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Conceptual Design Study for Japanese Fusion DEMO Reactor

Hiroyasu UTOH

QST, Joint Special Design Team for Fusion Demo

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 63, Mar. 2026. Presentation given at ISS 2025, Nagasaki, Japan, Dec. 2025.

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Contents

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- Introduction
- ITER-size JA DEMO reactor concept
  - ✓ Basic concept
  - ✓ Option: Higher magnetic field & Larger TF coil
- Summary

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Introduction -Recent situation in JA-

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In recent years, the circumstances surrounding DEMO development in Japan have changed significantly.

- The design activity to date is implemented in accordance with the roadmap and action plan formulated by MEXT, and the conceptual design was scheduled to be completed by FY2026.
- In response to the global fusion situation, the Cabinet Office has formulated "Fusion Energy Innovation Strategy" in Apr. 2023.
- In Jun. 2024, the Cabinet Office has decided "Integrated Innovation Strategy 2024", stated that "Japan will aim to realize fusion energy as soon as possible by preparing a timetable that includes necessary national efforts toward achieving the first demonstration of power generation in the 2030s ahead of other countries".
- In Jun. 2025, Cabinet Office has revised "Fusion Energy Innovation Strategy".

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Fusion Energy Innovation Strategy (Revised)

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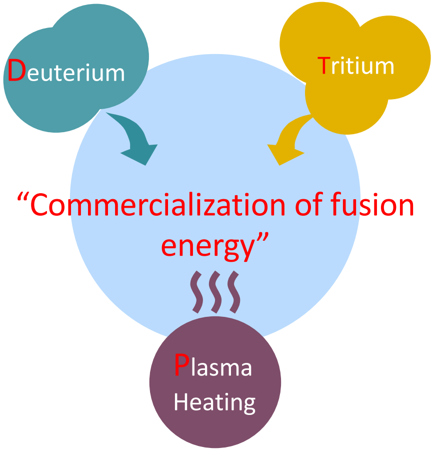
- The Cabinet Office revised "Fusion Energy Innovation Strategy" in June 2025 toward achieving the demonstration of power generation in the 2030s and establishing the fusion industry ecosystem.

Developing the Fusion industry

- Collaboration with J-Fusion. (International standardization, supply chain construction, intellectual property rights, business creation, investment promotion, etc.)
- Ensuring safety that is scientifically appropriate and internationally coordinated. (For the time being, it will be subject to the RI Act. Agile regulations will be applied according to new knowledge and technological developments.)
- Establishment of a Task Force toward promoting social implementation. (TRL evaluation, consideration of implementing entity and methods for selecting site.)



Developing Fusion Technology

- Acceleration of R&D for establishing technical basis toward DEMO. (Accelerating R&D with a view to developing a DEMO, including engineering design and full-scale technology development. Verification of an ITER-sized DEMO.)
- Strengthening research and development capabilities in both the public and private sectors including start-up companies. (Consider strengthening the funding functions of NEDO, JST, QST, etc. Promote challenges in various methods such as tokamak, helical, and laser depending on the level of technological maturity and milestone achievement.)
- Acquisition of core technologies through ITER project/BA activities. (Increase the number of Japanese staff and encourage their active participation in procurement.)

Framework for Promoting Fusion Energy Innovation Strategy

- Advancing the strategy with the Cabinet Office as the "control tower" together with relevant ministries and agencies.
- Establishment of the fusion technology innovation hubs in QST, NIFS and ILE etc.
- Establishment of a systematic human resource development programme through inter-university and international collaborations, and setting development goals.
- Environmental development for fostering public understanding through risk communication.

