Evaluation of plasma performance in JA DEMO steady-state operation

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1. Background

Development of plasma operation scenario by integrated modelling simulation is necessary for evaluation of steadily sustainable operating points and required component specifications in DEMO design activities.

Plasma scenario studies for JA DEMO by integrated modeling simulation

- Flux consumption reduction during ramp-up by EC [Wakatsuki NF(2017)016015]
- Fusion power control by pellet injection [Tokunaga FED(2017)620]
- Steady-state operation scenario [Sakamoto FEC(2018)FIP/3-2]
- External heating power required for L–H transition [Sugiyama FED(2023)113369]
- Pulsed operation scenario [Sugiyama NF(2024)076014]

To ensure that plasma performance required for the achievement of DEMO goals will be obtained, plasma scenario should be developed based on analyses within a wide range of assumptions, considering the modelling uncertainties.

2. Summary

Plasma performance in JA DEMO steady-state operation has been evaluated using integrated modelling code GOTRESS+.

- Comparison with the result of systems analysis
  → Higher P_{aux}, β_N & H_H are required for P_{fus} ~ 1.5 GW & f_{NI} > 1 w/ P_{sep} ~ 280 MW.
- Dependence of performance on selection of turbulent thermal transport model
  → BgB, CDBM & Coppi-Tang models predict similar values of main parameters.
- Dependence of performance on H&CD condition
  → Optimum balance between P_{NBI} & P_{EC} exists (P_{NBI} / P_{EC} ~ 75 / 40 MW).
  → P_{fus} & f_{NI} increase with increasing ρ_{EC} for ITB sustainment.
- Dependence of performance on electron density profile
  → P_{fus} & f_{NI} increase, and H_H decreases with increasing density peaking factor.

3. JA DEMO [Tobita FED18, Sakamoto FEC18]

Steady-state tokamak DEMO concept, targeting:

- steady, stable electric power generation in plant scale
- reasonable availability using remote maintenance scheme
- overall tritium breeding to fulfil self-sufficiency of fuels
- 2-hour pulsed operation is also possible.

Size & Configuration

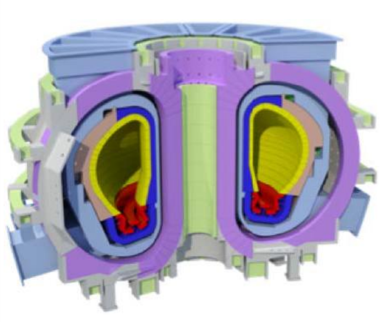
Para.	Steady state / Pulse (2hr)
R_p (m)	8.5
a_p (m)	2.42
A	3.5
κ_{95}	1.65
δ_{95}	0.33
q_{95}	4.1
V_p (m^3)	1647
I_p (MA)	12.3
B_T (T)	5.94
B_T^{max} (T)	12.1

Absolute Performance

Para.	Steady state	Pulse (2hr)
P_{fus} (MW)	1462	1085
P_{net} (MWe)	303	185
Q	17.5	13
P_{alp} (MW)	293	217
P_{CD} (MW)	83.7	83.5
T_e (keV)	16	12.9
n_e ($10^{19}m^{-3}$)	6.6	6.5
W_{th} (MJ)	786	630
τ_E (s)	2.67	2.66
NWL (MW/m²)	1.0	0.74

Normalized Performance

Para.	Steady state	Pulse (2hr)
HH_{98y2}	1.31	1.13
β_N	3.4	2.6
f_{BS}	0.61	0.46
f_{CD}	0.39	0.32
n_e/n_{GW}	1.2	1.2
f_{He}	0.07	0.07
f_{Ar}	0.0023	0.0023
f_{rad}^{core}	0.22	0.21



