Fusion Reactor Design Parameters

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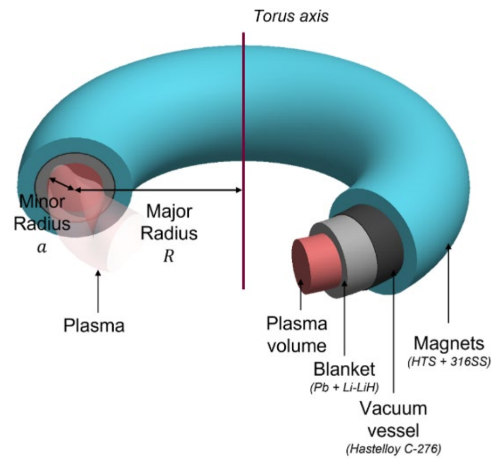
Basic Design

Magnetic Field on Axis (B):



- Represents the magnetic field strength at the center of the plasma.
- Key driver of plasma confinement and reactor performance.

Plasma Major Radius (R or R_{major}):

- The distance from the reactor's central axis to the plasma's center.
- Affects the reactor's size and cost.

Plasma Minor Radius (a or R_{minor}):

- The radius of the plasma cross-section.
- Relates directly to the aspect ratio (A = R/a).

Plasma Aspect Ratio (A = R/a = R_{major}/R_{minor}):

- Ratio of the major radius (R) to the minor radius (a).
- Indicates the plasma's shape; lower aspect ratios imply more compact designs.

Blanket Thickness (b):

- Thickness of the materials surrounding the plasma, responsible for neutron shielding and heat extraction.

Plasma Power

Fusion Power (P_{fus}):

$$P_{\text{fus}} = (E_{\text{n}} + E_{\alpha})P_{\alpha}/E_{\alpha} = 5P_{\alpha}$$

- Total power generated by fusion reactions in the plasma.
- E_n = neutron energy (14.1MeV), E_α = alpha particle energy (He^4, 3.5MeV)
- P_α = power deposited into the plasma by alpha particles produced during fusion reactions.

Thermal Power (P_{th}):

$$\begin{aligned} P_{\text{th}} &= f_{\text{m}} f_{\text{n}} P_{\text{fus}} + (1 - k_{\alpha})P_{\alpha} + P_{\text{rad}} + P_{\text{h}} \\ &= f_{\text{m}} f_{\text{n}} P_{\text{fus}} + P_{\alpha} + P_{\text{aux}}. \end{aligned}$$

- Total thermal power injected into the blanket.
- Approximately 20% of P_{th} is surface heating of first wall and 80% of P_{th} is volumetric heating in blanket due to neutrons.

Fraction of neutron-to-alpha fusion power (f_n):

- $f_n = E_n / (E_n + E_\alpha) = 0.8$ = percent of fusion power that becomes neutrons.

Fusion Gain (Q or Q_{plasma}):

- Ratio of fusion power (P_{fus}) to auxiliary heating power (P_{aux}).

Radiated Power (P_{rad}):

- Power lost through radiation, such as Bremsstrahlung radiation. This is most photons that cause surface heating against first wall.

Diffused Power (P_h):

- Power lost due to energy diffusion from the plasma.

Plasma Volume (V_a):

- Total volume of the plasma.
- Affects energy confinement and overall reactor performance.

Site Electrical Power

$$P_e = \eta_{th} P_{th} - \frac{P_{aux}}{\eta_{aux}} - \frac{P_{pump}}{\eta_{pump}} - P_{cryo}$$

Net Electric Power (P_e):

- Electric power delivered to the grid after subtracting power consumption by plant systems.

Heat Conversion Efficiency (η_{th}):

- Efficiency of converting thermal power into electric power (e.g. 49%).
- Depends on the plant's heat extraction and power cycle systems.

Auxiliary Heating Power (P_{aux}):

- External power input to heat the plasma to fusion conditions.

Auxiliary System Efficiency (η_{aux}):

- Efficiency of systems providing auxiliary heating power (e.g. 30%), from microwave and ion beam generators.
- Impacts the reactor’s net power output.

