Critical Physics Issues for Tokamak Power Plants

D J Campbell¹, F De Marco², G Giruzzi³, G T Hoang³, L D Horton⁴, G Janeschitz⁵, J Johner³, K Lackner⁴, D C McDonald⁶, D Maisonnier¹, G Pereverzev⁴, B Saoutic³, P Sardain¹, D Stork⁶, E Strumberger⁴, M Q Tran⁷, D J Ward⁶

¹ EFDA, CSU Garching, Germany
² Association Euratom-ENEA Frascati, Italy
³ Association Euratom-CEA, Cadarache, France
⁴ Association Euratom-Max-Planck-Institut für Plasmaphysik, Garching, Germany
⁵ Association Euratom-Forschungszentrum Karlsruhe, Germany
⁶ Euratom-UKAEA Fusion Association, Culham, United Kingdom
⁷ Association Euratom-Confédération Suisse, Lausanne, Switzerland

This work, supported by the European Communities, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
EU studies of commercial power plants developed 4 concepts:

- size decreases from (A) to (D) with advances in physics and materials

Relatively simple scaling developed for Cost of Electricity:

\[
\text{CoE} \propto \left( \frac{1}{A} \right)^{0.6} \frac{1}{\eta_{th}} \frac{1}{P_e^{0.4} \beta_N^{0.4} f_{GW}^{0.3}}
\]

Initiation of studies to define DEMO device have stimulated review of key physics issues which influence design of power plants.
Synopsis

• Context for analysis of physics basis for tokamak power plants

• Key physics issues for a tokamak fusion power plant:
  • operating scenarios
  • confinement properties
  • current drive requirements
  • high density, highly radiating regimes
  • mhd stability
    • plasma control
    • $\alpha$-particles

• Conclusions
• The extrapolation required beyond the level of performance typical of present devices can be characterized relatively simply:

  • confinement enhancement factor: \( H_{98(y,2)} = \frac{\tau_E}{\tau_{98(y,2)}} \sim 1 \) (1.3 - 1.6)

  • beta-normalized: \( \beta_N = \frac{\beta}{I_p / aB} \leq 4 \ell_i < 4 \) (4 -6)

  • fractional Greenwald density: \( f_{GW} = \frac{n}{n_{GW}} = \frac{n}{I_p / \pi a^2} \sim 1 \) (0.9 - 1.5)

• these parameters characterize proximity to operational limits

• In power plants, there are of course additional important parameters which influence behaviour and fusion performance:

  • current drive: \( f_{bs}, \gamma_{CD} \)

  • radiation: \( f_{rad}, Z_{eff} \)

  \( \alpha \)-particle physics: eg \( v_\alpha/v_A, \beta_\alpha, n_\alpha/n \)
The CoE expression provides an insight into the key elements influencing the economics of a fusion power plant:
- operation at high $\beta_N$ and high density is favoured for their direct impact on CoE
- however, the CoE dependence masks the underlying physics which determines the reactor operating mode and fusion performance

Analysis to date indicates that CoE should be lower for steady-state tokamak designs ⇒
- fully non-inductive steady-state operation must be sustained
  ⇒ “advanced scenario” implies complex control with limited actuators
- high confinement ($H_{98} > 1$), high-$\beta_N$ ($\beta_N > 4l_i$), high current drive efficiency ($\gamma_{CD} \propto T_e$) essential
- high density ($f_{GW} > 1$): efficient use of $\beta$
  highly radiating scenarios ($f_{rad} > 80\%$ to protect divertor)
- mhd stability against sources of confinement degradation and disruption

⇒ Can we meet the physics challenges of sustaining steady-state operation in the regime relevant to power plants?
Steady-State Operation

- Development of an integrated “advanced scenario” satisfying all reactor-relevant requirements remains challenging

plasma with reversed central shear + sufficient rotational shear

internal transport barrier ⇒ enhanced confinement

reduced current operation + large bootstrap current fraction

active mhd control

reduced external current drive + current well aligned for mhd stability and confinement enhancement

Steady-state operation + High fusion power density
“Hybrid” Operation

• “Hybrid” operation provides long pulse capability (eg technology testing in ITER) ⇒ possibility of extension to steady-state?

