Critical Physics Issues for DEMO

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with thanks to the speakers at the recent European Fusion Physics Workshop
Background

- The necessary plasma current and size of tokamak fusion reactor depends strongly on a few key physics parameters.
- As part of the EU DEMO study, these key parameters are being re-visited with a view to identifying priority work for the short term and for ITER (European Fusion Power Plant Conceptual Study).
### Background

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Size [GW&lt;sub&gt;e&lt;/sub&gt;]</td>
<td>1.55</td>
<td>1.33</td>
<td>1.45</td>
<td>1.53</td>
</tr>
<tr>
<td>Fusion Power [GW]</td>
<td>5.00</td>
<td>3.60</td>
<td>3.41</td>
<td>2.53</td>
</tr>
<tr>
<td>Major Radius [m]</td>
<td>9.55</td>
<td>8.6</td>
<td>7.5</td>
<td>6.1</td>
</tr>
<tr>
<td>TF on axis [T]</td>
<td>7.0</td>
<td>6.9</td>
<td>6.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Plasma Current [MA]</td>
<td>30.5</td>
<td>28.0</td>
<td>20.1</td>
<td>14.1</td>
</tr>
<tr>
<td>Average Temperature [keV]</td>
<td>22</td>
<td>20</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Average Density [m&lt;sup&gt;-3&lt;/sup&gt;]</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>$\beta_N$ (thermal, total)</td>
<td>2.8, 3.5</td>
<td>2.7, 3.4</td>
<td>3.4, 4.0</td>
<td>3.7, 4.5</td>
</tr>
<tr>
<td>$H_H$ (IPB98y2)</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Bootstrap Fraction</td>
<td>0.45</td>
<td>0.43</td>
<td>0.63</td>
<td>0.76</td>
</tr>
<tr>
<td>$P_{\text{add}}$ [MW]</td>
<td>246</td>
<td>270</td>
<td>112</td>
<td>71</td>
</tr>
<tr>
<td>$n/n_G$</td>
<td>1.2</td>
<td>1.2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Divertor Peak Load [MW/m&lt;sup&gt;2&lt;/sup&gt;]</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>$Z_{\text{eff}}$</td>
<td>2.5</td>
<td>2.7</td>
<td>2.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Beta limit

- Two high $\beta$ regimes being tested:
  - ‘Advanced’ regimes which require strong current profile control and wall stability of ideal MHD but which hold out the hope of steady-state operation
  - Improved H-mode or ‘Hybrid’ regimes which are limited by NTMs but allow long pulse operation

(R. Buttery, 13th EFPW)
Beta limit: Advanced regimes

- In the presence of a conducting wall, higher $q_{\text{min}}$ and broader pressure profiles allow access to high $\beta$
- In DIII-D, $\beta_N$ of 5.1 is theoretically possible at $q_{\text{min}} = 2.1$

(A. Garofalo, 2005 APS)
Beta limit: Advanced regimes

- $\beta_N$ of 4 has been demonstrated in DIII-D
- The regime is transient as no one has the current drive capability to hold the current profile constant

⇒ We need (at least) one divertor tokamak with strong off-axis CD capability and a conducting wall

(A. Garofalo, 2005 APS)
Beta limit: Improved H-mode

- The improved H-mode is often accompanied by neoclassical tearing mode activity.
- There is an on-going debate about whether the NTMs help to control the current profile, allowing very long pulse operation.
- The regime is limited at the highest $\beta$ by (2,1) NTMs.

(A. Stäbler, 2004 IAEA)
Beta limit: Improved H-mode

- The $\beta$ limit for the improved H-mode is usually close to the ideal no-wall limit
- $\beta_n \approx 3$ has been achieved, for durations longer than the current resistive diffusion time
- High density operation has been shown to be compatible with improved H-modes

(M. Wade, 2004 IAEA)
Beta limit: Improved H-mode

- Several machines are working on controlling NTMs using ECCD:
  - Replace the missing current in the island formed by the NTM
  - Suppress NTM trigger mechanisms (sawteeth)
  - Adjust the current profile to reduce the pressure gradient drive at the critical rational surface

(Nagasaki, 2004 IAEA)
Beta limit: Issues

- We need to demonstrate true steady advanced regimes in a tokamak with a conducting wall and a large off-axis CD capability
- We need to demonstrate reliable feedback and control of resistive wall modes so as to allow operation above the no-wall limit
- We need to understand the role of NTMs in redistributing current in improved H-modes
- We need to study the scaling of the NTM limit with increasing machine size
- We need to demonstrate reliable tracking and control of NTMs using ECCD
- We need to quantify the influence of high beta operation on fast particle transport
Confinement & Modelling

- Here, the news is good!

