Session 2: DEMO Physics Gaps and Impact on Engineering Design

Introduction

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A highly nonlinear system far away from thermodynamic equilibrium
An object in the centre of a power plant defining the loading conditions
Main design parameters of the machine:

- vacuum vessel: major radius $R$, aspect ratio $A$, shape
- toroidal and poloidal magnetic field coil system $B_t, B_p$ (tokamak: $I_p$)
- auxiliary heating and current drive power $P_{CD}$
- fuelling and pumping requirements (gas fluxes)

Output parameters

- fusion power and plasma $Q^\prime$: $P_{fus} = Q P_{CD}$
- thermal loading conditions
- pulse length $\tau_{pulse}$ and duty cycle (tokamak issue)
- mechanical loading conditions

Design rules link design parameters and output parameters

Note: on this level, no distinction made between tokamak and stellarator
Simple scaling for fusion power

In the optimum temperature range, fusion power is proportional to $p^2 V$:

$$P_{fus} = \frac{\tilde{c}_1 \beta^2 B^4 R^3}{A^2}$$

with

$$\beta = \frac{\langle nT \rangle}{B^2/\(2\mu_0\)}$$

In tokamaks, MHD instabilities set a limit to $\beta_N = \frac{\beta}{I/(aB)}$ (Troyon-Limit)

so that

$$P_{fus} = c_1 \frac{\beta_N^2 B^4 R^3}{q_{95}^2 A^4}$$

(note safety factor $q_{95} \sim aB/(A I_p)$)
Loss power from plasma $W/\tau_E$ expressed through scaling law for $\tau_E$:

**tokamak:** ITER98($p,y2$)  
$\tau_E \sim H^{3.23} \tau_{Bohm} \rho^{*-0.7} \beta^{-0.9} q^{-3} A^{-0.73} ...$

**stellarator:** ISS04  
$\tau_E \sim H^{2.52} \tau_{Bohm} \rho^{*-0.79} \beta^{-0.19} q^{-1.06} A^{0.0} ...$

Insert this into the power balance

**tokamak:**  
$$Q = \frac{P_{fus}}{P_{AUX}} = \frac{P_{fus}}{P_{loss} - \frac{1}{5} P_{fus}} = \frac{5}{\frac{c_2}{c_1} H^{3.23} \beta_{N}^{0.1} R^{2.7} B^{3.7} - 1}$$

$$\frac{5 c_2}{c_1} H^{3.23} \beta_{N}^{0.1} R^{2.7} B^{3.7} - 1$$

**stellarator:**  
$$Q = \frac{P_{fus}}{P_{AUX}} = \frac{P_{fus}}{P_{loss} - \frac{1}{5} P_{fus}} = \frac{5}{\frac{\tilde{c}_2}{\tilde{c}_1} H^{2.56} \beta^{0.81} R^{2.79} B^{3.79} - 1}$$

- strongly nonlinear in $R$, i.e. will define 'minimum size'
- high $H$-factor (good confinement) and low $q_{95}$ (high $I_p$) help a lot!
Evaluating $c_1$ and $c_2$ from ITER $Q=10^*$ / HELIAS Option A**, one gets

- i.e. ignition at a minimum size of $R = 7.5 \text{ m} / 15.5 \text{ m}$, respectively
- above, tokamak $Q$ determined by $P_{CD}$, stellarator practically ignited

$^* (A=3.1, R=6.2 \text{ m}, B=5.2 \text{ T}, q_{95}=3.1, H=1, \beta_N=1.8, Q=10, P_{fus}=400 \text{ MW}, P_{loss}=120 \text{ MW})$

$^{**} (A=10.5, R=14 \text{ m}, B=4.5 \text{ T}, q=1, H=1.8, \beta=4.3, Q=10, P_{fus}=500 \text{ MW}, P_{loss}=150 \text{ MW}$

according to F. Warmer et al., Plasma Phys. Control. Fusion 2016)
Total solenoid flux $\Phi_{tot}$ consumed by ramp-up $\Phi_0$ and flat top $\Phi_{res}$

$$\Phi_{tot} = \Phi_0 + \Phi_{res}$$

The flux consumed in flattop is given by

$$\Phi_{res} = c_5 \tau_{pulse} \frac{B_t}{q_{95}} (1 - f_{CD} - f_{bs})$$

where

- $f_{CD} = \text{fraction of externally driven current}$
- $f_{bs} = \text{fraction of bootstrap current}$

Pulse length can now be derived from the flux balance

$$\tau_{pulse} = \frac{q_{95}(\Phi_{tot} - \Phi_0)}{c_5 B (1 - f_{CD} - c_6 0.7 q_{95} \sqrt{A \beta_N})}$$

- yields a 'resonance denominator' (singularity = steady state)
- note: as for $P_{fus}$, $\beta_N$ helps, but now $q_{95}$ should be as high as possible!
Simple scaling law for tokamak pulse length

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ITER Q=10 scenario*

low $q_{95}$ (maximum $I_p$)

high fusion power (Q=10)

pulsed (400 s)

ITER Q=5 scenario**

high $q_{95}$ and $H$ (maximum $f_{bs}$)

lower fusion power (Q=5)

steady state

Typical trade-off in advanced tokamak scenarios: increase $q$, compensate with improved confinement (higher $H$)

*(A=3.1, $R=6.2$ m, $B_T=5.2$ T, $q_{95}=3.1$, $\beta_N=1.8$, $f_{CD}=0.1$, $\Phi_{tot}=120$ Wb, $\Phi_0=90$ Wb, $\tau_{pulse}=400$ s)

**(A=3.3, $q_{95}=5.1$, $\beta_N=2.5$, $f_{CD}=0.5$, $H=1.5$)
Additional constraints from power exhaust

4/5 of $P_{fus}$ in neutrons, load the wall at $\sim 1 \text{ MW} /\text{m}^2$

1/5 of $P_{fus}$ in charged particles, load narrow ring in the divertor, potentially damaging

- limit power flux across separatrix to $P_{sep} = f_{LH} P_{LH}$ (H-mode power threshold)
- can be achieved by seed impurity radiation, but must not compromise core performance
- establish ‘detached’ divertor solution (PFCs protected by ‘cushion’ of neutrals)
- relevant dissipative processes (radiation, charge exchange…) all need high density

⇒ Exhaust constraints tend to impact core

- core impurity seeding may cool and dilute plasma core
- high density difficult to achieve in large device ($n_{GW} \sim B/(q_{95}R)$)
If it is that simple, why this session?

There are considerable uncertainties in several of the relations used

- scaling laws for $\tau_E$ and $P_{LH}$ are empirical with little physics basis
- scaling laws have been derived for ITER, not DEMO conditions (DEMO will have higher $\beta$, higher $n/n_{GW}$, higher $f_{rad}$)
- stability limits depend on plasma profiles and hence in principle need sophisticated control if operating close to them
- divertor detachment cannot be predicted quantitatively today

This session focuses on these uncertainties (= knowledge gaps) and how we intend to close them

- uncertainties in core physics (R. Hawryluk) and exhaust (H. Reimerdes)
- additional constraints arising from scenario integration (V. Chan)
- effect of uncertainties on the final outcome / design margins (H. Lux)
- status of stellarator knowledge base (J. Miyazawa)