• Hybrid scenario:
  - H-mode plasma with \( q_0 \sim 1 \)

• Recent results from hybrid operation:
  - \( H_{98} > 1 \) relevant to reactor-like scenarios
  - \( \beta_N \sim 3.5 \) without RWM control (high \( l_i \))
  - \( n \sim 0.8 n_{GW} \), achieved to date
  - significant bootstrap current component ⇒ extended pulse length
  - \( q_0 \sim 1 \)
    ⇒ current profile control less demanding
    ⇒ less sensitivity to Alfvén eigenmodes and TF ripple losses
  - edge plasma requirements still crucial
    - ELM behaviour, radiation
  - \(~ zero shear~
  - \text{Standard H-mode}
Understanding energy confinement in advanced/hybrid scenarios is at focus of present studies
  • quoted H-factors are typically target values

Access conditions for both regimes remain uncertain:
  • progress required in both experimental and theoretical areas

Reactor plasma will differ from present plasmas:
  • \( T_e \approx T_i \)
    • low momentum input
    • broad transport barriers required in advanced scenarios
    • possible non-linear coupling between \( \alpha \)-heating profile, current profile, transport properties and mhd stability
    \[ \Rightarrow \text{is limiting factor in advanced scenarios confinement or stability?} \]

Lack of understanding of physics and role of edge pedestal is a key limitation on predictive capability (but not the only one)
• ITPA SSO TG analysis indicates that, at present, hybrid operation exhibits better plasma performance than advanced scenarios

Current Drive

- Majority of power plant studies aim for $f_{bs} \sim 80-90\%$
  - design values of pressure driven currents in ST studies often $>90\%$
  - requires advanced scenario with $\beta_N > \beta_{N,\text{no wall}}$ ($f_{bs} \propto \beta_p$, $\beta_p \beta \propto \beta_N^2$)

- Remaining non-inductive current driven by mixture of classical H&CD systems:
  - $\gamma_{\text{CD}} = n_{e,20} R_0 I_{\text{CD}} / P_{\text{aux}} \propto T_e$
  - confirmed extensively in experiments
  - extrapolation of factor 2-10 in $T_e$ to reactors
  - $j(r)$ control also necessary

- Technology a related issue:
  - $\eta_{\text{plug}} \sim 60\%$ typically assumed
  - LHCD/ICRF need reliable coupling
  - 1.5 - 2 MeV NBI often assumed

T Oikawa et al, Nucl Fusion 21 1575 (2001)
Current Drive: Profile Control

- Are expectations of $\gamma_{\text{CD}}$ consistent with $j(r)$ control requirements?

\[
J_{\text{equil}} = J_0 (1 - Q^2)^2
\]

<table>
<thead>
<tr>
<th>H&amp;CD System</th>
<th>$\gamma_{\text{CD}} \times 10^{20} \text{AW}^{-1} \text{m}^{-2}$</th>
<th>Deposition radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBCD</td>
<td>0.6 – 0.7</td>
<td>$\rho \geq 0$</td>
</tr>
<tr>
<td>LHCD</td>
<td>~ 0.3</td>
<td>$\rho &gt; 0.8$</td>
</tr>
<tr>
<td>FWCD</td>
<td>0.3 – 0.4</td>
<td>$\rho \sim 0$</td>
</tr>
<tr>
<td>ECCD</td>
<td>~ 0.12</td>
<td>$\rho \geq 0$</td>
</tr>
</tbody>
</table>

- Estimates of $\gamma_{\text{CD}}$ in a DEMO-like device with $<T_e> \sim 20$keV indicate range of expected CD efficiencies and deposition radii

EFPW13 (2005)

- For all PPCS models, with $P_{\text{EC}} = 0.33 P_{\text{aux}}$, $j_{\text{ECCD}}$ of same order as $j_{\text{equil}}(r)$ at all radii
  - ECCD has significant control capability in power plants

S Alberi, EFPW13 (2005)
Sustaining high density operation in the improved confinement scenarios favoured for power plants is challenging:

- Density in relevant scenarios generally low
- Several density limiting mechanisms:
  - no comprehensive theory
  - operation above $n_{GW}$ remains challenging
- Decoupling of SOL recycling and core will be important:
  - pellet injection needs to be exploited
- Implications of recent observations of density peaking at low-$\nu^*$ should be explored:
  - impact on transport of high-Z impurities crucial
  - $\alpha$-heating beneficial (ITER important)?