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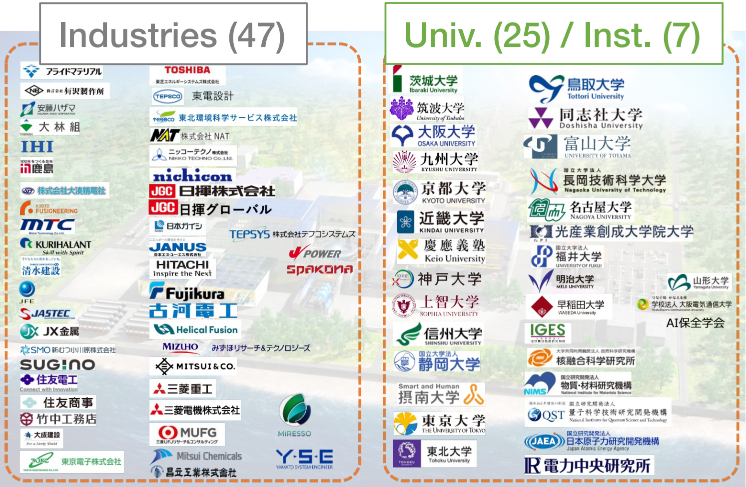
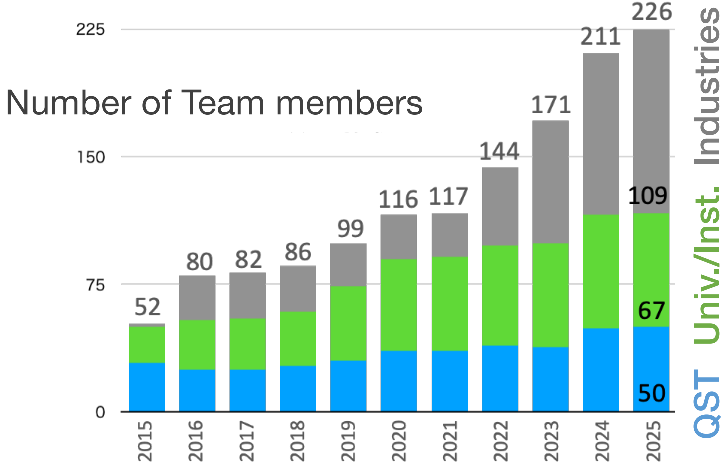
Joint Special Design Team for Fusion DEMO

- An all-Japan design team based on industry-academia collaboration
- Promoting conceptual design through information sharing and consensus building

20th General Meeting@2025.11.18

- The number of members from industry recently increased. ➔Industries: 47





Original concept of JA DEMO

Since the original concept of the JA DEMO was defined in JA Model 2014 [1], the pre-conceptual design has been completed on the fusion DEMO reactor.

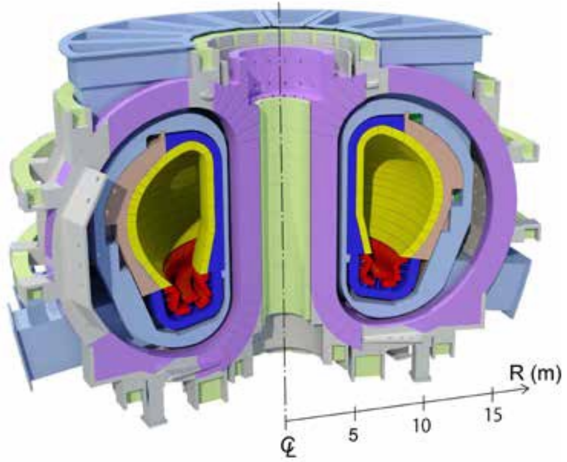
Operational flexibility

- JA DEMO was proposed in 2014 to provide operational flexibility from pulse to steady-state with R_p=8.5m for (plasma current lamp-up) large CS coil and P_{fus}~1.5GW for divertor heat load.
  ➡P_{fus}~1.5 GW for Steady state

Technological feasibility

- ITER technologies as much as possible
  - ✓ Blanket: ITER-TBM strategy in Japan
  - ✓ Divertor: Water cool. and W mono-block divertor
  - ✓ Magnet: Radial Plate, CICC etc.

[1] Y. Sakamoto et al., IAEA FEC 2014



R_p / a_p	8.5 m / 2.4 m
Aspect ratio	3.5
Fusion output	1.4 GW
Net electric power	~250 MW
Plasma current	12.3 MA
Toroidal field on axis	6.0 T
Max. toroidal field	~14 T

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Acceleration of JA DEMO Program

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For demonstration of electricity generation in the 2030s, QST started to investigate acceleration scenario of JA DEMO having a **scientific and technical significance** for leading to social implementation.

