Operational Margins and Impact on Design

Outline

• Methodology
• Uncertainties
• Design margins for
  – European pulsed DEMO
  – CFETR (Unfortunately not enough time!)
• Summary
Systems Modelling

• Simple (0D to 1D) models of all parts of a fusion power plant
• Optimise a design with respect to a given figure of merit (minimise R, minimise costs, maximise Q, maximise pulse length) within physics laws and engineering constraints
• PROCESS systems code = Europe’s lead systems code used for EUROfusion DEMO design studies

Uncertainty Quantification Method

Monte-Carlo Sampling

- Gaussian distribution
- Lower/Upper half Gaussian
- Uniform sampling
2 important questions

- What uncertainties do you assume?
  - Current focus on plasma physics uncertainties (with references to previous presentations)

- What question are you trying to answer?
  - What is the best/worst performance we can expect from the current European DEMO baseline design? → fixed build, maximising Q
## Uncertainties

<table>
<thead>
<tr>
<th>Description</th>
<th>Type</th>
<th>Mean</th>
<th>Std</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper bound on the density limit, lower half</td>
<td>Gaussian</td>
<td>1.2</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Upper bound on radiation corrected H-factor</td>
<td>Gaussian</td>
<td>1.2</td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Core radius in radiation corrected confinement</td>
<td>Gaussian</td>
<td>0.6</td>
<td>0.15</td>
<td>0.6</td>
</tr>
<tr>
<td>Thermal α-particle fraction</td>
<td>Gaussian</td>
<td>0.1</td>
<td>0.025</td>
<td>0.1</td>
</tr>
<tr>
<td>W number density fraction</td>
<td>Gaussian</td>
<td>10^{-4}</td>
<td>5 x 10^{-5}</td>
<td></td>
</tr>
<tr>
<td>Maximum ratio of $P_{sep}/R$ [MW/m]</td>
<td>Gaussian</td>
<td>15</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Lower bound on L-H threshold limit</td>
<td>Gaussian</td>
<td>1.0</td>
<td>0.25</td>
<td>1.0</td>
</tr>
<tr>
<td>Bootstrap current fraction multiplier</td>
<td>Gaussian</td>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Rad. wall load peaking factor</td>
<td>Uniform</td>
<td>2.0</td>
<td>3.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Uncertainties

• Variation in divertor figure of merit
• Variation in confinement scaling
• Restrictions:
  – No constraints on density/temperature profile peaking!
  – Currently no consistent pedestal modelling!
  – Also no ELM treatment (e.g. Eich scaling 2)
  – No X-point radiator and no div/SoL model
European DEMO

- 500 MW net electricity
- 2 hr pulse length

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius R [m]</td>
<td>9.1</td>
</tr>
<tr>
<td>Minor Radius a [m]</td>
<td>2.9</td>
</tr>
<tr>
<td>Aspect ratio A</td>
<td>3.1</td>
</tr>
<tr>
<td>Elongation $\kappa_{95}$</td>
<td>1.59</td>
</tr>
<tr>
<td>Triangularity $\delta_{95}$</td>
<td>0.33</td>
</tr>
<tr>
<td>Number of TF coils $n_{TF}$</td>
<td>18</td>
</tr>
<tr>
<td>Aux. heating [MW]</td>
<td>50</td>
</tr>
<tr>
<td>Vacuum $B_T$ [T] at R</td>
<td>5.7</td>
</tr>
<tr>
<td>Plasma vol. [m$^3$]</td>
<td>2500</td>
</tr>
<tr>
<td>Pedestal top density [m$^{-3}$]</td>
<td>$6.78 \times 10^{19}$</td>
</tr>
<tr>
<td>Pedestal top temperature [keV]</td>
<td>5.5</td>
</tr>
</tbody>
</table>

## European DEMO | performance

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Optimise Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net electric power [MW]</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>Burn time [hrs]</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>Fusion power [MW]</td>
<td>2037</td>
<td>2651</td>
</tr>
<tr>
<td>Plasma current [MA]</td>
<td>19.6</td>
<td>21.2</td>
</tr>
<tr>
<td>Safety factor $q_{95}$</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>$\beta_{N,tot} [% m T MA^{-1}]$</td>
<td>2.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

- Assuming BoP allows +10%/-20% margins on $P_{net,el}$
- Can always reduce from optimum performance
- Energy storage/grid needs to be able to cope with shorter/longer pulses
Results | Optimise Q