Divertor targets in a power plant are likely to be constrained to the same heat flux limits as ITER: \( \sim 10 \text{MWm}^{-2} \)
- parallel heat flux is \( >100 \text{MWm}^{-2} \) in ITER and can reach \( \sim 1 \text{GWm}^{-2} \) in reactors
- \( \alpha \)-power to plasma typically factor of \( > 5 \) greater than in ITER, but reactor divertor target area factor of ~ 1-2 that of ITER,

Tungsten likely to be the material of choice for high power flux surfaces, based on erosion lifetime and tritium retention characteristics
- divertor temperature should be \( <10 \text{eV} \) to limit erosion rate

⇒ Only feasible solution to satisfy these constraints appears to be radiating mantle/ (semi-) detached divertor
- implies impurity seeding to promote radiation, while effective impurity control must be retained to minimize core contamination
- better understanding of core/ divertor radiation distribution required
• Radiation from reactor plasmas:
  • 80-90% of loss power will need to be radiated in core and divertor - significant fraction in core
  • radiation fraction must be maintained with acceptable core impurity concentration and plasma performance (Matthews: $P_{\text{rad}} \propto (Z_{\text{eff}}^{-1})$
  • synchrotron and bremsstrahlung not insignificant - improved modelling treatment essential
  • demonstration required for viable reactor scenario: plasmas with radiation dominated by seeded impurities using high-Z wall
Power Exhaust/ Impurities III

- Transient events are of even greater significance than in ITER
  - availability and first wall lifetime considerations set severe limitations on frequency and magnitude of pulsed events
- Disruptions will essentially have to be eliminated
  - typical estimates in literature set frequency at 0.1 -1 per year
  - issues:
    - thermal quench: ~ 1GJ
    - current quench: ~ 1GJ
    - runaway electrons: >10MA if not suppressed
- ELMs too will essentially have to be eliminated
  - ELM-enhanced erosion might already set PFC lifetime limits in ITER

⇒ ELM control/ suppression techniques

MHD Stability at High-\(\beta\)

- Reactor requirement for high-\(\beta\) \((\beta_N > 3)\) arises from two major considerations:
  - high fusion power for high system efficiency (minimize recirculating power)
  - high bootstrap current fraction to minimize current drive power
    \(f_{bs} \sim \epsilon^{-0.5} h(\kappa) \beta_N q_c\)

- In advanced scenarios, it is assumed that equilibrium can be optimized to operate near ideal mhd limit:
  - resistive wall modes limiting
    - RWM control with stabilizing wall and active feedback required
    \(\Rightarrow (m, n)\) requirements? importance of rotation?
  - neoclassical tearing modes with \(m/n > 2\) might also be an issue

- In hybrid regime, it is assumed that adequate \(\beta\) can be sustained \((<3.5)\) without exceeding “no-wall” ideal limit:
  - neoclassical tearing modes limiting - critical mode \(m/n = 2/1\)
    - control via localized ECCD demonstrated (power requirements?)
Growth rates for low-n kinks for an optimized “advanced” equilibrium:
- modes with $n>1$ are likely to be most unstable as $\beta$-limit approached
- confirmed in experiments?

- 2/1 NTMs can be stabilized in hybrid regime while retaining high-$\beta$ and confinement quality

G Pereverzev et al, FEC-21, paper IAEA-CN-149-FT/P5-23
C C Petty et al, FEC-20, paper IAEA-CN-116
## Advanced scenario

### Multiple confinement barriers

- Designed to satisfy steady-state objective
- Large $f_{bs}$ reduces external CD needs
- Operates beyond no-wall $\beta$-limit with active stabilization
- Demanding control requirements
  - Access conditions/ confinement properties for reactor to be established
  - Needs to achieve $f_{GW} \geq 1$ and $f_{rad} \sim 80-90\%$
  - $\alpha$-particle confinement/ stability properties to be established

## Hybrid scenario

### Edge confinement barrier

- Essentially long-pulse regime
- Moderate $f_{bs}$ with large external CD needs ($\Rightarrow$ high $\gamma_{CD}$)
- Possibly operates within no-wall $\beta$-limit, but active NTM stabilization
- Control requirements may be less severe than AS
A steady-state tokamak power plant requires physics parameters which are simultaneously close to the limits of what is achievable on the basis of our (experimental and theoretical) understanding.

To develop steady-state operation and prepare the Physics Basis for DEMO/Power Plants, fusion programme must address, in particular:

- exploration of relevant scenarios and characterization of their access/transport properties
- demonstration of required degree of current profile control with required level of current drive efficiency
- consistency of scenario with high density/high radiation regime with acceptable level of fuel dilution - high-Z wall materials!
- realization of sustained gain in accessible beta through active control of mhd instabilities
- establish satisfactory $\alpha$-particle confinement (ITER)

Conclusions