Scientific significance

- ✓ Burning plasma with significant self-regulation (self heating dominated): Q>10

Technical significance

- ✓ Demonstration of net electric power: $P_{net} > 0$

Main concept Minimizing the path to the construction and low-risk

- Experience of ITER construction
  - ➢ Shortest construction start time by using ITER-compliant core components
- Plasma operation scenario well elaborated for ITER
  - ➢ Demonstration of power generation using burning plasma (Q=10)
- Resource rationalization through phased approach

➡ **ITER-size JA DEMO by phased approach**

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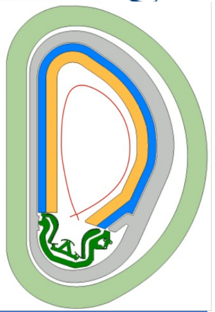
Phased approach strategy of JA DEMO

QST

- **Phase I :** Install blankets specialized for power generation and shielding to secure a plasma volume comparable to ITER and demonstrate P_{net}~0 in short pulse operation.
- **Phase II :** Replace with breeding blankets and thin shielding, and demonstrate fuel breeding and P_{net}~0 in high beta long pulse operation.
- **Phase III :** Improve the efficiency of heating and current drive devices, and enhance plasma performance in steady-state operation.



	Phase I Demonstration of electricity production	Phase II Demonstration of tritium breeding	Phase III Demonstration of steady-state operation
Obj.	• Short pulse (several min.) • P_{gross} > ~180 MW • P_{net} ~ 0	• Long pulse (several hours) • P_{net} ~0 • Self-sufficiency of fuel (TBR>1)	• Steady-state operation • P_{net} > 0 （~100MW） • Self-sufficiency of fuel (TBR>1)
Spec.	• ITER baseline scenario ✓ Fusion output: 500 MW ✓ Q value: 10 ✓ Pulse length: ~400 s • Electricity production and shielding BLK ✓ Same size as ITER shielding BLK ($t_{E\&S\text{-}BLK}$=0.45 m)	• JA DEMO baseline scenario ✓ Fusion output: >500 MW ✓ Q value: 10 ✓ High β_N: 3.4 ✓ High HH_{98y2}:1.41 • Tritium breeding BLK ✓ JA DEMO breeding BLK ($t_{B\text{-}BLK}$=0.5 m) ✓ Thin shielding (t_S=0.35 m)	• JT-60SA scenario (High β & High confinement) ✓ Fusion output ~1 GW ✓ High efficiency heating and current drive • Tritium breeding BLK ✓ JA DEMO breeding BLK ($t_{B\text{-}BLK}$=0.5 m) ✓ Thin shielding (t_S=0.35 m)

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Image of schedule aiming for electricity demonstration in the 2030s

QST

2030 | 2040 | 2050

Conceptual design | Eng. & manuf. design Full-scale R&D | Construction & Assembly | Phase 1 Electricit | *Upgrade* | Phase 2 Fuel breeding | *Upgrade* | Phase 3 Full operation

Items to consider:
Implementing body of DEMO const.
Land survey, site selection
Safety regulations

Reflecting knowledge of JT-60SA & ITER

Electricity demonstration

DONES irradiation

Assembly (3y)

Buildings (Tokamak complex, etc.) (9y)

Component manufacturing (10y)

strong support of industry

Facility design (2y)

TF coil manufacturing (4 lines, 7y)

Facility (2y)

Large-scale facility construction and R&D (1)

Large-scale facility construction and R&D (2)

Full-scale R&D for construction

Full-scale R&D for construction & manufacturing for Phase 1

Full-scale R&D for construction & manufacturing for Phase 2

Full-scale R&D for construction & manufacturing for Phase 3

Involvement of academia and industry, including startups

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Challenges on ITER-size JA DEMO concept

Challenges

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

To ease the plasma performance requirements of the original ITER-size JA DEMO reactor, we considered option.

		Phase II	Phase III
Size & Configuration	R_p / a_p (m)	6.2 / 1.65	6.2 / 1.65
	A	**3.76**	**3.76**
	κ_{95}	1.7	1.7
	q_{95}	4.0	3.68
	I_p (MA)	7.36	8.0
	B_T (T)	5.29	5.29
	Pulse length	3.98 hrs	S.S.
Performance	P_{fus} (MW)	510	820
	Q	10	14.4
	P_{net} (MWe)	9.3	82.5
	P_{gross} (MW)	195	307
Plasma Performance	HH_{98y2}	**1.41**	**1.50**
	β_N	**3.4**	**4.3**
	f_{GW} (n_e/n_{GW})	1.19	1.20

