DEMO Plasma Physics

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Goals

- Satisfying a power balance while producing 1500 MW of fusion power

- Maintain plasma stability
    - Kink Instability
    - MHD Instabilities

- Minimizing the heat flux on the plasma facing components on the confinement boundary.

- Impose impurity limit.

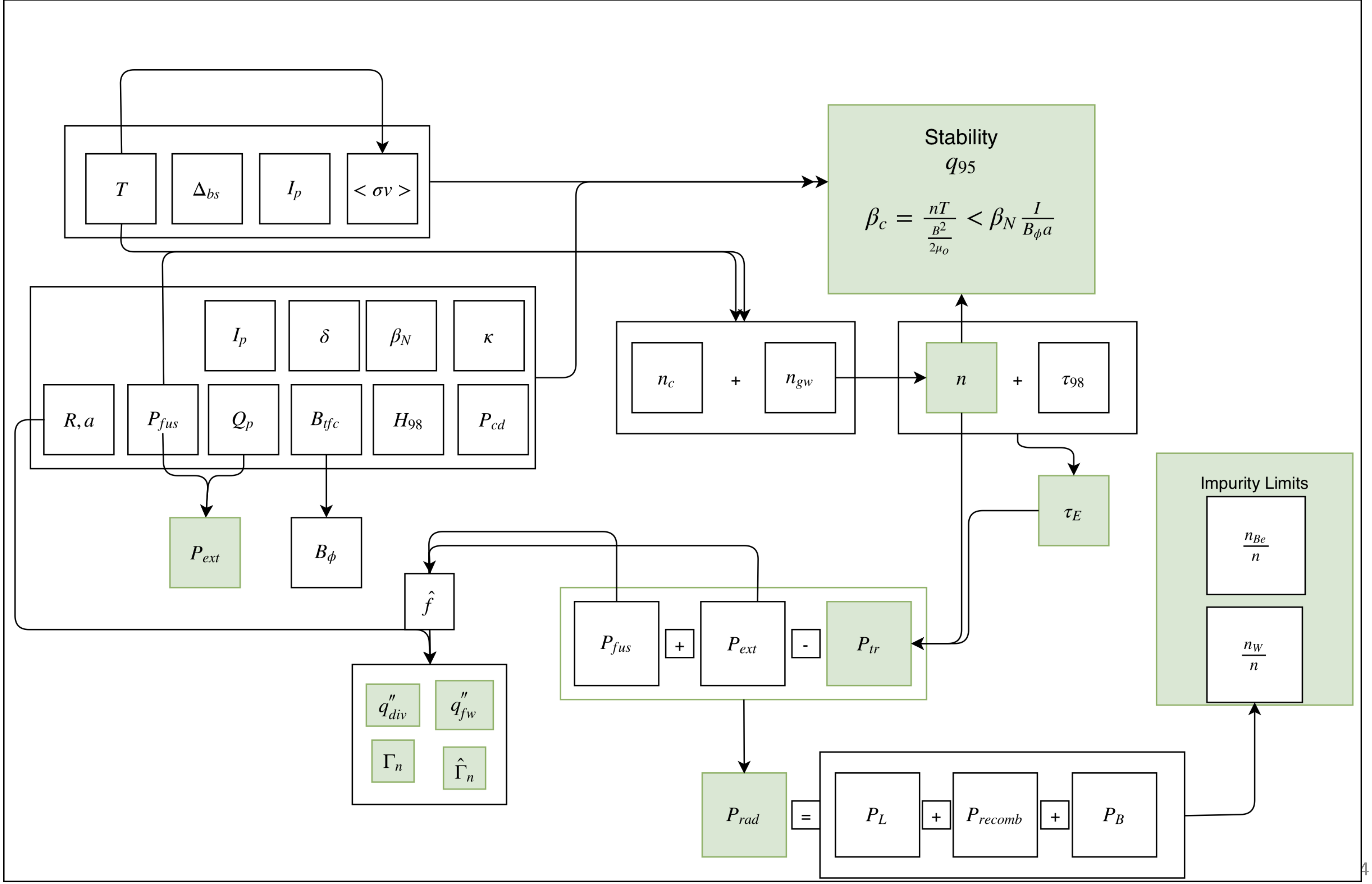
- Minimize radiation flux damage to plasma facing components.

Approach

- Determine, using the initial conditions and average parameters given by Dr. Stacey, the first iteration of parameters by leveraging the equations and relevant scaling parameters in ref. 7.

