Conceptual Design Study for Downsizing of Fusion DEMO Reactor

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Abstract

- This paper reports a conceptual design study for a downsized fusion DEMO reactor.
- Based on the system code analysis, this conceptual design study investigated a reactor concept that can both demonstrate power generation and tritium self-breeding in an ITER-size DEMO reactor.
- By improving the in-vessel components step by step in a single device, the DEMO rector concept was presented that could achieve a net electric power of more than 0 with ITER-like parameters in Phase 1, demonstrate comprehensive tritium breeding for self-realization with JA DEMO-like parameters in Phase 2, and achieve the net electric power of 100 MW-class with JT-60SA-like parameters in Phase 3.
- In addition, by evaluating the impact of key components for miniaturization in the DEMO reactor, such as superconducting magnets and blanket, the R&D items that are important for miniaturization of the reactor were clarified.

Background / Introduction

- The conceptual design of the Japanese demonstration (DEMO) reactor is being carried out by the Joint Special Design Team for fusion DEMO to establish the Japanese DEMO concept, named "JA DEMO" [1-2].
- On the other hand, from the viewpoint of early power generation demonstration, the larger reactor in the conventional JA DEMO concept leads to a more extended construction period and higher development risk.
- Therefore, based on ITER's experience in manufacturing toroidal field coils and its ability to foresee burning plasma (high energy multiplication), for the early power generation demonstration, a conceptual design study was carried out on a DEMO reactor downsized from JA DEMO (R_p = 8.5 m) to the ITER size (R_p = 6.2 m), with a step-by-step approach to demonstrate early power generation and tritium breeding, and to obtain the net electric power of 100 MW-class.

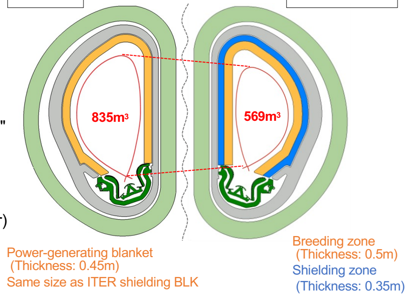
ITER-class DEMO reactor concept

Basic concept

- Scientifically and technically significant power generation demonstration:
  ➔ Burning plasma (Q > 10), net electrical output (P_{net} > 0).
- Low-risk, steady construction in the shortest possible time:
  ➔ An ITER-class DEMO reactor that can leverage the ITER procurement achievements. (Same size as ITER TF coil & Vacuum vessel)
- Step-by-step approach:
  ➔The first-phase goal of the DEMO reactor is "power generation demonstration" with subsequent modifications to achieve the DEMO reactor goals.

Challenges

- Phase 2: Plasma volume reduced by 30% with the addition of a breeding blanket.
  - ✓ Confinement performance: 1.5 times that of Phase 1 (strong ITB/negative shear)
  - ✓ β_N: 1.8 times that of Phase 1 (above the beta limit without walls)
- Phase 3: An even greater challenge than Phase 2 is required.
  - ✓ β_N: 2.4 times that of Phase 1



	Phase 1: System Integrating Operation (Power Generation Demonstration)	Phase 2: Blanket Functional Test (Fuel Breeding Demonstration)	Phase 3: Extended Operation (Steady-State Operation Demonstration)
Goals	• Short pulse operation (Several min.) • P_{gross} > ~180MW • P_{net} ~ 0	• Long pulse operation (Several hours) • P_{net} ~ 0 • Confirmation of tritium self-sufficiency	• Steady-state operation • P_{net} > 0 (~ 100 MW) • Demonstration of tritium self-sufficiency • Confirmation of maintenance scenario
Specific ations	● ITER-Based Operation Scenario ✓ P_{fus}: ~500MW ✓ Q: 10 ✓ Pulse Width: ~400 seconds ● Power Generation Blanket ✓ Dedicated to Power Generation ✓ Same size as ITER ● Heating and Current Drive Device ✓ ECH only	● Operation scenario with increased plasma pressure ✓ P_{fus}: ≥ 500 MW ✓ Q: ~ 10 ● Fuel breeding demonstration: ✓ Breeding blanket ● Heating/current drive device ✓ ECH & NBI ● Heat storage system (optional)	● Operation scenario reflecting the results of JT-60SA (even higher plasma pressure, higher plasma confinement) ✓ P_{fus}: > 500 MW ● Improved efficiency of heating and current drive device ● Improved breeding blanket ● Confirmation of the procedure and time for blanket replacement by remote handling.

Main parameters of the ITER-class DEMO reactor for each operational phase.

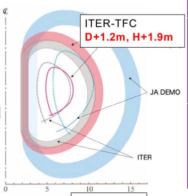
		Phase 1	Phase 2	Phase 3
Size & Configuration	R_p / a_p (m)	6.2 / 2.0	6.2 / 1.65	6.2 / 1.65
	A	3.1	**3.76**	**3.76**
	V_p (m^3)	835	569	569
	κ_{95}	1.7	1.7	1.7
	q_{95}	3.0	4.0	3.68
	I_p (MA)	14.96	7.36	8.0
	B_T (T)	5.29	5.29	5.29
	Pulse width	337sec	3.98 hrs	Steady-State
Performance	P_{fus} (MW)	492	510	820
	Q	10	10	14.4
	P_{net} (MWe)	7.31	9.3	82.5
	P_{gross} (MW)	188	195	307
	P_{ADD} (MW)	49.2	51.0	56.8
Plasma Performance	f_{BS} (%)	21.7	58.9	68.9
	n_e ($10^{19}m^{-3}$)	9.95	8.9	9.74
	HH_{98y2}	0.95	**1.41**	**1.50**
	β_N	1.8	**3.4**	**4.3**
	f_{GW} (n_e/n_{GW})	0.85	1.19	1.20
BLK	Breeding / shielding zone		0.5 / 0.35	0.5 / 0.35
	Net TBR		1.05	1.05