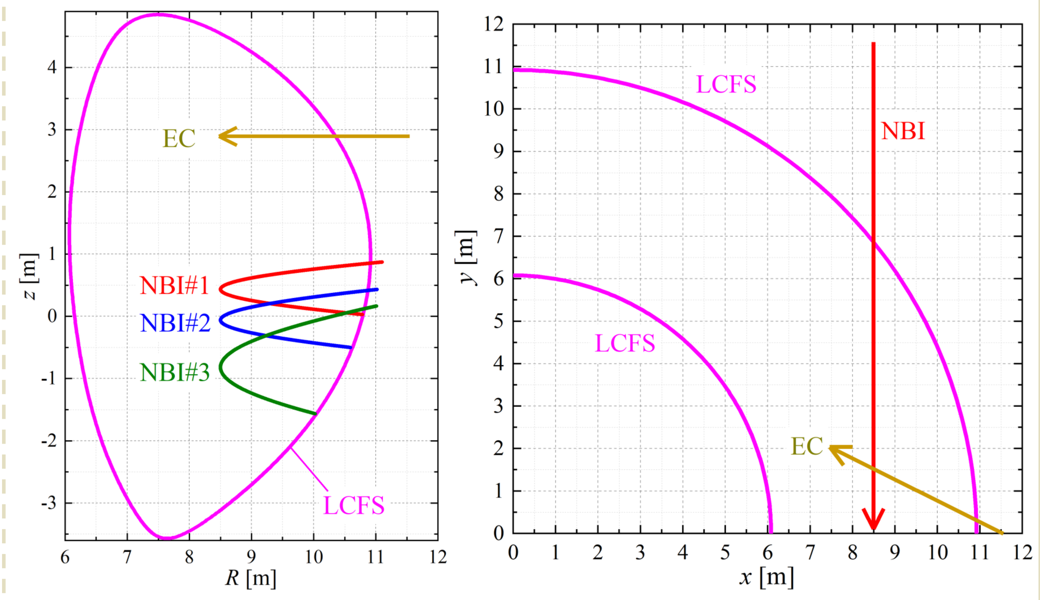
4. Analysis model and assumptions

GOTRESS+ [Honda NF(2021)116029]

- **ACCOME** [Tani JCP(1992)332]
  Equilibrium and bootstrap current
- **OFMC** [Tani JPSJ(1981)1726]
  NBCD and NBH profiles
- **EC-Hamamatsu** [Hamamatsu FED(2001)53]
  ECCD and ECH profiles
- **GOTRESS** [Honda POP(2019)102307]
  T_e & T_i profiles, prescribing density profiles
  - CDBM[Fukuyama PPCF(1995)611], Bohm-gyroBohm (BgB) [Erba NF(1998)1013] Coppi-Tang (CT) [Jardin NF93] are compared.
  - n_{ped}/n_{GW}=0.85、$T_{e,ped}$=$T_{i,ped}$=3 keV are assumed.
  - e, D, T & Ar are considered.