- Iterate on the parameters that are not fixed for this reactor, referencing the DEMO studies from various countries as bounds on these parameters and determine if the constraints are still satisfied[1-6].

- Consult with the other groups to determine if our choice of plasma parameters violate their constraints.



T
Δ_{bs}
I_p
$< \sigma v >$
Stability
q_{95}
$\beta_c = \frac{nT}{\frac{B^2}{2\mu_o}} < \beta_N \frac{I}{B_\phi a}$
I_p
δ
β_N
κ
R, a
P_{fus}
Q_p
B_{tfc}
H_{98}
P_{cd}
n_c
+
n_{gw}
n
+
τ_{98}
τ_E
Impurity Limits
$\frac{n_{Be}}{n}$
$\frac{n_W}{n}$
P_{ext}
B_ϕ
$\hat{f}$
P_{fus}
+
P_{ext}
-
P_{tr}
q''_{div}
q''_{fw}
Γ_n
$\hat{\Gamma}_n$
P_{rad}
=
P_L
+
P_{recomb}
+
P_B

Reference Parameters

Parameter	EU[1]	Japan(A)[2]	Japan (B)[2]	Japan (C)[2]	Korea (A)[3]	Korea (B)[3]	India[4]	China[5]	US (ACT1)[6]
q	N/A	5.5	5.4	5.3	3.5 - 6	3.5 - 6	N/A	4.6	4.5
τ [s]	2.59	1.69	1.97	2.27	2.27	2.36	N/A	2.49	1.78
β	4	6.7	5.7	4.1	4.2	4.2	3.3	4	4.75
R [m]	7.5	5.1	5.5	6.5	6	6.5	7.7	7.2	6.25
r [m]	2.5	2.1	2.1	2.1	1.8	2	2.6	2.1	1.56
B_{max} [T]	13.6	18.2	16.4	14.6	16	16	17.8	N/A	11.8
B_0 [T]	6	5.6	6	6.8	7.72	7.72	6	6.86	6
Q	30	48	52	54	24.4	30	30	35	42.5
T [keV]	16	N/A	N/A	N/A	19	19	21.5	15.4	20.5
P_{fus} [GW]	3.41	3	3	3	1.7	2.4	3.3	2.55	1.8
I [MA]	20.1	17.4	16.7	15	11	12.5	17.8	14.8	10.95

**Red values extrapolated*

Reference Parameters (cont.)

Parameter	EU[1]	Japan (A)[2]	Japan (B)[2]	Japan (C)[2]	Korea (A)[3]	Korea (B)[3]	India[4]	China[5]	US (ACT1)[6]
Avg e. density [10^20/m^3]	1.2	0.94	0.98	1	1.08	1.12	0.93	1.5	1
Wall loading [MW/m^2]	2.2	3.4	3.2	2.7	N/A	2	2.34	2.3	2.45
$\boldsymbol{\kappa}$ *(elongation)*	1.9	2.05	2	1.9	1.8	1.8	N/A	1.85	2.2
δ *(triangularity)*	0.47	N/A	0.4	0.4	0.4	0.4	N/A	0.45	N/A
A *(aspect ratio)*	3	2.5	2.6	3.1	3.33	3.25	3	3.4	4.5

Guiding Parameters

- Specified by Prof. Stacey
  - Plasma Power, P_{th} = 1500 MW
  - Plasma Heating and Current Drive Power, P_{CD} < 60 MW
  - Q > 25
  - Plasma Current, I = 16 MA
  - Toroidal Field Coil Strength, B_{TFC} = 11.8 T
  - Triangularity, δ = 0.40
  - Major Radius, R = 6.5 m
  - Minor Radius, a = 1.5 m
  - Blanket-Shield Thickness, $\Delta_{BS} = 1.0\ m$
- Selected from literature or iteration
  - Temperature, $\mathrm{T} = 14\ \mathrm{keV}$
  - $< \sigma v >_{\mathrm{fus}} = 2.3 \times 10^{-22} \mathrm{m}^3 \mathrm{s}^{-1}$
  - Q = 27

Achieving a Power Balance

Target: 1500 MW of fusion power

$$P_{DT} = \frac{1}{4} n^2 < \sigma v > U \, V_p$$

Plasma density: $\bar{n} = 1.1 \times 10^{20} \, m^{-3}$

$$\tau_E = 0.0562 \, I^{0.93} B_{\phi}^{0.15} P^{-0.69} \bar{n}_{e20}^{0.41} \times M^{0.19} R^{1.97} A^{-0.58} \kappa^{0.78} H_{98}$$