Option: Higher magnetic field & Larger TF coil

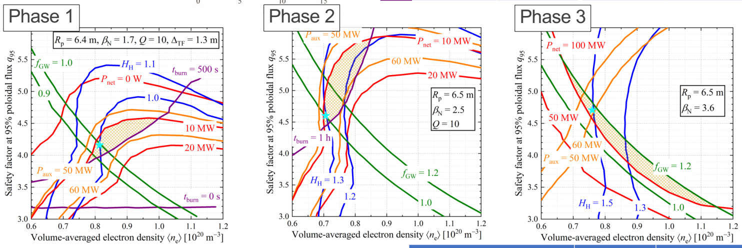
By increasing the B_t and V_p, the performance requirements for plasma are relaxed.

- ✓ TF coil width: +1.2 m from ITER-TFC
- ✓ Plasma surface outer position: Max. 8.6 m (from 16 TF coils, 1% TF ripple)
- ✓ R_p: Max. 6.5 m when A ≦ 3.1

- Phase 1&2 are expected to be feasible with conservative plasma performance.
- Phase 3 is expected to be feasible with improved plasma performance, functional material development.



		Phase 1	Phase 2	Phase 3
Size & Configuration	R_p / a_p (m)	6.4 / 2.2	6.5 / 2.1	6.5 / 2.1
	A	2.91	**3.10**	**3.10**
	κ_{95}	1.7	←	←
	q_{95}	4.16	4.60	4.71
	I_p (MA)	13.5	10.6	10.4
	B_T (T)	5.56	5.47	←
	Pulse width	564sec	1.08hrs	Steady-state
Performance	P_{fus} (MW)	540	531	917
	Q	10	10	15.9
	P_{net} (MWe)	11.3	10.9	107
	P_{gross} (MW)	206	203	342
	P_{ADD} (MW)	54.0	53.2	57.5
Plasma Performance	f_{BS} (%)	27.2	44.4	64.3
	n_e ($10^{19}m^{-3}$)	8.14	7.06	7.56
	HH_{98y2}	**1.00**	**1.30**	**1.50**
	β_N	**1.7**	**2.5**	**3.60**
	f_{GW} (n_e/n_{GW})	0.99	1.00	1.15

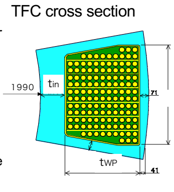


Required TFC R&D Items

- Development of a new attachment for TF coil fabrication
- Development of a high-current conductor
  ✓85kA@ϕ39mm (Ic=71 A/mm²: 1.3 times that of the ITER conductor)
- Development of high strength cryogenic steel
  ✓Stress on the coil case will increase by approximately 200 MPa

The issues are the increased development time due to R&D and manufacturing costs.

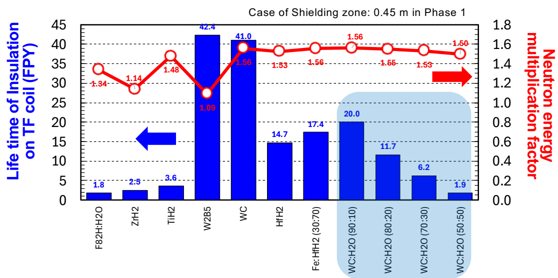
TFC cross section



	ITER	Option
SC strand	Nb_3Sn	Nb_3Sn
Number of TFC	18	16
B_{tmax}	11.8 T	**~ 13 T**
Conductor current	68 kA	**85 kA**
Number of turns per TFC	134	134
Total magneto motive force	164 MAT	182 MAT
Total magnetic energy	41 GJ	~55 GJ
Design stress	667 MPa	**800 MPa**
Width / Height of TFC	8/12.3 m	**9.2/14.2 m**

Blanket & Sheilding

- **Fuel production option in Phase 1**
  Tritium can be produced by loading materials for fuel production (breeding and multiplying materials)
  ✓Net TBR = 0.75 (Breeding zone: 0.2 m, Shielding zone: 0.25 m)
  ✓Net TBR = 0.84 (Breeding zone: 0.25 m, Shielding zone: 0.2 m)
- **Improved shielding performance**
  Improving shielding performance is very important to ensure operational time in Phases 2 & 3.
  ✓Tungsten carbide (WC) is a promising candidate.



Conclusion

- In a DEMO reactor downsized to ITER size, the goal is to demonstrate power generation with positive net electric power and fuel self-sufficiency.
- This is followed by a step-up of in-vessel components and core plasma performance based on various R&D results in addition to ITER and JT-60SA to achieve a fusion reactor with a single device.
- The concept of a fusion energy reactor that can generate 100 MW-class net electric power was established by stepping up the performance of the in-vessel components and core plasma based on the results of various R&D activities.

Reference

[1] K. Tobita et al., Fusion Sci. Technol. 75 (2019) 372-383.
[2] Y. Sakamoto et al., 27th IAEA Int. Conf. on Fusion Energy (2018) FIP/3-2
[3] H. Utoh et al., Fusion Engineering and Design 202 (2024) 114345.