PHYSICS OF CFETR

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Mission of CFETR

• Complementary with ITER
• Demonstration of fusion energy production
• Demonstration of T self-sufficiency with TBR ≥1.2
• Exploring options for DEMO blanket & divertor solution
• Solution for easy remote maintenance of in-vessel modules

Core plasma of CFETR

• Fusion power $P_{\text{fus}} = 50 \sim 200\text{MW}$;
• Long pulse or steady-state operation with an annual duty cycle time $\geq 0.3 \sim 0.5$

The goal of CFETR is to build a reactor for fusion energy production being possible!
Physics basis

• Based on the existing experiments
• Adopting ITER physics and technical basis

Task of this report

Focused on qualitative determination of the engineering parameters of the device and possible operating modes based on different assumptions of plasma performances by a zero-dimensional system study
Principles for Core plasma design

• To assure the success of the baseline targets:
  ➢ Based on already proven physics
  ➢ Operation within all stability boundaries (conservative implementations)

• To keep capabilities for very advanced scenarios
  ➢ Explore newest advances of physical understanding and technology developments

• To keep flexibilities for research of advanced physics and developments of new technologies
Input

- Fusion power and gain, neutron load on the wall, plasma (burning) duration, etc
- Physics basis (operation scenarios, stability margins, plasma control, etc)
  - ITER baseline: type I ELM-H mode, hybrid, (RS)
- Constraints (heat load on divertor plates, cost, nuclear license)

- Baseline: $P_{\text{fus}} \sim 200\text{MW}$ in H-mode for $>1000\text{s}$
- Steady-state: $P_{\text{fus}} \sim 200\text{MW}$ in Hybrid
- Potential: $Q_{pl} > 5$
Basic consideration

• Easy plasma control:
  ➢ $\beta_N < 4*li$ within ideal pressure limit
  ➢ $j(r)$ alignment to pre-empty instabilities.

• Readily access:
  ➢ Standard H-mode and improved H-mode (Hybrid)
  ➢ Reversed magnetic shear as backup.

• Sufficient for tritium breeding:
  ➢ Single null configuration.
  ➢ Minimize space for H&CD power, diagnostics and fueling, etc.
System study

• Zero dimensional model
  ➢ Based on the scaling rules

• One dimensional model
  ➢ Based on existing transport models (equilibrium, transport, stabilities)

• Scale from existing plasmas
  ➢ Based on physical relations and existing experiments

$P_f/V_{ol} \sim n_D n_T \langle \sigma v \rangle U_f, \langle \sigma v \rangle \sim T^2$ near 10 kev

$\sim n^2 T^2 \sim \text{pressure}^2$
Zero-dimensional model

- For fusion gain and power:
  \[ Q \propto \beta_N H / q_{95}, \quad P_{\text{fus}} \propto \beta_N^2 l^2 B^2 \]
  - Favor to increase pressure \((\beta_N)\) and confinement \((H)\)
  - Emphasis on high current \((1/q_{95})\)

- For steady-state:
  \[ Q \propto \beta_N^3 / [f_{DL}^2 (1 - f_{BS})], \quad f_{BS} \propto \beta_N q_{95} \]
  - Strongly favor to increase pressure \((\beta_N)\), and decrease density \((f_{DL} = n/n_{GW})\), and high bootstrap current fraction \((f_{BS})\)
  - Does not favor high current (despite \(1/q_{95}\))

Setting \(\beta_N < 3.1\)
Allowed \(H_{98} < 1.6\)
However, strong toroidal rotation for high \(H\)

(2nd Int. Wksp. MFE in China/TCL/2012)
Operation modes

Fusion energy:

\[ W_{\text{fus}} = P_{\text{fus}} \times t_b \propto (\beta_N B^9 a^9/f_{DL}^3)^{1/2} (\psi_{CS} - \psi_I)/q_{95}(1 - f_{BS} - f_{CD}) \]

favor high \( \beta_N \) and low density

- At low \( q_{95} \), higher \( P_{\text{fus}} \), expensive for SSO
- At high \( q_{95} \), easier SSO, but lower \( P_{\text{fus}} \)
- SSO with high \( P_{\text{fus}} \) possible only operating near the pressure limit at modest \( q_{95} \), but with disruption risk?

