mode stability $S^*/E < 3.5$
- Present database limited by $E < 10, S^* < 27$
- NB driven FRC’s with high pressure of beam ions are expected to be more stable.
### DEMO-lite, DEMO-E, and Commercial PEG

<table>
<thead>
<tr>
<th></th>
<th>DEMO-lite</th>
<th>DEMO-E</th>
<th>CPEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma radius, rs (m)</td>
<td>0.80</td>
<td>1.20</td>
<td>1.25</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>6.0</td>
<td>6.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Fusion power (MW)</td>
<td>40</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>Q</td>
<td>3</td>
<td>5.20</td>
<td>7.00</td>
</tr>
<tr>
<td>NB power in plasma (MW)</td>
<td>40</td>
<td>40</td>
<td>140</td>
</tr>
<tr>
<td>Net electrical power (MW)</td>
<td>NA</td>
<td>34</td>
<td>380</td>
</tr>
<tr>
<td>Required $n\tau_p\ (10^{21} \text{ s/m}^3)$</td>
<td>10</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Confinement margin for TAE scaling*)</td>
<td>5.6</td>
<td>5.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Ash concentration (%)</td>
<td>&lt;10</td>
<td>4.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

*)Confinement margin = $\tau_p$(scaling)/$\tau_p$ (required)
DEMO-lite (ITER type)

- Demonstration of $Q > 1(3)$ with pB$^{11}$ fuel at pulse length up to 500 s
- No electrical power production
- Does not require high efficiency of NB’s
- Cold, water cooled wall
- Assumed parallel development of efficient NB’s, hot wall technology, direct energy convertors, etc
### DEMO-lite plasma parameters

<table>
<thead>
<tr>
<th>Q</th>
<th>3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required $n_\tau_p$ (s/m^3)</td>
<td>1.0E+22</td>
<td>4.5E+21</td>
</tr>
<tr>
<td>Ash concentration (%)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Ion density, $n_i$ (10^20m^-3)</td>
<td>1.42</td>
<td>1.44</td>
</tr>
<tr>
<td>Fusion power (MW)</td>
<td>45</td>
<td>44</td>
</tr>
<tr>
<td>Radiation power (MW)</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>Convective loss (MW)</td>
<td>12</td>
<td>38</td>
</tr>
<tr>
<td>Proton beam power (MW)</td>
<td>10.8</td>
<td>22.5</td>
</tr>
<tr>
<td>Boron beam power (MW)</td>
<td>4.3</td>
<td>5.8</td>
</tr>
<tr>
<td>RF power (MW)</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Confinement time (s)</td>
<td>100</td>
<td>31</td>
</tr>
<tr>
<td>Confinement margin*)</td>
<td>5.6</td>
<td>18</td>
</tr>
<tr>
<td>$S^*/E$</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$S^*$</td>
<td>43</td>
<td>43</td>
</tr>
</tbody>
</table>

*) Confinement margin = $\tau_p$(scaling)/$\tau_p$ (required)
Physics issues for the reactor

- Gas/recycling control
- Plasma fueling
- Ash control requirements
- Energy conversion
Core plasma fueling is required

- Hydrogen can be fueled solely by NBs

- Boron core fueling must to be developed. Viable candidates are
  - Injection of Compact Toroids (CT)
  - Boron ion beams (developed earlier by TAE)
  - Boron NB’s - 500-700 keV to penetrate into core (based positive ion technology)

- Tests with two component plasmas at C-2W
Gas handling is much easier in FTC

- At $T \sim 300$ keV CX cross section is very small. No CX loss for NB or hot plasmas

- Neutral ionization length is $< 1$ cm. No neutral can penetrate in SOL plasma
Gas handling in divertors

- **Fueling and exhaust composition**

<table>
<thead>
<tr>
<th></th>
<th>Fueling (%)</th>
<th>Exhaust (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>67</td>
<td>29</td>
</tr>
<tr>
<td>Borons</td>
<td>33</td>
<td>5</td>
</tr>
<tr>
<td>He</td>
<td>0</td>
<td>66</td>
</tr>
</tbody>
</table>

- **Total exhaust rate** \( G \sim 10^{20} \text{ 1/s} \)

- **It is much easier to achieve required gas condition**
  - The required pumping speed \( \sim 250 \text{ m}^3/\text{s} \) (compare with 2000 m\(^3\)/s in C2W!)
  - Predominantly He with Hydrogen and Boron impurities
Ash control is critical for pB$^{11}$

- Without ash control: $C_{He} \sim 70\%-80\%$ resulting in a very low $Q$
- It takes about 100 s to build up ash
- High $Q$ requires very efficient ash control
- Required ash concentration $< 5\%$
Energy conversion

- 80% of fusion energy goes to the side wall in form of x-rays (~150keV). Converted in electricity by a thermal cycle (50% efficiency)
- Convective energy loss into expanders (20% of fusion power) can be converted electrostatically in expanders
- Ions are accelerated by $\text{grad}B$ and electric potential in the convertors to $E_\parallel \sim 1.2-1.5 \text{ MeV}$ with $E_{\text{perp}} < 10 \text{ keV}$
- Technology developed for mirror machines in 70th (85% efficiency demonstrated)
DEMO-lite

High energy beams

SC magnets

Low energy beams

Cryostat

Expander
Summary

- Higher Q ~ 6-8 is possible with new cross sections
- Many physics and engineering challenges to address but no stoppers
- C-2W will address some of the critical physics issues. A parallel R&D work is equally important
TRI ALPHA ENERGY
THE POWER OF INGENUITY