NBI condition
E_{NBI} = 1.5 MeV, R_{tan} = 8.5 m, θ_{pol} = 3.5, 4, 8°

EC wave injection condition
f_{EC} = 190 GHz, θ_{tor} = 30°, θ_{pol} = 0°



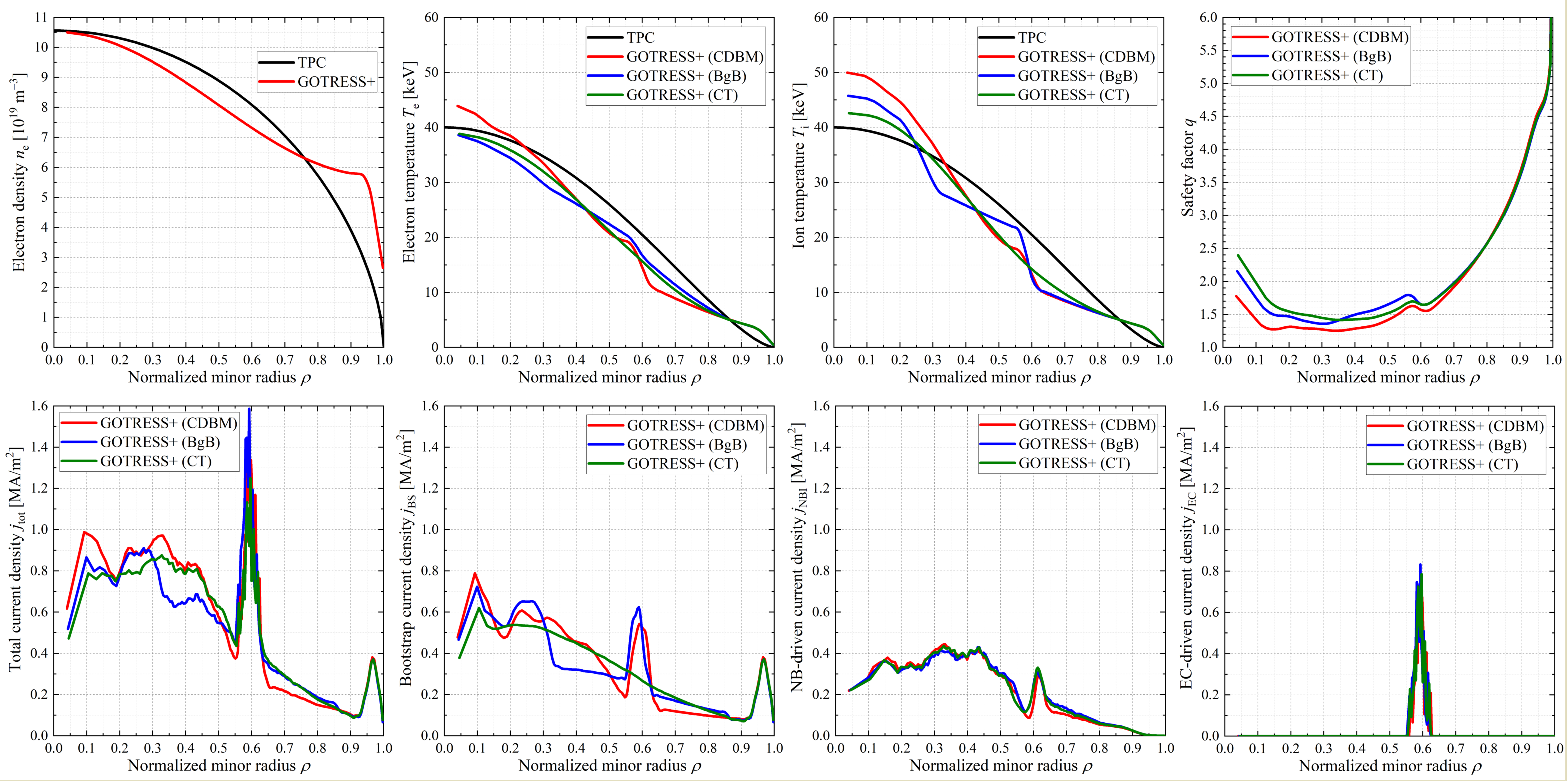
5. Comparison of main parameters with systems analysis and thermal transport model dependence

Comparison with result of systems code (TPC)

- For P_{fus} ~ 1.5 GW & f_{NI} ~ 1 w/ same level of f_{GW}, Higher P_{aux}, β_N, H_H are required, & Q decreases.
- To keep divertor heat flux below tolerance, P_{sep} is adjusted to be ~280 MW [Asakura NF17].
  → Higher Z_{eff}, H_H are required.

Thermal transport model dependence
3 models predict similar performance despite different profiles.

Para.	TPC	CDBM	BgB	CT
P_{fus}[MW]	1462	1483	1490	1508
P_{NBI}[MW]	83.7	75	75	75
P_{EC} [MW]	0	40	40	40
Q	17.5	12.9	12.9	13.1
f_{GW}	1.2	1.28	1.29	1.29
β_N	3.4	3.67	3.62	3.65
H_H	1.31	1.55	1.51	1.53
f_{BS}	0.61	0.61	0.62	0.62
f_{CD}	0.39	0.42	0.45	0.43
Z_{eff}	1.84	2.6	2.6	2.6