(2nd Int. Wksp. MFE in China/TCL/2012)
Operation modes

- $f_\alpha > 50\%, f_{bs} > 50\%, (~80\% \text{ for AT})$?
- Type I ELM-H mode as baseline?
  - Robust (easy access)
  - High pedestal allows fusion relevant temperatures in most of the volume
  - Heat load due to ELM crash
  - Confinement strongly degrades with heating power ($\tau \sim P^{-0.69}$)
- AT modes for steady-state operation to demonstrate reactor relevant physics and technology feasibilities
  - Need further advance of physics

\[
\beta_N = 100\beta a B_0 / I_p \leq 3
\]

\[
n_{20} \leq n_{GR} \equiv 0.27 I_p / a^2
\]

\[
q_{95} \geq 3
\]

Need assessment of synergy effect of operation mode with heating/current drive, control, PWI, etc
**AT physics?**

Ion heating dominated

\[ P_{th}^{ITB} \leq 30 \text{MW on ions} \]

However, power preferentially deposit on electrons for reactor relevant plasma

stiffness can be mitigated by rotation, ITB formation and sustainment
Current drive

- $\eta_{CD}$ increased with $T_e$ and decreased with $n_e$.
- Higher confinement for higher $f_{bs}$
- Averaged: $\xi \approx 0.36$ in present study

\[
\frac{I_{CD}}{P_{CD}}; \quad \gamma = n_{20} \frac{I_{CD_A}}{P_{CD_W}}; \quad \zeta = \gamma^{33/3} / T_{e,keV}
\]

<table>
<thead>
<tr>
<th></th>
<th>LHCD</th>
<th>ECCD</th>
<th>FWCD</th>
<th>NBCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>0.3-0.4</td>
<td>$\geq 0.2$</td>
<td>0.07</td>
<td>0.5 (2 MeV)</td>
</tr>
<tr>
<td>[A/(Wm²)]</td>
<td>(indep. of $T_e$)</td>
<td>(ITER prediction)</td>
<td>(ITER prediction)</td>
<td>(DEMO prediction)</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>n.a.</td>
<td>$\geq 0.3$</td>
<td>0.1-0.2</td>
<td>0.4-0.5</td>
</tr>
<tr>
<td>[A/(Wm² keV)]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_{CD}$</td>
<td>0.3 (present)</td>
<td>0.3 (present)</td>
<td>0.5 (present)</td>
<td>0.3 (present)</td>
</tr>
<tr>
<td></td>
<td>0.5 (goal)</td>
<td>0.5 (goal)</td>
<td>0.7 (goal)</td>
<td>0.5 (goal)</td>
</tr>
<tr>
<td></td>
<td>(100 % coupling)</td>
<td></td>
<td>(100 % coupling)</td>
<td></td>
</tr>
<tr>
<td>$\gamma^{*}\eta_{CD}$</td>
<td>0.09-0.2</td>
<td>0.09 - 0.15</td>
<td>0.05-0.15</td>
<td>0.12-0.25</td>
</tr>
<tr>
<td>(compare to 0.25)</td>
<td></td>
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</tbody>
</table>
SSO modes

Fusion energy availability and high reliability drive the choice of (improved) H-mode with:

- Modest $q_{95}$ and $H_{98}$ ($\beta_N$)
- Relative low density $f_{DL}$ and hence higher $f_{CD}$

Engineering parameters of CFETR

- Base on superconducting tokamak approach.
- Multi-iteration and optimization among plasma performance and engineering constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(m)</td>
<td>5.7</td>
</tr>
<tr>
<td>a(m)</td>
<td>1.6</td>
</tr>
<tr>
<td>A</td>
<td>3.56</td>
</tr>
<tr>
<td>κX</td>
<td>2.0</td>
</tr>
<tr>
<td>δ</td>
<td>0.4</td>
</tr>
<tr>
<td>Vp(m³)</td>
<td>576</td>
</tr>
<tr>
<td>Sp(m²)</td>
<td>587</td>
</tr>
<tr>
<td>B0(T)</td>
<td>5.0</td>
</tr>
<tr>
<td>Ip(MA)</td>
<td>10~8</td>
</tr>
<tr>
<td>P(MW)</td>
<td>50/8</td>
</tr>
</tbody>
</table>

The radial build of the machine
CFETR engineering concept

(Y.T. Song, TPO-11)

