Plasma Heating and Current Drive

Stephen Hardwick
Jake Inman

Overview

- Objective: Design a non-inductive heating and current drive system for a DEMO reactor that is viable to be used commercially to generate electricity.
- Initial outline parameters dictated:
  - $P_{Thermal} = 1000MW$
  - $Q_P = \frac{P_{Fusion}}{P_{CD} + P_{Heating}} = 30$
  - Carbon impurity of 3%
- Design Steps and Calculations
  - Inductive heating (Ohmic) and start up
  - Non-inductive heating requirements
  - Current Drive requirements at steady state
  - Steady State operations

Design Parameters

- Overall Reactor design
  - $a = 1.75m$
  - $R_o = 6m$
  - $\kappa = 2.1$
- Parameters calculated or chosen by other groups
  - Plasma Physics
    - $T_E = 12.5keV$
    - $I_P = 12MA$
    - $q_{95} = 3.71$
    - $\tau_E^{98} = 2.73s$
  - Electromagnets
    - $B_{\phi o} = 5.5T$

Inductive Startup

- The maximum temperature that can be achieved through ohmic heating is:

$$T_e(keV) < [1.46\frac{Z_{eff}}{[q(a)]^2}(\frac{aB_\phi}{R_0})^2]^{\frac{2}{5}} = .93(keV)$$

- Z_{eff} is calculated using:

$$Z_{eff} = \sum_{j \neq e} \frac{n_j z_j^2}{n_e} \approx 3.08$$

- Ohmic power contribution is negligible at steady state due to low value but is calculated using:

$$P_\Omega(MW/m^3) = 7 \times 10^{-2} \frac{Z_{eff}}{T_e^{\frac{3}{2}}(keV)}[\frac{1}{q(a)}]^2(\frac{B_\phi}{R_0})^2 = .228MW$$

Inductive Startup, contd.

- The minimum necessary volt-seconds required to start up and maintain the necessary plasma current are shown by:

$$\Delta\phi_{ind} \approx \mu_o R_o[ln(\frac{8R_o}{a\sqrt{\kappa}}) + \frac{l_i}{2} - 2] = 148.47V \cdot s$$

$$\Delta\phi_{res} \approx C_E \mu_o R_o I_p^f \approx 36.19V \cdot s$$

$$\Delta\phi = \Delta\phi_{ind} + \Delta\phi_{res} \approx 184.66V \cdot s$$

- The central solenoid provides most of these volt-seconds for startup, and is represented by:

$$\Delta\phi_{CS} = \pi B_{OH} r_v^2[1 + \frac{\Delta_{OH}}{r_v} + \frac{1}{3}(\frac{\Delta_{OH}}{r_v})^2] = 178.51V \cdot s$$

- Since $\Delta\phi_{CS} < \Delta\phi$, we will rely on the poloidal coils to provide approximately 6 Vs to drive the current.

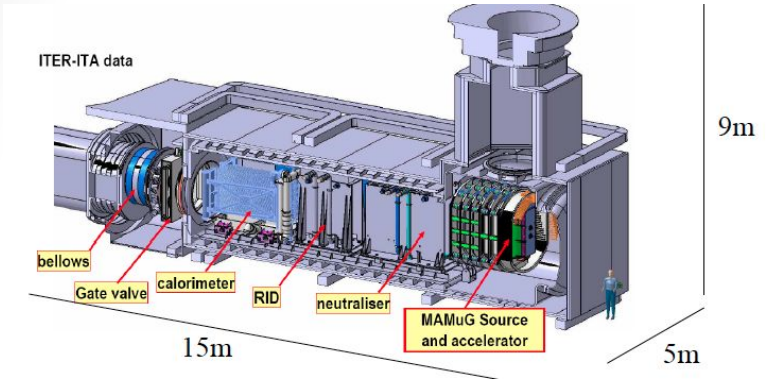
Non-inductive Startup

- In order to raise the temperature of the plasma past the ohmic temperature max, external heating is needed to raise the temperature to the required levels.