Confinement time: τ_E = 4.6 s

$$P_{tr} = \frac{3\bar{n}_e k_B T}{\tau_E} V_P$$

Transport Power Loss: P_{tr} = 119 MW

Q_P = 27

$$P_{fus} + P_{ext} = P_{tr} + (P_{rad})_{max}$$

Max External Power: P_{ext} = 56 MW

Max Radiative Power Loss: P_{rad} = 1437 MW

Plasma Density

- Operational Limit: $n_{GW} \leq \frac{I}{\pi a^2} 10^{20}\ [m^{-3}]$
  - Known as the Greenwald Limit.
- Operating density: $\bar{n} = C * n_{GW}$
- Determine C: $\frac{1}{4}(C\ n_{GW})^2 < \sigma v > T^2 U_{fus} V_p = 1500\ MW$

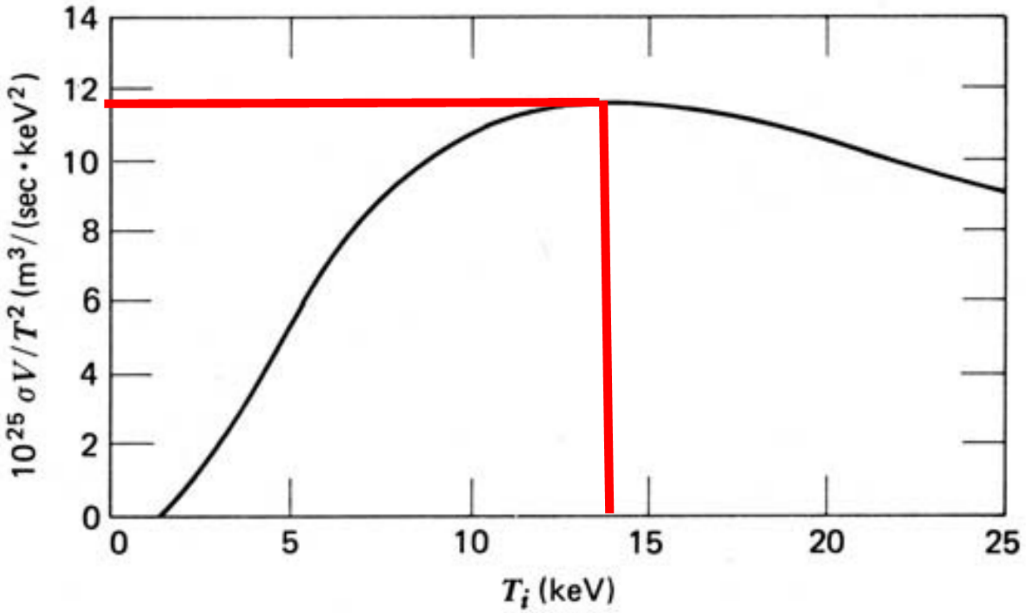


Fig. 1: Fusion Reaction Parameter[7]

$$T = 14\ \text{keV}$$
$$\frac{<\sigma v>_{fus}}{T^2} \cong 11.8 \times 10^{-25} \frac{m^3}{s - keV^2}$$
$$U_{fus} = 17.6\ \text{MeV}$$
$$V_p = 2\pi^2 R a^2 \kappa \cong 720\ m^3$$

$$C = 0.50$$

$$\bar{n} = 1.1 \times 10^{20}\ m^{-3}$$

Confinement

- Confinement time (sec):

$$\tau_{98} = 0.0562 I^{0.93} B_{\phi}^{0.15} P_{ext}^{-0.69} \bar{n}_{20}^{0.41} M^{0.19} A^{-0.58} \kappa^{0.78}$$

$$H_{98} = 1.7$$

$$\boxed{\tau_E = \tau_{98} H_{98} = 4.6\ s}$$

Accurate only for H-mode plasmas.

$$\mathrm{I = 16\ MA}$$

$$\mathrm{B_{\phi} = B_{TFC}\left(1 - \frac{a + \Delta_{BS}}{R}\right) = 7.3\ T}$$

$$\mathrm{P_{ext} = 56\ MW}$$

$$\mathrm{\bar{n}_{20} = 1.1\ m^{-3}}$$

$$\mathrm{M = 2.5\ amu}$$

$$\mathrm{R = 6.5\ m}$$

$$\mathrm{A = \frac{R}{a} = 4.3}$$

$$\mathrm{\kappa = \frac{b}{a} = 2.5}$$

Confinement (cont.)