- Confinement is clearly scaling more favourably with $\beta$ than the normal scaling law predicts

- This is very positive for ITER (either long pulse or near-ignition is possible) and is already close to the confinement assumed for DEMO

(G. Sips, 13th EFPW)

Confinement & Modelling

- 1D modelling using the turbulence-based codes is not so optimistic (Q~10 is typical)
- The beneficial effect of toroidal rotation shear is lost in ITER (and a reactor)
- The predictions depend very strongly on the assumed confinement in the edge transport barrier

⇒ The role of the ETB needs to be investigated & a co-ordinated modelling effort is required (and is underway)

(C. Kessel, SSO ITPA meeting, Nov. 2005)
Confinement & Modelling

- The situation with advanced regimes is much more uncertain.
- This is due to the lack of long pulse data to build a confinement scaling and the relatively wide variety of possible regimes.
- It seems likely, however, that advanced regimes will be more limited by stability and current drive requirements than confinement.

(G. Sips, PPCF 47 (2005) A19)
Confinement & Modelling: Issues

• We need to understand the role of the edge transport barrier in the observed confinement improvement in improved H-modes

• We need to build a database of steady advanced H-mode discharges which will allow the construction of a confinement scaling

• We need more data in discharges with Ti~Te and with low momentum input

• We need to co-ordinate our analysis of these regimes, testing codes against the results from a variety of machines
Current Drive

- The PPCS designs assumed a current drive efficiency $\gamma_{CD}$ which follows the Mikkelsen-Singer formula:

$$\gamma_{CD} \equiv \frac{I_{CD}n_eR_0}{P_{CD}} [AW^{-1}10^{20}m^{-2}] \propto T_e$$

- The assumed temperature dependence of the CD efficiency drives the plant designs to high temperature

- PPCS Model C has 7.4 MA of CD using 112 MW of power and thus $\gamma_{CD} \sim 0.6$
Current Drive: ECCD

- Theory is advanced enough to describe accurately the CD efficiency:
  \[ \gamma_{CD} \equiv \frac{T_e[keV]}{32.7} \zeta_{ec} \]
- Taking \( \zeta_{ec} = 0.2 \), one finds \( \gamma_{CD} \sim 0.1 \) for DEMO (at 20 keV)
- ECCD is not suitable for bulk current drive

(S. Alberti, 13th EFPW)
Current Drive: ECCD

- Assuming ~1/3 of the auxiliary power in DEMO could be allocated to ECCD, the local current density can significantly altered.
- ECCD is a viable option for mode control in DEMO (given the need for real-time control, it is presently the only option).

\[
J_{\text{equil}} = J_0 (1-q^2)^2
\]
Current Drive: ICCD

- Ion cyclotron waves could provide CD in DEMO via electron Landau damping
- For 78 MHz in PPCS Model A, the simulated CD efficiency is 0.45
Current Drive: ICCD

- The resulting CD is on-axis - it could be used for bulk CD but not for control in advanced regimes

(L-G. Eriksson, 13th EFPW)
Current Drive: LHCD

Tore Supra, $T_{e0} = 5$ keV

ITER, $T_{e0} = 30$ keV

$n_{\parallel} = n_{\parallel}(T_e)$

(G. Giruzzi, 13th EFPW)

$n_{\parallel} \approx n_{\parallel\text{-launched}} \Rightarrow \gamma_{CD} < 0.4$
Current Drive: LHCD

- In DEMO, where the temperatures are predicted to be very high, the Landau damping restricts LHCD to the outermost 20% of the plasma

⇒ Advanced regimes with such far off-axis CD must be developed

(G. Giruzzi, 13th EFPW)
Current Drive: NBI

- The current driven by neutral beam injection is found to experimentally be consistent with (numerical) theory predictions.

(S. Günter, 13th EFPW)

(T. Oikawa, NF 41 (2001) 1575)
Current Drive: NBI

- The current drive efficiency increases with electron temperature and beam energy

⇒ High beam energies and negative ion-based plasma sources will be required for ITER and DEMO

(S. Günter, 13th EFPW)

(T. Oikawa, NF 41 (2001) 1575)
Current Drive: NBI

(S. Günter, 13th EFPW)

- Current profile control has been observed in JT-60U
- This was done at low input power (2 MW). Similar results more recently in AUG

(S. Ide, IAEA (1994))
Current Drive: NBI

- In AUG, at higher input powers, the observed current profile modification is not consistent with standard theory
- Additional fast particle diffusion is required

⇒ Priority to determine how generally this applies (and why)

(S. Günter, 13th EFPW)

(S. Ide, IAEA (1994))
Current Drive: Issues

• We need to prove that we can dynamically detect and control NTMs (and then increase the beta)

• We need to demonstrate that the assumed figure of merit is applicable to ITER and DEMO

