Fusion Power Associates 42nd Annual Meeting and Symposium
Pathways to Fusion Power
December 15-16, 2021

Fusion Energy Research & Development in QST

- ITER, JT-60SA and Fusion Engineering-

Fusion Energy Directorate
National Institutes for
Radiological Science and Technology

Presented by
Yutaka KAMADA

1. Japanese Strategy of Fusion Energy Development toward Carbon Neutral Society

Scientific Feasibility

Achievement of Break-even condition

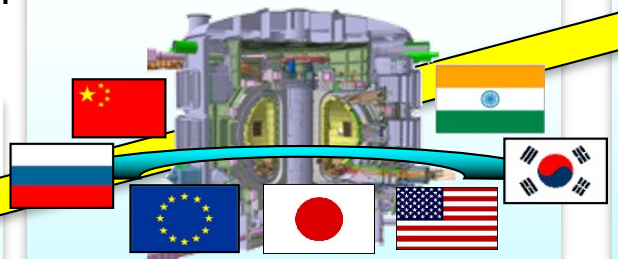
*DT- equivalent fusion gain 1.25

*Ion Temp. 520MºC

JT-60

Scientific & Technological Feasibility

DT Fusion gain = 10 Integrated Fusion Technology



ITER

Technological Demonstration & economical Feasibility

DEMO

Practical Use

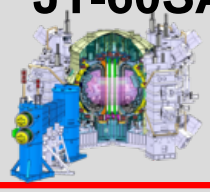
Support ITER

Foster Next Generation

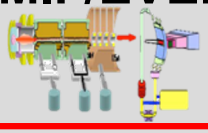
Complement ITER

Broader Approach (BA) Activity

JT-60SA

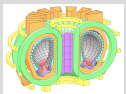


IFMIF/EVEDA

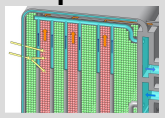


IFERC

DEMO Design



Blanket Development



Academic Research

University Tokamaks etc.

GEKKO-XII

LHD

Fusion Energy: Social & Governmental expectation is remarkably increasing in Japan.

Legend
- When to achieve the target
- Target to achieve
- When to decide transition to the next phase
- Figure of activities required

A Roadmap toward Fusion DEMO Reactor

Exhibit

~2020~ ~2025~ ~2030~ ~2035~ ~2050~

Intermediate C&R (check and review) | Intermediate C&R | Third phase | C&R | Fourth phase

① **ITER project** (run by int'l collaboration)
- Construction phase
- First Plasma
- Plasma control test toward DT burning
- Operation phase
- DT burning and ignition
- Burn control & engineering test
- Long plasma burning at energy gain factor more than 10

BA activities (phase II) (run by int'l collaboration)

② **JT-60SA** (part of BA activities)
- Initial research phase
- Integrated research phase
- Extended research phase

⑨ **4th phase (DEMO) Decision to transition**

Ready to commercialize

First Plasma

③ **Fusion neutron source** (run also thru int'l collaboration)
- Technology demonstration & engineering design
- Construction
- Fusion neutron irradiation test
- Validation of steady-state operation
- Acquisition of irradiation data

④ **DEMO R&D** (run also thru int'l collaboration)
- Concept design & elemental technology development

Engineering design & full-scale technology development
(1) DEMO design activities
(e.g.: development test of full-scale superconductive coils, development of remote maintenance technologies for the DEMO, development of heating/current drive systems)
(2) Development of integrated plant simulator for DEMO
(3) Safety research & tritium handling technologies
(e.g.: safety discussion including verification and validation (V&V), development of fuel system including technologies for handling a large amount of tritium)
(4) Reactor engineering and related foundation research
(e.g.: material development including design criteria, development of measurement/control units, divertor development including heat load test)

- Completion of engineering design based on prospective social acceptability & economic feasibility
- Construction & operation of DEMO

Bird's-eye view by the Joint Special Design Team for Fusion DEMO

⑤ **Blanket development**
- Safety demonstration test
- Engineering test (test blanket module (TBM))
- Validation of tritium recycle

⑥ **Research on large helical devices**

⑦ **Research on high-power lasers**

Advancement from academic research to development research also anticipated

⑧ **Social relations activities**
- Social relations activities toward realization of the DEMO

ITER

Two JA TF coils
under assembly at the site

ITER – Japanese In-kind Contribution: going well

Manufacturing technology of ITER components => DEMO.