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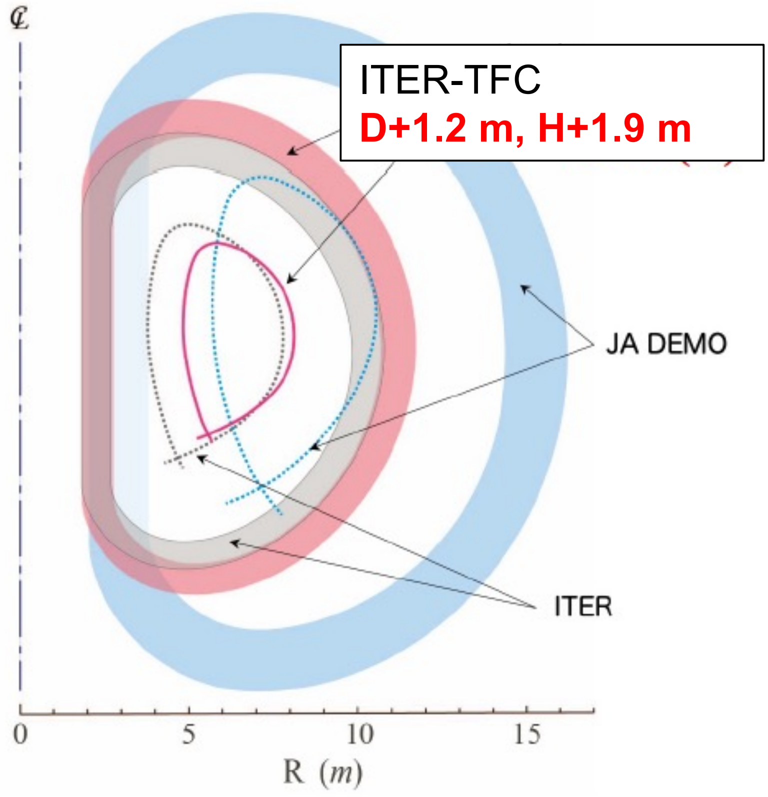
Option: Higher magnetic field & Larger TF coil

QST

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

- ✓ TF coil width: +1.2 m from ITER-TFC (keeping the ITER TF coil fabrication facilities as far as possible within the usable range
- ✓ 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 (R_{cs} decreased slightly:)



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- Phase I & II are expected to be feasible with conservative plasma performance.
- Phase III is expected to be feasible with improved plasma performance, functional material development.

		Phase I	Phase II	Phase III
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 length	564 sec	1.08 hrs	S.S.
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
Plasma Performance	HH_{98y2}	0.95	**1.30**	1.50
	β_N	1.8	**2.5**	**3.60**
	f_{GW} (n_e/n_{GW})	0.85	1.00	**1.15**

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Option: Higher magnetic field & Larger TF coil

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)
    - ➔Short twist pitch stranded wire, High-strength, high-performance SC wire
- Development of high strength cryogenic steel
  - ✓ Stress on the coil case will increase by approximately 200 MPa
    - ➔R&D of high strength cryogenic steel

	ITER TFC	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**

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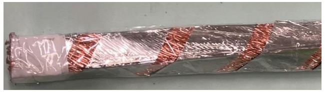
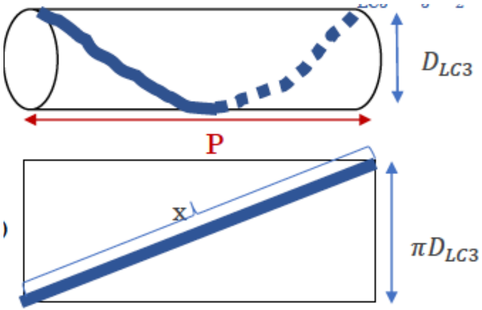
Feasibility study of short twist pitch stranded wire structure

- R&D was conducted using ITER CS type strands (Nb_3Sn), and both ITER strands and DEMO strands (4th strand) were used.

With Furukawa Electric Co., Ltd.