- Magnet based on ITER-like technology
- Solenoid: 160V*s
- TF: 5T at R=5.7m
- PF: ITER-like vertical divertor and possible snowflake or super-X divertor configurations
Peaked density beneficial for fusion power

ITER: $S_n \sim 0.2$
FDF: $S_n \sim 0.25$

More relevant for ITER: $S_n \sim 0.5$

CFETR, low density, similar temperature with ITER, hence lower $v_{eff}$
Reasonable assumption: $1 \geq S_n \geq 0.5$, $ST \sim 1$
# CFETR Operating Modes

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>ITER-SS</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_p (MA))</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>(P_{aux} (MW))</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65~70</td>
<td>65</td>
<td>59</td>
<td>65</td>
</tr>
<tr>
<td>(q_{95})</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
<td>4.9</td>
<td>4.9</td>
<td>5.2</td>
<td>3.9</td>
</tr>
<tr>
<td>(W (MJ))</td>
<td>171~174</td>
<td>193</td>
<td>270~278</td>
<td>171</td>
<td>255</td>
<td>287</td>
<td>540</td>
</tr>
<tr>
<td>(P_{Fus} (MW))</td>
<td>197~230</td>
<td>209</td>
<td>468~553</td>
<td>187~210</td>
<td>409</td>
<td>356</td>
<td>1000</td>
</tr>
<tr>
<td>(Q_{pl})</td>
<td>3.0~3.5</td>
<td>3.2</td>
<td>7.2~8.5</td>
<td>2.7~3.2</td>
<td>6.3</td>
<td>6.0</td>
<td>15</td>
</tr>
<tr>
<td>(T_{i0} (keV))</td>
<td>17.8~18.5</td>
<td>29</td>
<td>19.8~20.8</td>
<td>20.6~21</td>
<td>21</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>(N_{el} (10^{20}/m^3))</td>
<td>0.75</td>
<td>0.52</td>
<td>1.06</td>
<td>0.65</td>
<td>0.94</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(n_{GR})</td>
<td>0.6</td>
<td>0.42</td>
<td>0.85</td>
<td>0.65</td>
<td>0.95</td>
<td>0.82</td>
<td>0.85</td>
</tr>
<tr>
<td>(\beta_N)</td>
<td>1.59~1.62</td>
<td>1.8</td>
<td>2.51~2.59</td>
<td>2</td>
<td>2.97</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>(\beta_T (%))</td>
<td>~2.0</td>
<td>2.3</td>
<td>3.1~3.25</td>
<td>2</td>
<td>2.97</td>
<td>2.8</td>
<td>4.2</td>
</tr>
<tr>
<td>(f_{bs} (%))</td>
<td>31.7~32.3</td>
<td>35.8</td>
<td>50~51.5</td>
<td>50</td>
<td>73.9</td>
<td>48</td>
<td>47</td>
</tr>
<tr>
<td>(\tau_{98Y2} (s))</td>
<td>1.82~1.74</td>
<td>1.55</td>
<td>1.57~1.47</td>
<td>1.37</td>
<td>1.29</td>
<td>1.94</td>
<td>1.88</td>
</tr>
<tr>
<td>(P_{N/A} (MW/m^2))</td>
<td>0.35~0.41</td>
<td>0.37</td>
<td>0.98</td>
<td>0.33~0.37</td>
<td>0.73</td>
<td>0.5</td>
<td>1.38</td>
</tr>
<tr>
<td>(I_{CD} (MA))</td>
<td>3.0~3.1</td>
<td>7.0</td>
<td>2.45</td>
<td>4.0</td>
<td>2.76</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>(H_{98})</td>
<td>1</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>1.5</td>
<td>1.57</td>
<td>1.2</td>
</tr>
<tr>
<td>(T_{burning} (S))</td>
<td>1250</td>
<td>SS</td>
<td>2200</td>
<td>M/SS</td>
<td>SS</td>
<td>??</td>
<td></td>
</tr>
</tbody>
</table>
Operating regimes

CFETR normal operating regime is close to ITER SS

Upgrade toward to PPCS, but still within No-wall limit

Aggressive physics assumption verification?
Very complicated Integration? Require real demonstration!
Diagram of Modes low ne