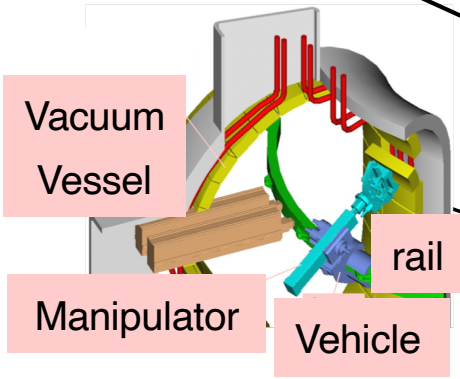
CS

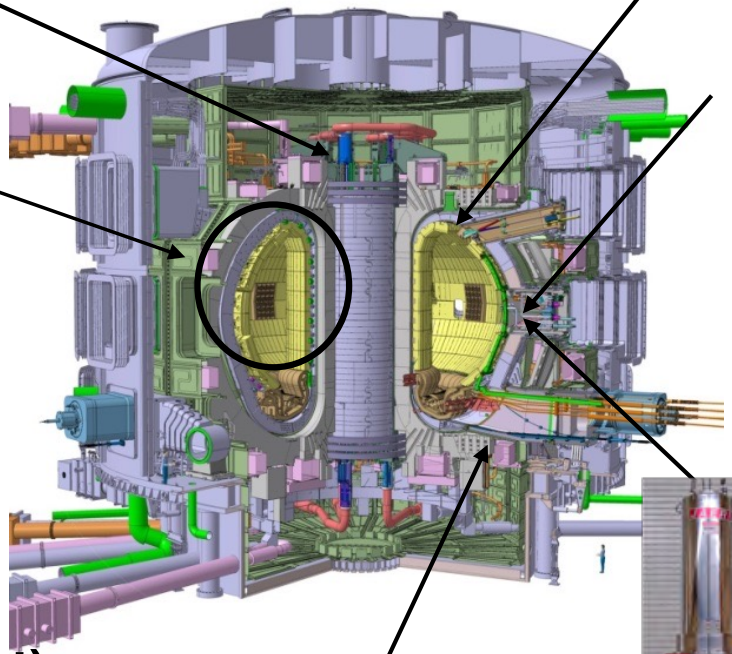
All 49 conductors completed & delivered to U.S. Mar. 2018.

TF Coil

9 TF Coils and all 19 Coil Structures

5 TF coils were delivered to the site by Dec. 2021.





NBI system

1-MV PS were installed in the NBTF site at RFX in Italy.

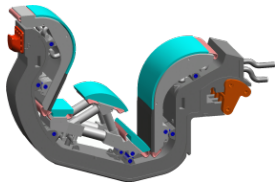
Commissioning is on going.

Remote Handling

Manufacturing design in progress.

Divertor (Outer Target)

Based on the major design change to full tungsten divertor, prototype manufacturing is in progress.



ECH system

8 out of 24 gyrotrons are procured by JA.

5 gyrotrons have passed the Factory Acceptance Test.

Good Progress with high manufacture accuracy: TF Coils (5 already at ITER site) & TF Coil Structures

Ceremony for the 3rd TF Coil Completion was held at Toshiba（June. 7, 2021）

*This TF coil is the first one for Toshiba.

9 TF Coils

Delivery to the ITER Organization

Mass production is going well.