Liquid Wall Pumping Power (P_{pump}):

- Power required to maintain liquid metal blanket flow for cooling and shielding.
- Includes pressure drop contributions like gravitational, viscous, and magneto-hydrodynamic (MHD) effects.
- η_{pump} = efficiency to convert wall power to liquid wall pumping power (P_{pump}), e.g. η_{pump} = 20%

Cryogenic Power (P_{cryo}):

- Cryogenic system operating power.

Cryogenic Power Fraction (f_{cryo}): $P_{cryo} = f_{cryo} \times P_{th}$

- Fraction of the total power (P_{th}) for cryogenics to cool the magnets, e.g. $f_{cryo} = 1.3\%$
- Influences overall power consumption.

First Wall

Wall Loading Power (P_{WL}):

- Power load on the reactor's plasma-facing surfaces, critical for material design (MW_t/m^2).
- $P_{WL} = P_{th} / S_a$ S_a = surface area of plasma facing wall

Neutron Wall Loading Power (N_{WL}):

- Neutron power per unit area on the plasma-facing components (MW_t/m^2).
- A critical parameter for material selection and component lifetime.

Blanket

Tritium Breeding Ratio (TBR):

- Measures the reactor's capability to produce sufficient tritium for self-sustaining operation.
- Depends on blanket composition and neutron flux.

Neutron Multiplication Factor (f_m):

- Enhancement of neutron power due to interactions in the blanket.

Fusion

$$D + T \rightarrow \mathrm{He}^4(\alpha \text{ particle}) + \text{neutron (n)} + \text{Energy}.$$

Input: Deuterium (D) and Tritium (T)
Output: Alpha particles (He^4 helium, 3.5 MeV) and Neutrons (14.1 MeV)

Neutron-to-Alpha Fusion Power Ratio (f_n):

- Fraction of fusion power carried by neutrons relative to alpha particles.

Plasma

Volume-Averaged Plasma Temperature (T):

- Average temperature of the plasma volume, crucial for achieving fusion conditions.

Plasma Internal Energy (W): $W = 3 \times n_e \times T \times V_a$

- Total energy stored within the plasma.
- Depends on density, temperature, and plasma volume.

Plasma Energy Density (n or n_e):

- Line-averaged electron density (n_e) of the plasma (grams / m^3).
- Related to fusion reaction rates and power balance.

Energy Confinement Time (τ_E): $\tau_E = W / P_{loss}$

- Time over which the plasma retains its energy, critical for sustaining fusion reactions.
- Confinement Time (τ_E) is defined as ratio between plasma thermal energy power density ($W = MW/cm^3$ in plasma) and power lost to plasma (P_{loss}).

Triple Product ($n \times T \times \tau_E$): $n \times T \times \tau_E \;\; \alpha \;\; B^4 \times V_a$

- Triple product scales with 4th power of magnet field (B) and plasma volume (V_a).

Normalized Plasma Pressure (β):

- Ratio of plasma pressure to magnetic pressure, indicating how effectively the plasma is confined.

Rotational Transform ($\iota_{2/3}$):

- A measure of the magnetic field's twist at the plasma edge.
- Helps maintain plasma stability and confinement.

Bremsstrahlung Radiation Constant (CB):

- A numerical factor used in calculating radiative power losses.
- Depends on plasma properties like density and effective ion charge (Z_{eff}).

Re-Normalization Factor (f_{ren}):

- A factor used to adjust the confinement scaling law based on the specific plasma configuration.

Effective Ion Charge (Z_{eff}):

- Describes the contribution of impurities to the plasma charge state.
- Affects energy loss through radiation.

Synchrotron Radiation Loss (P_{synch}):

- Power lost through synchrotron radiation.
- Less significant than Bremsstrahlung but important in high-magnetic-field scenarios.

Cost Models

Capital Cost Components (TCC, TDC):

- Total capital cost (TCC) includes direct and indirect costs of the plant.

- Total direct costs (TDC) focus on equipment, construction, and components.

Levelized Cost of Electricity (COE):

- Economic metric representing the overall cost of electricity generation over the plant's lifetime ($/MWh).