- Threshold power for H-mode:

$$P_{LH} = \left(\frac{2.84}{M}\right) B_{\phi}^{0.82} \bar{n}_{20}^{0.58} R a^{0.81} = 55.9 \text{ MW}$$

- Ohmic Heating Power:

$$P_{\Omega} = 2.8 \times 10^{-15} \frac{(Z_{eff} I^2)}{a^4 T_e^{3/2}} V_P = 2.3 \text{ MW}$$

$$\boxed{P_{\Omega} + P_{ext} = 57.9 \text{ MW} > P_{LH}}$$

Power Losses

- Losses due to Transport:

$$P_{tr} = \frac{3\bar{n}k_B T}{\tau_E} V_P = 119\ \mathrm{MW}$$

- Losses due to Radiation:

$$(P_{rad})_{max} = P_{fus} + P_{ext} - P_{tr} = 1437\ \mathrm{MW}$$

The *maximum* allowable power loss from radiation

Power Losses (cont.)

- Bremsstrahlung Radiation

$$P_B = 4.8\,(10^{-43}) Z^2 n_z \bar{n} T^{1/2} \left(\frac{MW}{m^3}\right)$$

- Line Radiation

$$P_L = 1.8\,(10^{-44}) \frac{Z^4 n_z \bar{n}}{T^{1/2}} \left(\frac{MW}{m^3}\right)$$

- Recombination Radiation

$$P_R = 4.1\,(10^{-46}) \frac{Z^6 n_z \bar{n}}{T^{3/2}} \left(\frac{MW}{m^3}\right)$$

Power Losses (cont.)

$$(P_B + P_L + P_R)V_P = (P_{rad})_{max}$$

Imposes impurity density limit:

$$n_{z,max}(Z) = \frac{(P_{rad})_{max}}{1.5 \times 10^{-19} Z^2 + 3.9 \times 10^{-22} Z^4 + 6.4 \times 10^{-25} Z^6} \ (m^{-3})$$

$$\frac{n_{Be}}{\bar{n}} = 5.2$$

$$\frac{n_W}{\bar{n}} = 1.1 \times 10^{-4}$$

Plasma Stability

- Multiple forms of instability:
  - Kink
  - Ballooning
  - Pinch
  - Many others

Fig. 3: Pinch Instability[7]

- Arise as a result of differences between kinetic and magnetic pressure.

Plasma Stability (cont.)