The final TFCS for EU (Toshiba)

	JA TFC								
	1	2	3	4	5	6	7	8	9
Double Pancake	M	M	T	M	T	M	T	T	M
Winding Pack	M	M	T	M	T	M	T	T	M
TF coil FAT	M	M	T	M	T	M	T	T	M

19 TF Coil Structures (TFCS)

	TFCS for JA									TFCS for EU									
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	10
Inboard	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Outboard	H	H	T	H	T	H	T	T	H	H	H	H	H	T	T	T	T	T	T
Shipping																			

Green: completed, M: MHI, T: Toshiba, H: HHI

1MV NB Power Supply: Seismic Design being finalized

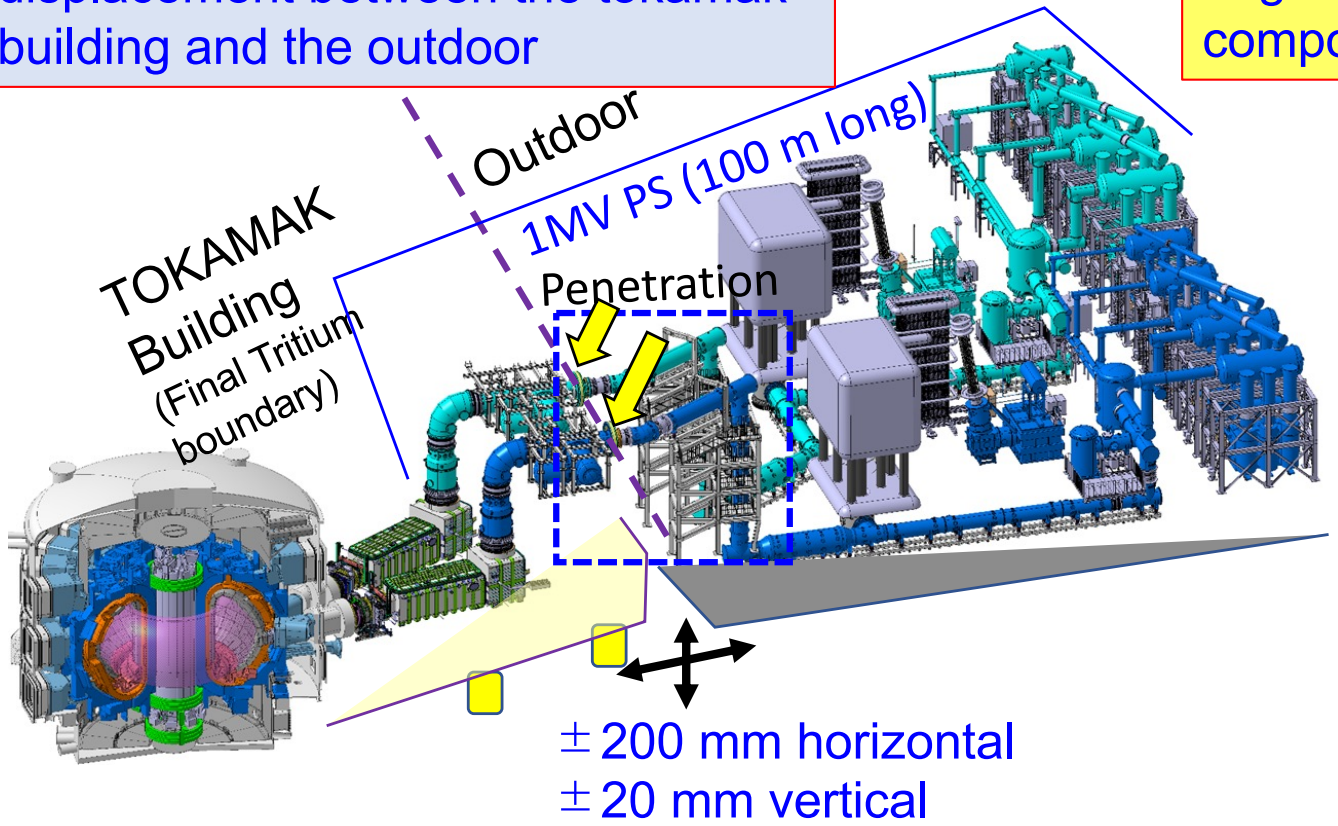
dc power supply (1MV, 60 A, 3600 s) development is ongoing based on the NB Test Facility (NBTF)