Dash line: same $P_{aux}$
Dot line: same $H_{98}$

$I_p = 8$ MA
$I_p = 10$ MA

$P_{aux} = 50$
$P_{aux} = 60$
$P_{aux} = 70$
$P_{aux} = 80$

$n_{eG} = 0.65$

$H_{98} = 1.0$
$H_{98} = 1.1$
$H_{98} = 1.2$
$H_{98} = 1.3$

$\beta_N$
1.420
1.585
1.750
1.915
2.080
2.245
2.410
2.575
2.740

Time$_{flattop}$ (s)

SS
Diagram of Modes high ne
**CFETR plasma**

- SSO at 10&8MA with large fraction of current drive at low density for fusion power of 200MW.
- Modest $H_{98} \leq 1.3$ achieving $\beta_N$ within pressure limit.
- Possible high gain operation for sufficient burning time.
- Possible ITER-like steady-state regime.
- Possible upgrading to achieve DEMO-like plasma.

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Existing performance in JET, but with torque input

(M.N.A. Beurskens, Nucl. Fusion 53 (2013))
Equivalent Torque

\( T_{\text{eNB,D3D}} = T_{\text{NB,CFETR}} \left( \frac{I_{\text{D3D}}}{I_{\text{CFETR}}} \right) \left( \frac{\tau_{\text{E,CFETR}}}{\tau_{\text{E,D3D}}} \right) \)

- 33MW NBI at 300keV equivalent to \(~4\text{Nm}\) in DIII-D and JET
- Rice scaling: \( \text{MA} = 0.037 \)
- Possibly enough to achieve the confinement and stabilize resistive wall modes

Strong confinement dependence on toroidal rotation

(Garofalo, et al., Nucl. Fusion 51 (2011))

(J.E.Rice, et al., Nucl. Fusion 47 (2007))

(M.N.A. Beurskens, Nucl. Fusion 53 (2013))
Stabilities

- $\beta_N$ within pressure limit, RWM may be not a big concern
- Sawteeth-free discharge is principally compatible
- Fine-aligned ECCD may suppress NTMs

Improved H-mode are often accompanied by NTMs but allow long pulse operation

(T.C. Luce, 2010 IAEA) (A. Stäbler, 2004 IAEA)
Energetic particles

- RS not compatible with energetic particle driven modes
- Several control methods emerge, but need further validation.

ECH deposition location is varied relative to mode location ($\rho_{q_{\text{min}}}$)

Deposition near $q_{\text{min}}$ stabilizes beam-driven RSAEs in DIII-D

- Localized electron cyclotron heating (ECH) alters stability and consequent fast-ion transport
- Can we turn off deleterious modes in a reactor?

Fraction of burned tritium

Typically ~0.25% in the steady state operation

Higher current and density, possible to 0.4~0.5%

\[
R_{TBurn} = \frac{\eta_{fuel} \times 100}{1 + \frac{n_{eAvg} V_P f_i}{P_f/W_f} \left( \frac{1 - R_{cycl}}{\tau_T} + \lambda_T + \frac{\delta W}{W_f} \right)}
\]
Equilibrium

Reduced controllability for plasma equilibrium and vertical stability due to weak coupling between plasma and PF coils and VV.

Assumption for vertical stability:
- 0.6m thick, 1.5m long toroidal segments
- Material with resistance similar to Cu
- 6 turns ICs top and bottom symmetrically

<table>
<thead>
<tr>
<th>ΔZ (cm)</th>
<th>V_max (KV)</th>
<th>I_max (KA/turn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>3.8</td>
<td>13.3</td>
</tr>
<tr>
<td>16</td>
<td>7.5</td>
<td>26.5</td>
</tr>
</tbody>
</table>

Engineering achievable
**Divertors**

Simulation shows that a peak heat load on divertor plates exceeding 10MW/m² and peak temperature up to 500eV in CFETR. A double radiative feedback technique has been demonstrated for power exhaust (Kallenbach, Nucl. Fusion 52 (2012)).

Innovative concepts of Snowflake (and Super-X divertors) with flux expansion by 2~3 times (Z. Luo, TPO-15).

![Diagram of divertor system](image-url)
Summary

• The engineering parameters of the device has been determined by considering engineering constraints.
• Possible operating modes based on conservative physical assumption, should be readily achievable.
• Potentially, more ambitious operating modes possible if the more advanced physics.
• Transport analysis using a drift-wave–based model with an edge boundary condition is under the way.
• EAST will provide opportunities to address key physics issues and demonstrate operating regimes of CFETR