		Twist pitch	
		1st20(±5), 2nd45(±10), 3rd**80**(±10), 4th**150**(±15) (equivalent to ITER CS twist **pitch**)	1st20(±5), 2nd45(±10), 3rd**120**(±10), 4th**275**(±25) (equivalent to ITER CS twisting **rate**)
SC strand	ITER CS grade Nb_3Sn	**A-1** Void ratio: 35.7%  Sub-wrap breakage and local plastic deformation	**A-2** Void ratio: 29.5%  No significant deformation
	Cu-Nb reinforced Nb_3Sn	**B-1** Void ratio: 25.7%  No significant deformation	

Twisting rate:
how long the actual length per pitch of the twisted cable is relative to the twist pitch



$$TR(\%) = \left(\frac{x}{P} - 1\right) \times 100 = \left(\frac{\sqrt{P^2 + \pi^2 D^2}}{P} - 1\right) \times 100$$

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Feasibility study of short twist pitch stranded wire structure

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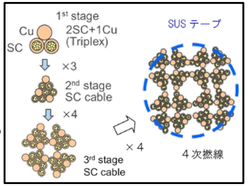
- ✓ Prototype of innovative high-strength Nb_3Sn wire
- ✓ Acquisition of basic stress resistance data for high-strength Nb_3Sn wire

Joint with N.Banno (NIMS)

- ✓ Understanding the strand twist trajectory and comprehensive numerical analysis based on the trajectory

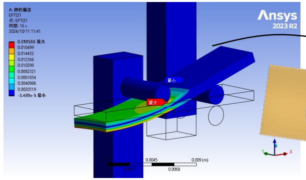
Joint with T. Yagai (Sophia Univ.)

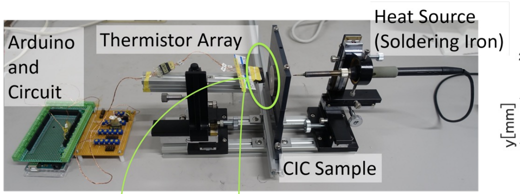
CuNb-reinforced bronze-route Nb_3Sn wires made by **Furukawa Electric**, and distributed-tin (DT) Nb_3Sn wires reinforced with brass matrix made by **Kobe steel**

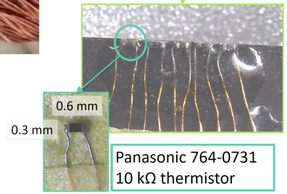


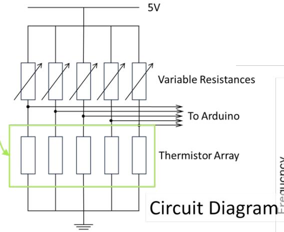
Verifying the feasibility of manufacturing the prototype conductor at a full scale

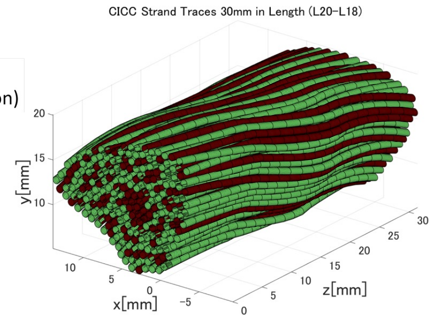
Development of an in-situ bending stress Ic measurement probe