- Kinetic Pressure

$$p = nT(1.602 * 10^{-16}) = 250\ kPa$$

- Magnetic Pressure

$$m = \frac{B_\theta^2}{2\mu_0} = 21MPa$$

- Beta

$$\beta = \frac{p}{m} = .012 = \ 1.2\%$$

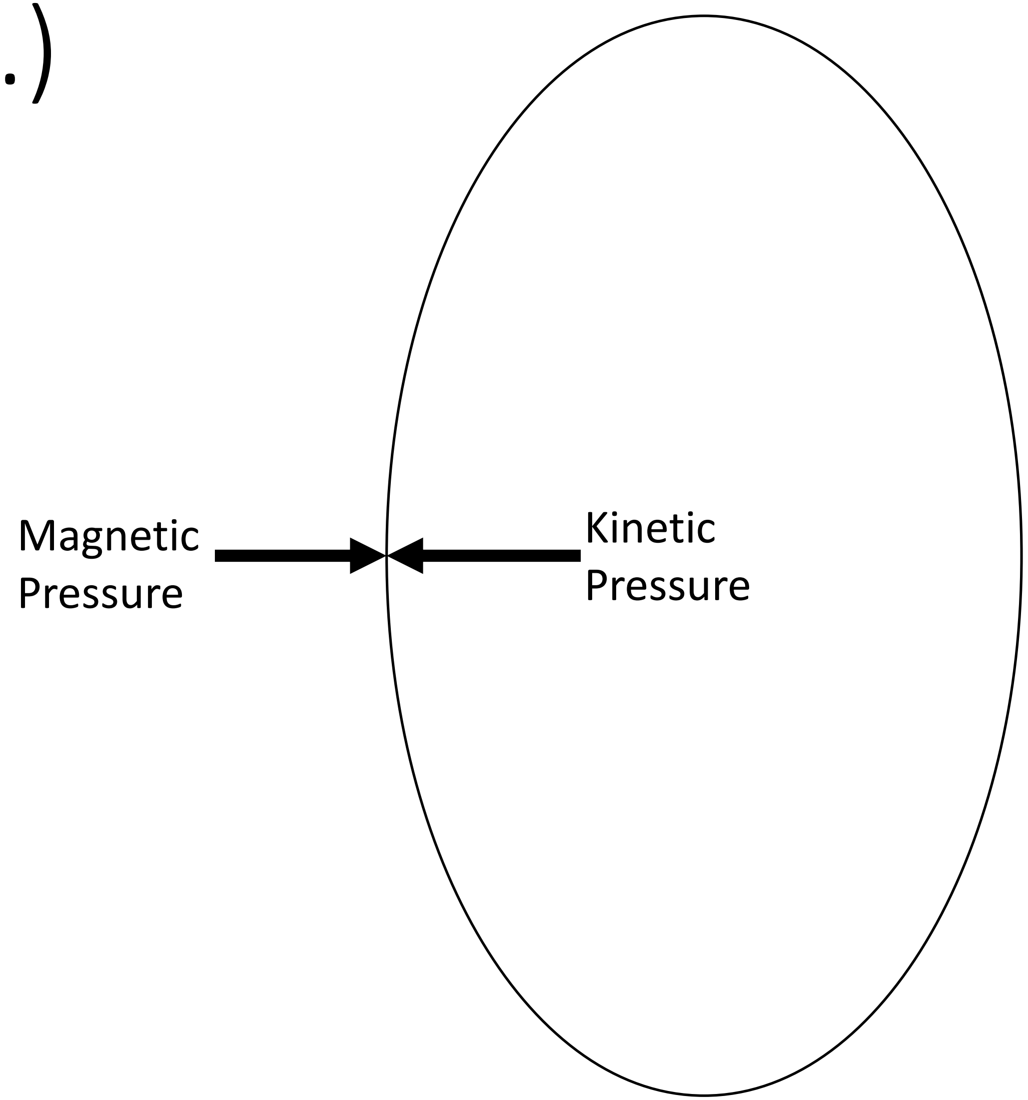


Fig. 2: Simplified toroidal cross section with pressures.

Plasma Stability (cont.)

- MHD Instabilities: includes many types of instability
  - Ballooning Limit:

$$\beta < \beta_N \left(\frac{I}{aB}\right) \longrightarrow 0.8\% < \beta_N$$

Satisfied as $\beta_N < 4\%$

- Kink instability
  - Characterized by q_{95}:

$$q_{95} = \frac{5a^2B}{2R\mu_o I}\left(1+\kappa^2(1+2\delta^2-1.2\delta^3)\right)\left(\frac{1.17-\frac{0.65}{A}}{1-\frac{1}{A^2}}\right) \geq 3$$

$$q_{95} = 3.1$$

Heat Fluxes

- First Wall heat flux:

$$q''_{fw} = \frac{(0.2P_{fus} + P_{aux})(1 - f_{div})\hat{f}_{fw}}{2\pi R\left(2\pi a\sqrt{\frac{1}{2}(1+\kappa^2)}\right)(1 - \epsilon_{div})} = 0.35\,\mathrm{MW\,m^{-2}}$$

  - Representative values[7]: $f_{div} = 0.5$, $\hat{f}_{fw} = 2$, $\epsilon_{div} = 0.1$
- Divertor heat flux:

$$q''_{div} = \frac{(0.2P_{fus} + P_{aux})f_{div}f_{dp}\hat{f}_{dp}}{\Delta_{div}2\pi R} = 3.6\,\mathrm{MW\,m^{-2}}$$

  - Constrained to < 5 MW/m^2
  - Representative values[7]: $f_{dp} = 0.3$, $\hat{f}_{dp} = 5$
- Could be a limiting factor in DEMO

Neutron Power Flux

- Causes the most damage to, and determines the lifetime of the plasma-facing components.
- Average flux:

$$\Gamma_n = \frac{0.8 P_{fus}}{2\pi R \left(2\pi a \sqrt{\frac{1}{2}(1+\kappa^2)}\right)} = 1.6\,\mathrm{MW\,m^{-2}}$$

- Peak flux:

$$\hat{\Gamma}_n = \Gamma_n \hat{f}_n \sqrt{\frac{1}{2}(1+\kappa^2)} = 3.4\,\mathrm{MW\,m^{-2}}$$

  - Representative values[1]: $\hat{f}_n = 1.1$

Conclusion

- Determined parameters result in a power balance and stable steady-state operation.

- Total heating power exceeds requirement for H-mode.

- Heat fluxes on plasma-facing components are within tolerable limits.

References for Group 1: Plasma Physics

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