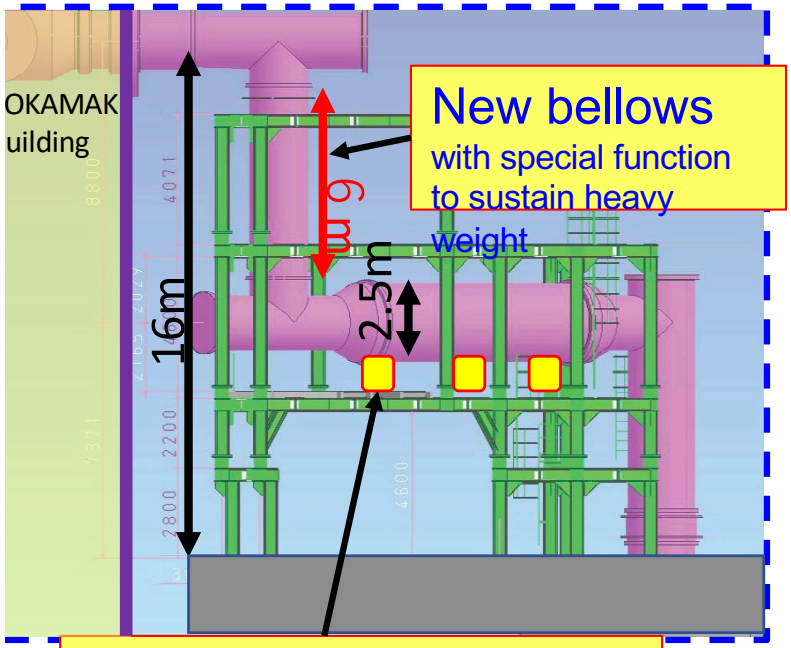
NBTF: Final acceptance test is on going.

ITER : Nuclear safety requirement as Tritium boundary
The PS penetrates into the tokamak building.

Issue = How to absorb large relative displacement between the tokamak building and the outdoor

Design of new structure to absorb this large displacement, and sustain heavy component (>50 t) has been completed.