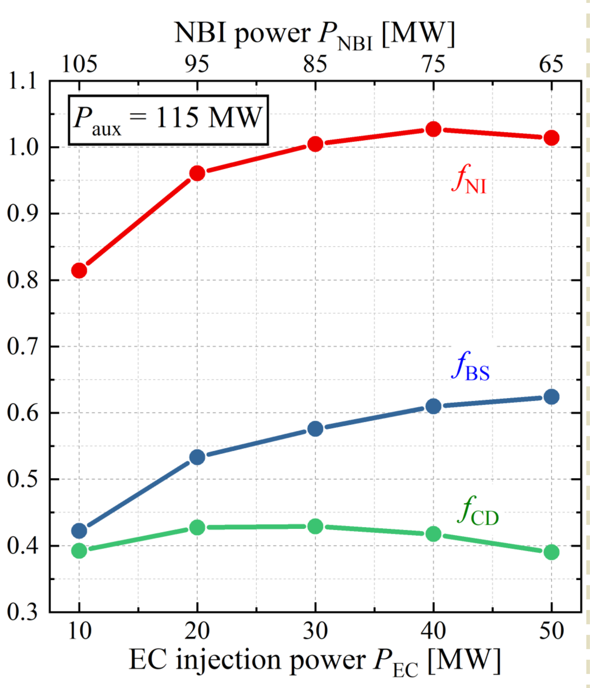


6. H&CD condition dependence (CDBM)

Balance between P_{NBI} & P_{EC}
NBI → main CD
EC → ITB sustainment

- High P_{EC} forms strong ITB.
  → T & f_{BS} increase.
- Trend of f_{CD}
  increases w/ increasing T_e
  decreases w/ P_{NBI}.

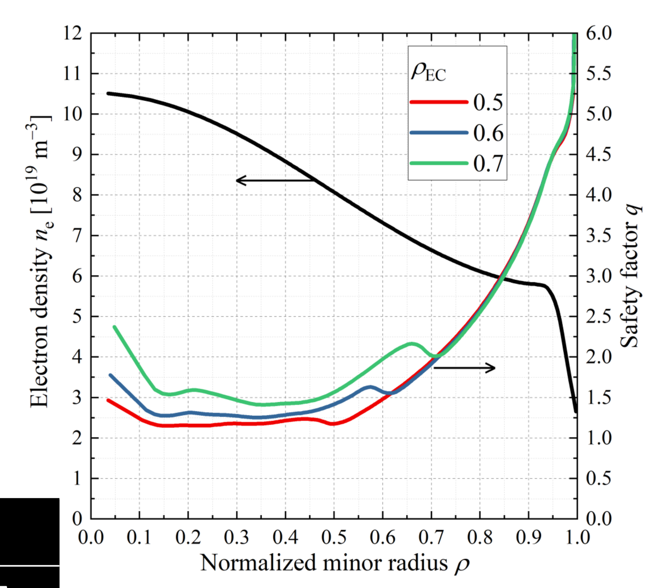
→Optimum balance is P_{EC}=40 MW & P_{NBI}=75 MW to maximize f_{NI}.