86.4%
Results | Individual parameters

![Graph showing individual parameters distribution](image-url)
Results | Individual parameters

![Graphs showing individual parameters](image)

- UB $n_{e,1}/n_{GW}$
- LB $f_{IH}$
- UB $n_{e,1}/n_{GW}$
- $r_{core}$
- $(P_{sep}/R)_{max}$
- UB $H$
- BS mult.
- $f_{W}$
- $f_{He}$

$t_{burn}[hrs]$
Results | Individual parameters

- Plasma Dilution has a big effect on the net electric output and the burn time.
- Density limit has a significant impact on net electric output.
- High impact on constraining operation margins!
- Improvement over earlier sensitivity studies due to distributions instead of minimum/maximum values. (Reflects assumptions though!)
Results | Divertor foM

\[ P_{\text{sep}} B_T / (R_{q95}) \text{[MW/m]} \]

\[ P_{\text{sep}} / R \text{[MW/m]} \]
Results | Divertor Constraint

![Graph showing the relationship between $(P_{sep}/R)_{max}$ and $P_{sep}/R$]
Results | Radiation Wall load

![Graph showing the relationship between $P_{sep}/R$ and $(P_{rad} \cdot f_{peak}/A_{wall})$ with a shaded area at 90.0%.](image)
Results | Confinement

- Petty 2008 – dimensionless, $\beta$ independent scaling
- No radiation correction
- H-factor limit at 1.0
- Early Results!
Results | Petty 2008

![Diagram showing the relationship between $P_{\text{net,el}}$ (MW) and $t_{\text{burn}}$ (hrs). The diagram includes a histogram and a scatter plot. The title "100.0%" is indicated at the top right of the histogram.]
Density is constrained, but temperature is not, high core temperature (51 keV on axis),

Note: Currently no consistent pedestal scaling in PROCESS, no constraints on temperature peaking!

High burn times due to high bootstrap fractions (60% for standard scenario) resulting from unrealistic temperature profiles.

Fusion power limited by divertor protection (17 MW/m) and wall load (1 MW/m²)! Not typically by confinement.
Results | Petty 2008

![Diagram showing data distribution with a histogram and scatter plot. The x-axis is labeled $P_{sep}/R$ [MW/m], and the y-axis is labeled $(P_{rad} \cdot f_{peak} / A_{wall})$ [MW/m$^2$]. A shaded area indicates 21.3% of the data points.]
Results | Petty 2008

Slide 22

The diagram shows a scatter plot with data points distributed on a graph. The x-axis represents $H$ and the y-axis represents $H_{\text{max}}$. The data points are shown in blue, and the histogram bars are also in blue, illustrating the distribution of the data.
Summary

• First step towards uncertainty quantification for European pulsed DEMO design assuming physics uncertainties only!
• High probability that performance margins for net electricity (>400 MW) and burn time (> 1 hr) are achievable
• Plasma dilution and density limit seem to have a high impact on operational margins!
• Assuming IPB98, constrained by divertor limits
• Assuming Petty 2008, promises better performance, but constrained by divertor AND wall load limits!
$f_{\text{peak}} = 3.3$

Wenniger et al., submitted to NF 2017
Results | Individual parameters (no wall const)

Graphs showing distributions of various parameters:
- $P_{\text{net,el}} [\text{MW}]$
- $f_{LH}$
- $n_{e,1}/n_{GW}$
- $r_{\text{core}}$
- $(P_{\text{eff}}/R)_{\text{max}}$
- $f_W$
- $f_{He}$

Graphs are labeled with UB and LB.
Reference value

Uncertainty resulting from a ± 10% input uncertainty

\[ \Delta T_{\text{burn}} \text{ and } \Delta P_{\text{el.net}} \text{ [%]} \]

Input parameter

\[ \kappa_{95}, \delta_{95}, P_{\text{sep}}/R, n/n_{\text{GW}}, T_{e,0}/\langle T_e \rangle, H, \gamma_{\text{CD}}, f_{\text{BS}} \]

Wenninger et al. (2016), accepted at NF
With IPB98(y,2) confinement
$P_{\text{Loss}} = P_{\text{Heat}} - P_{\text{rad, core}}$

$P_{\text{rad, core}} = P_{\text{sync}}$

$+V \int_0^{\rho_{\text{core}}} 2P_{\text{rad}}(\rho) \rho \, d\rho$

Lux et al. PPCF (2016)
Backup

Kovari et al. FED (2014)