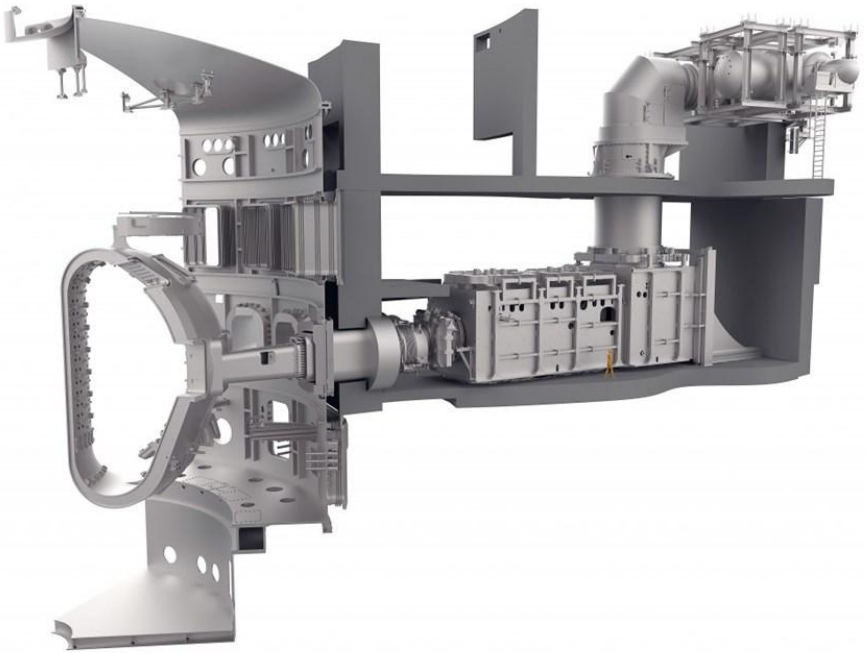
$$T_{Plasma} = T_{\Omega max} + (\tau_E P_{Heating} - \tau_E P_{Loss})(1 - e^{-\frac{t}{\tau_E}})$$

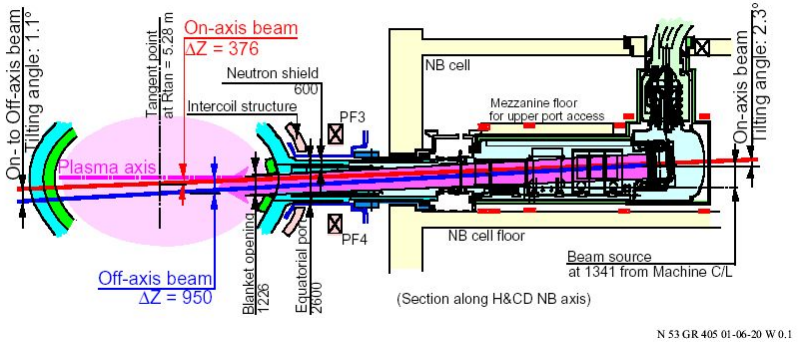
- The power losses are to account for radiation and transport losses during the heating cycle to achieve $T_{Plasma} = 12.5keV$
- Results
  - $P_{Heating} = 39.67MW$
  - $P_{HeatingITER} \approx 50MW$
  - Time to heat to $T_{Plasma} = 12.5keV$
    - This will be dependent on the number of ECHs that will be used to heat the plasma along: calculations have ranged from less than 1 second to 5 seconds