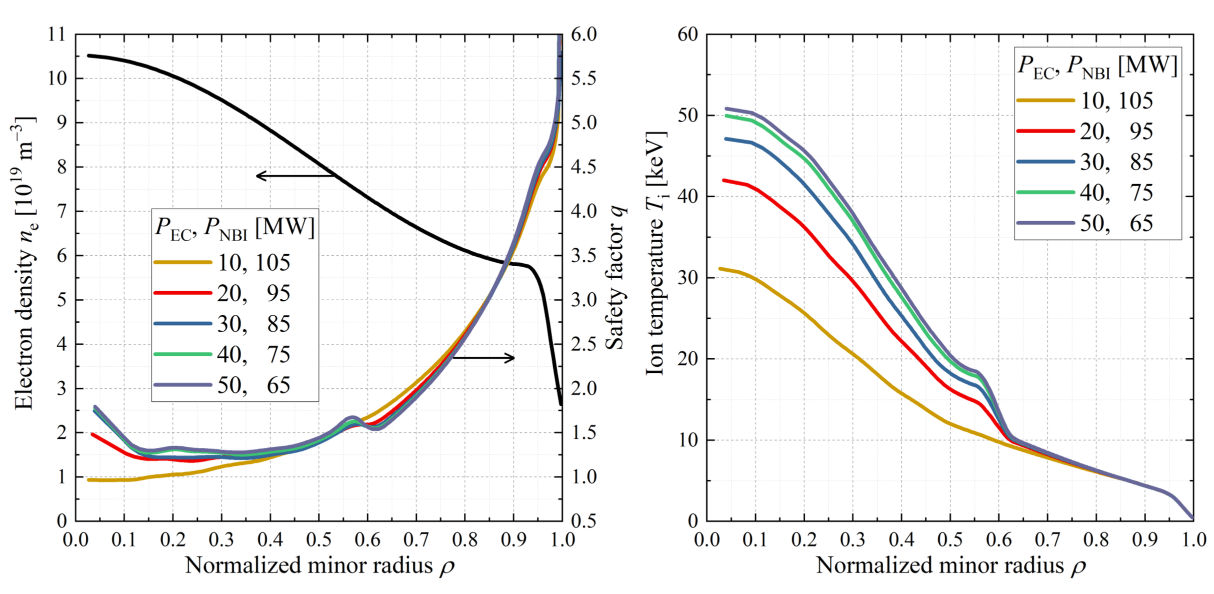
ECCD location (ρ_{EC})

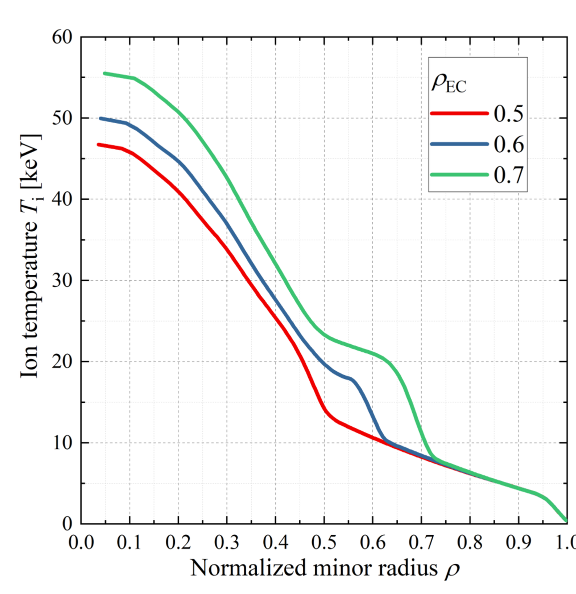
- f_{NI} & P_{fus} increase w/ ρ_{EC}.
- ρ_{EC} should be selected not to form multiple q = 2 surfaces.

→ Preferable ρ_{EC} is located in 0.6 < ρ < 0.7.



Para.	ρ_{EC}		
	0.5	0.6	0.7
P_{fus}[MW]	1311	1483	1882
P_{NBI}[MW]	75	75	75
P_{EC}[MW]	40	40	40
Q	11.4	12.9	16.4
f_{GW}	1.26	1.28	1.30
β_N	3.28	3.67	4.77
H_H	1.46	1.55	1.85
f_{BS}	0.54	0.61	0.75
f_{CD}	0.39	0.42	0.47
Z_{eff}	2.6	2.6	2.6





7. Density profile dependence (CDBM)

Pedestal density (n_{ped})
H_H & q_{min} increase, and f_{NI} & P_{fus} decrease w/ n_{ped} when f_{GW} is same level.

P_{fus} increases w/ n_{e0}/<n_e> by increase in T_i inside ITB.

Para.	n_{ped} / n_{GW}		
	0.7	0.85	1
n_{e0}/<n_e>	1.72	1.51	1.30
P_{fus}[MW]	1490	1483	1376
P_{NBI}[MW]	75	75	75
P_{EC} [MW]	40	40	40
Q	13.0	12.9	12.5
f_{GW}	1.27	1.28	1.25
β_N	3.67	3.67	3.52
H_H	1.49	1.55	1.61
f_{BS}	0.62	0.61	0.56
f_{CD}	0.45	0.42	0.38
Z_{eff}	2.6	2.6	2.6