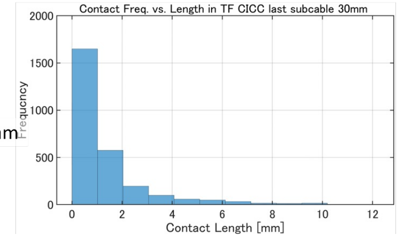












N. Banno et al., IEEE Trans. Appl. Supercond., **34**, 5, 8400505 (2024)

S. Hoshino et al., IEEE Trans. Appl. Supercond., **34**, 5, 4803904 (2024)

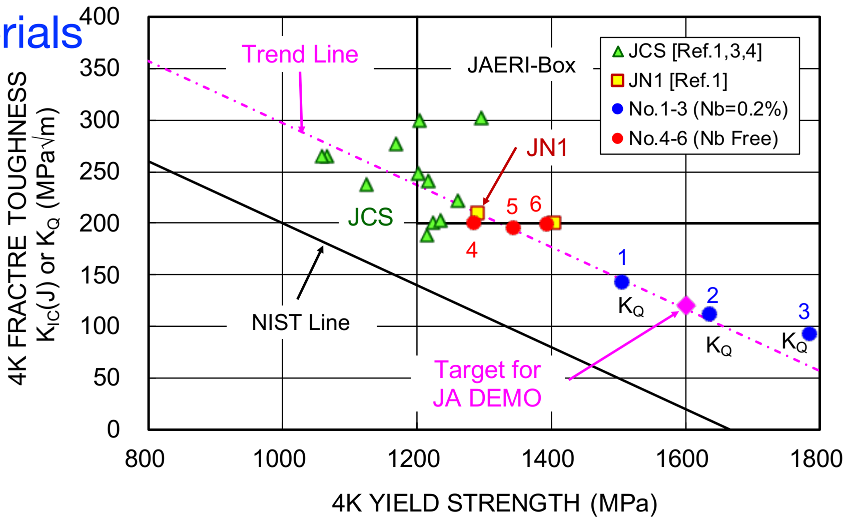
R&D of high strength cryogenic steel

- ITER adopts the 0.2% yield stress (YS) of 1000 MPa (JJ1).
- JA DEMO adopts the YS of >1200 MPa.
- Higher YS can be used because it has already been demonstrated that such material can be manufactured at the industrial level through the past development of Japanese Cryogenic Steels (JCS).

➢ Trial production and evaluation of new materials

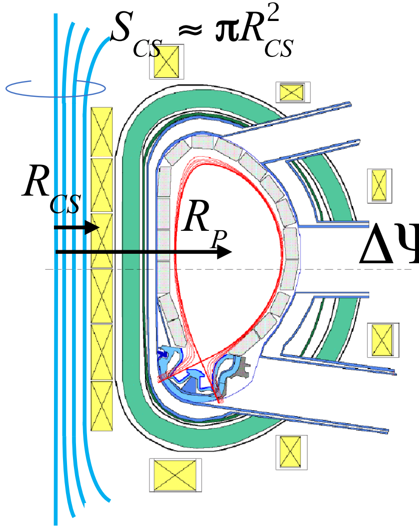
- ✓ YS increases with Nb due to finer grain
- ✓ Nb exhibits brittle behavior → requiring further investigation (Nb-free materials)
- ✓ V to strength increase is small → No V

Further R&D is needed to verify weldability and the feasibility of fabricating large structures.



Higher magnetic flux supply by CS option: - Concept of Hybrid CS -

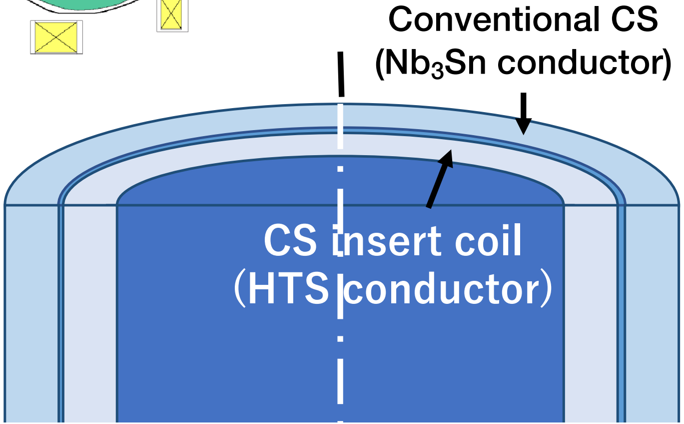
- Center Solenoid (CS) has an important role for plasma current ramp-up (poloidal flux supply) and an effect on reactor size (CS radius, R_{cs}).
- Larger CS flux requires higher B_{cs} or Larger CS radius. (trade-off with conductor and reactor system design)
- To evaluate an effect of “Hybrid CS” on reactor downsizing, conceptual study of Hybrid CS was started.



$$\Delta\Psi_{CS} \approx 2B_{CS} \cdot \pi R_{CS}^2$$

❖ Hybrid CS concept would provide higher CS flux on same CS outer radius (~**+20%**).
➔The pulse length is approximately **1.5 times longer**.

❖ Design optimization and R&D of HTS conductor on insert coil and detailed evaluation of AC loss will be done.



Summary

- Toward achieving the first demonstration of power generation in the 2030s having a scientifically and technically significance for leading to social implementation, phased approach strategy to accelerate JA DEMO program is investigated in QST utilizing the main components of ITER.
- Objective for each phase is defined as demonstration of electricity generation at least zero-net electric power in phase I, demonstration of tritium breeding in phase II and demonstration of steady-state operation at least hundred level electric power in phase III.
- In order to ease the plasma performance requirements for the second and third phases, QST are also considering design options that offer higher performance than ITER‘s TFC specifications. Utilizing the results and knowledge gained from R&D conducted so far in JA DEMO will be effective.