Heating Systems

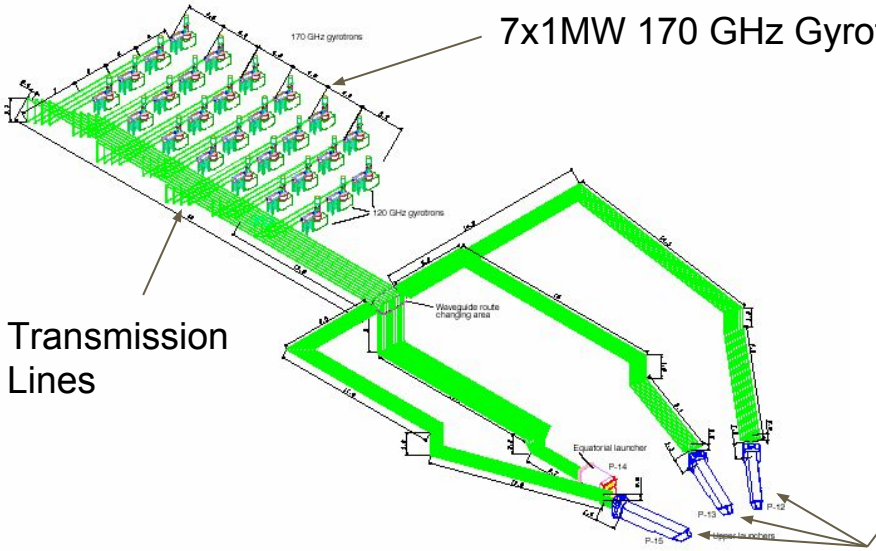


- Neutral Beam Injection (NBI):
  - 2 beams providing 16.5 MW of heating power per beam
  - 1 MeV D- ion beams (similar to that of ITER)
  - Injection ports of 0.9 m diameter are small enough to shield effectively
  - Beams will go co-current capable of being altered for on axis and off axis.



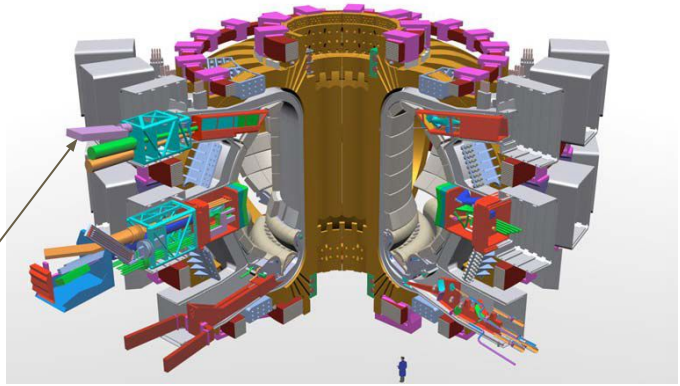


Heating Systems-ECH



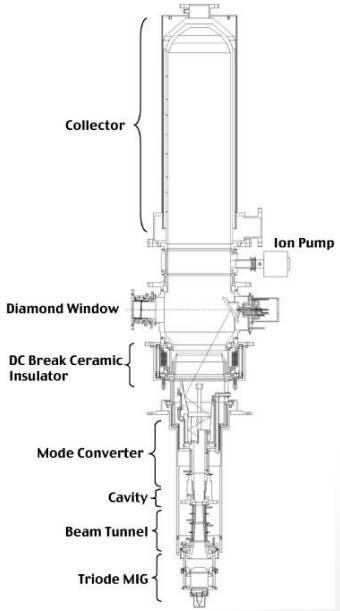
7x1MW 170 GHz Gyrotrons

Transmission Lines



Launchers

- Electron Cyclotron Heating (ECH):
  - 7 gyrotrons operating at a frequency of 170 GHz and 1 MW power each
  - Can be used for supplemental heating as well as minor adjustments to plasma shape during steady state



Steady State

- Bootstrap Current fraction assumption: 0.80
  - This value is based primarily on recent DEMO findings and economic necessity

	Device				
	DIII-D	ARIES-RS	ARIES-AT	KDEMO	DEMO-2
f_{BS}	≥0.80	0.88	0.91	0.83	0.7-0.8

- The current that is self-driven due to bootstrap current (I_{pBS}) and current driven by current drive systems (I_{CD}):

$$I_{pBS} = f_{BS} * I_p = 9.6MA$$

$$I_{CD} = (1 - f_{BS}) * I_p = 2.4MA$$

Steady State

- Efficiency of the current drive system (γ_{CD}) chosen: 0.46

	Device/Model				
	KDEMO	DIII-D/FSNF-AT	SABR (nom.)	SABR (ext.)	Euro PPCS
γ_{CD}	0.40	0.76	0.58	0.61	0.45-0.54

- η_{CD} is calculated using γ_{CD} through:

$$\eta_{CD} = \frac{\gamma_{CD}}{R_o n_{e20}} = .0768$$

- P_{CD} is the external power required to maintain the plasma current:

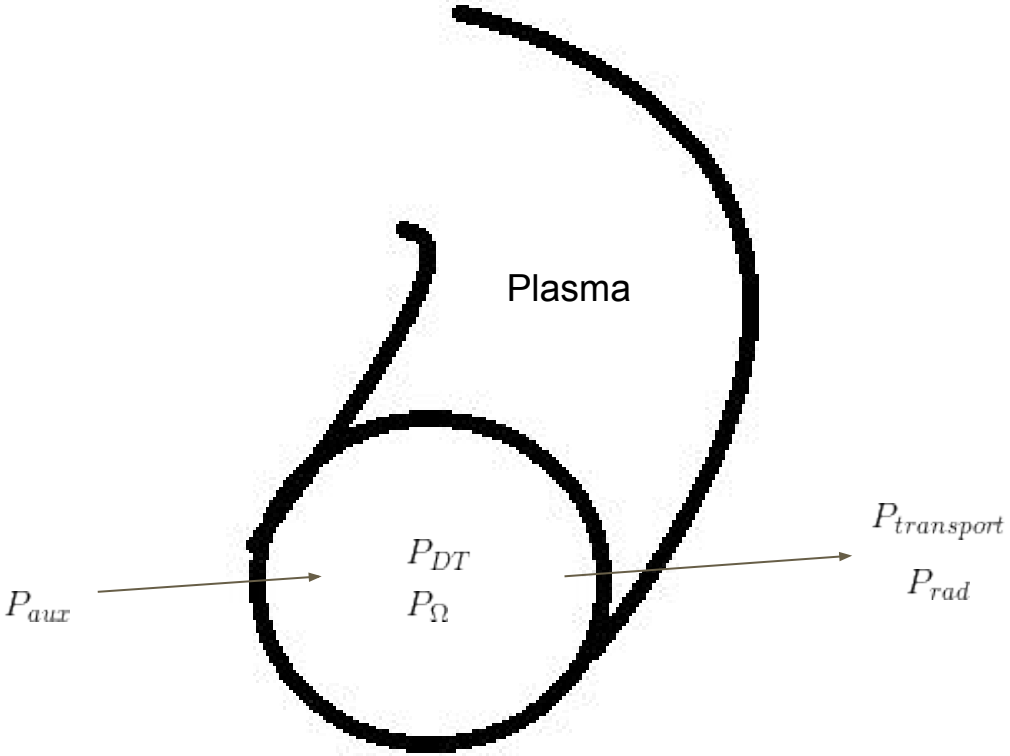
$$P_{CD} = \frac{I_{CD}}{\eta_{CD}} = 31.24MW$$

Current Drive System

- Most of the necessary heating power at steady state will be provided via fusion-α heating
  - ECRH gyrotrons can be used to supplement fusion-α heating during steady state if necessary

- Keeping the plasma current at 12 MA will be the greatest challenge during steady state
  - Two 3.7 GHz Lower hybrid current drive (LHCD) antennas will be relied upon exclusively for this task
  - Phasing out use of ion cyclotron current drive will increase overall efficiency while also eliminating unneeded openings in first wall

Gains and Losses



Power Balance

$$P_\Omega + P_\alpha + P_{aux} = P_{transport} + P_{rad}$$

- The ohmic power as annotated earlier is calculated using:

$$P_\Omega(MW/m^3) = 7 \times 10^{-2} \frac{Z_{eff}}{T_e^{\frac{3}{2}}(keV)} [\frac{1}{q(a)}]^2 (\frac{B_\phi}{R_0})^2 = .228MW$$

- $P_\alpha = P_{DT}$ and during start up will increase as the transport and radiative losses increase and is calculated at steady state using:

$$P_{DT} = \frac{1}{4} n^2 < \nu\sigma > UV \approx P_{transport} + P_{rad} + 1000MW$$

- $P_{transport} + P_{rad}$ is calculated using:

$$P_{transport} + P_{rad} \approx 4.8 \times 10^{-43} n^2 Z_{eff} T_e^{\frac{1}{2}} + 4.8 \times 10^{-2} \frac{T_e}{a^2} \approx 188.90MW$$

Power Summary

- Heating and Current drive

System	Power (MW)	No. of Systems Required	Total Power Provided (MW)
Neutral Beam Injectors	16.5	2	33
Lower Hybrid Antennas	15.5	2	31
Electron Cyclotron Gyrotrons	1	7	7

- Total power input at startup: 40.3 MW (33 MW NBI heating, 7 MW EC heating, 0.3 MW CS ohmic heating)
- Total power input at steady-state: ~32.5 MW (31 MW LH current drive)

Conclusions

- Heating and current drive systems for the DEMO reactor outlined are eminently feasible and economically viable
- The low requirements for non-inductive heating and current drive allow for a Q_p = 32.0 to be achievable, even using conservative estimates
- Recent technological advances have provided useful methods to avoid costly external power requirements

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