• We need to demonstrate the compatibility of advanced regimes with strongly off-axis current drive as would be available from LHCD in a reactor

• We need to determine the conditions which lead to anomalous spreading of the current drive by NBI

• We need to prove the temperature scaling of NBI at high temperature and beam energy (ITER)
Density & Radiation Limits

- One might expect the density limit in a tokamak to be set by the maximum density at which the plasma can support its radiative losses.
- This would lead to a power-dependent limit.
- Experimentally, one sees evidence of at least two other effects:
  - Poloidally-localised recycling leading MARFE formation
  - A density-dependent increase in transport

(M. Tokar, 13th EFPW)
Density & Radiation Limits

- The empirical Greenwald density limit describes experimental results to +/- 20%
  \[ n_G = \frac{I_p}{(\pi a^2)} = 1.59 g \frac{B_T}{q_{95} R} \]
- Very weak power dependence has been verified experimentally
- No firm physics basis (thus poor confidence in extrapolations)

(J. Schweinzer, 13th EFPW)
Density & Radiation Limits

• Data from AUG & JET are consistent with a scaling based on SOL detachment:

\[ n_{BLS} = 4.06 \frac{P^{0.094} B_T^{0.53}}{(q_{95} R)^{0.88}} \]

• This applies to H-mode discharges with heavy gas fuelling and thus flat density profiles

Density & Radiation Limits

- A Borrass-like scaling is significantly more pessimistic than Greenwald for reactors:

<table>
<thead>
<tr>
<th>Model</th>
<th>$n_e$</th>
<th>Peaking</th>
<th>$n_e(0)/n_{GW}$</th>
<th>$n_e(0.8)/n_{GW}$</th>
<th>$n_e(0.8)/n_{BLS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11</td>
<td>0.3</td>
<td>1.34</td>
<td>0.99</td>
<td>1.77</td>
</tr>
<tr>
<td>B</td>
<td>12</td>
<td>0.3</td>
<td>1.29</td>
<td>0.95</td>
<td>1.78</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>0.5</td>
<td>1.49</td>
<td>0.89</td>
<td>1.45</td>
</tr>
<tr>
<td>D</td>
<td>14</td>
<td>0.5</td>
<td>1.64</td>
<td>0.98</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Typical for present DL database

Shape model A, B

Shape model C, D
Density & Radiation Limits

- Density peaking at low collisionality is observed in both JET and AUG
- BUT, the correlation between collisionality and Greenwald density is strong as are the correlations between $\rho^*$, $\nu^*$ and the fuelling profile

⇒ More cross-machine comparisons, high power wave heating and, ultimately, ITER

\[ \nu_{\text{eff}} = \nu_{\text{ef}} / \omega_{\text{De}} \]

Density & Radiation Limits

- DEMO will have to operate with high Z PFCs and thus the tolerable density peaking is likely to be set by impurity accumulation.
- This is already observed in some circumstances in AUG.
- Impurity control can be re-established by applying central heating.

⇒ A high Z wall should be tested in ITER.

(Neu et al., NF 45 (2005) 209)
Density & Radiation Limits

• One can only really address the complex interactions between confinement, density limits and divertor power loading in the frame of an integrated model.

• Such modelling has highlighted an important link in the density limit model:
  
  - In present-day machines, edge thermal neutral fuelling is sufficient to strongly couple the separatrix and pedestal-top densities.

(Horton et al., NF 45 (2005) 856)
Density & Radiation Limits

- In DEMO (and in ITER), the increased machine size screens neutrals and the pedestal-top and separatrix densities are decoupled.

- It is then possible to separately optimise the core density for fusion performance and the separatrix density for divertor power load

⇒ Can we test this idea with pellets in JET at the highest currents?

Density & Radiation Limits: Issues

- We need to test the density limit and the separability of pedestal and separatrix densities in conditions of low thermal neutral penetration (high field in JET?)
- We need to systematically test the density limit in steady, pellet-fuelled conditions
- We need to determine the proper scaling of observed density peaking and thus its applicability to large machines
- We need to test the viability of high radiating power fractions in the regimes we propose to use in DEMO (hybrid & ITB) (confinement and confinement scaling)
- We need to perform an engineering assessment of the feasibility of exchanging the ITER first wall material
- We need to benchmark our integrated models more against existing machines, in particular against the new, higher resolution profile data which is now becoming available
Summary

• A main goal of the recently-launched EU DEMO studies is to identify and address the critical physics issues (today I have had time to discuss only four: beta limits, confinement, current drive efficiency and density limits.

• Priority research areas have been identified, with implications not only for the programmes of the present day machines but also for ITER.

• The results from this physics analysis, as well as from the newly launched tasks, are being fed back into the conceptual engineering design of DEMO. The goal is to establish a working dialogue between physicists and engineers.