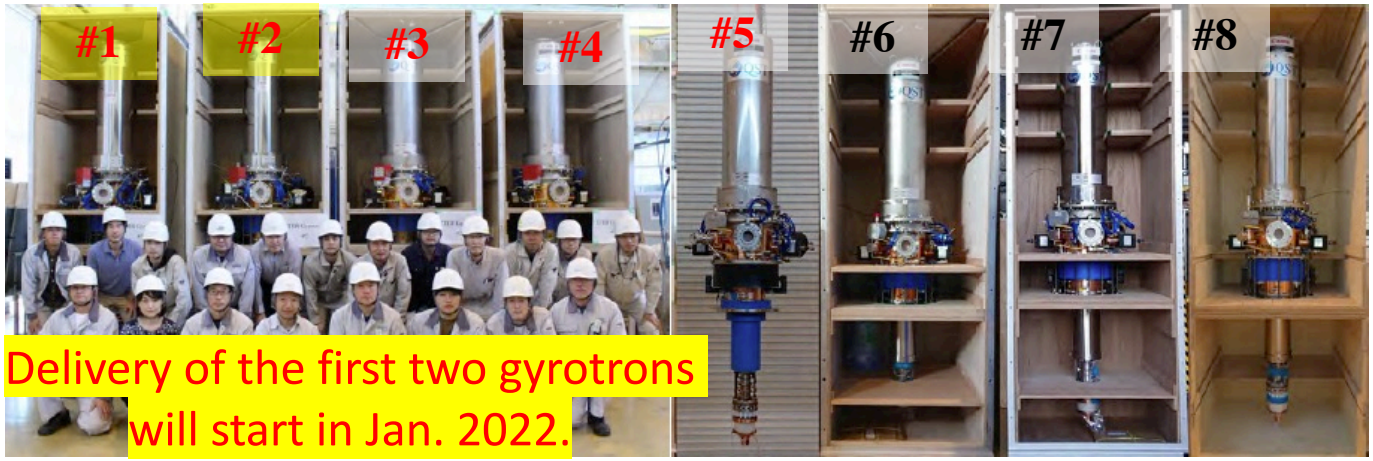


All 8 Gyrotrons Manufacture Completed

Factory Acceptance Tests of 4th and 5th gyrotrons were finished.

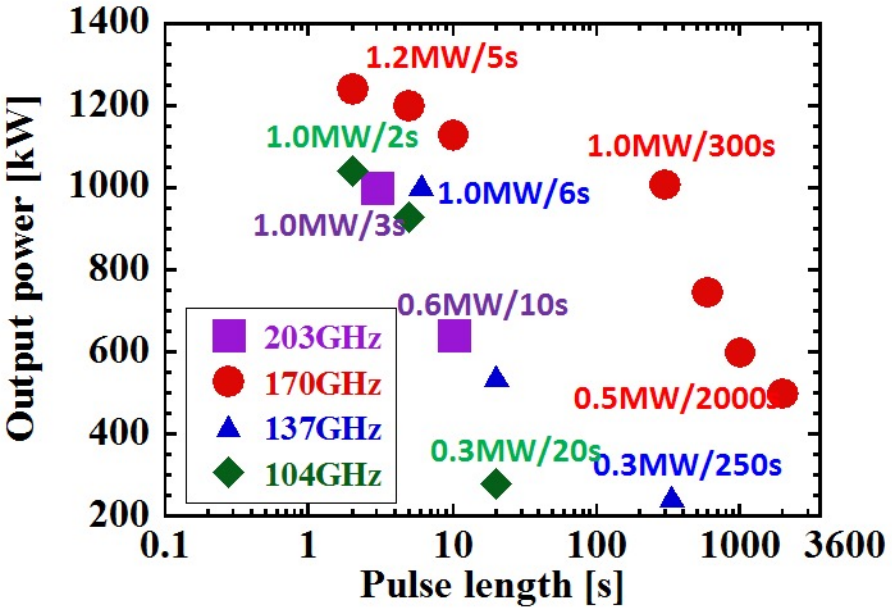
Functional Requirements

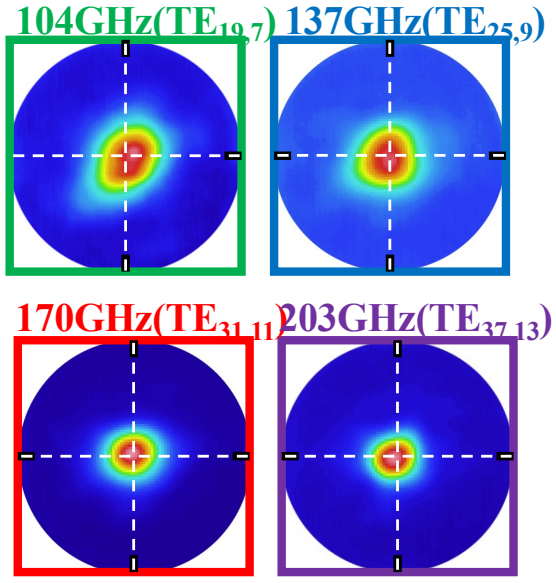
- Frequency/Power/Efficiency : 170GHz/≥1MW/≥50%
- Pulse duration : ≥ 300s
- Modulation : ≥ 60s at 1-5kHz
- Operation reliability : ≥ 90%

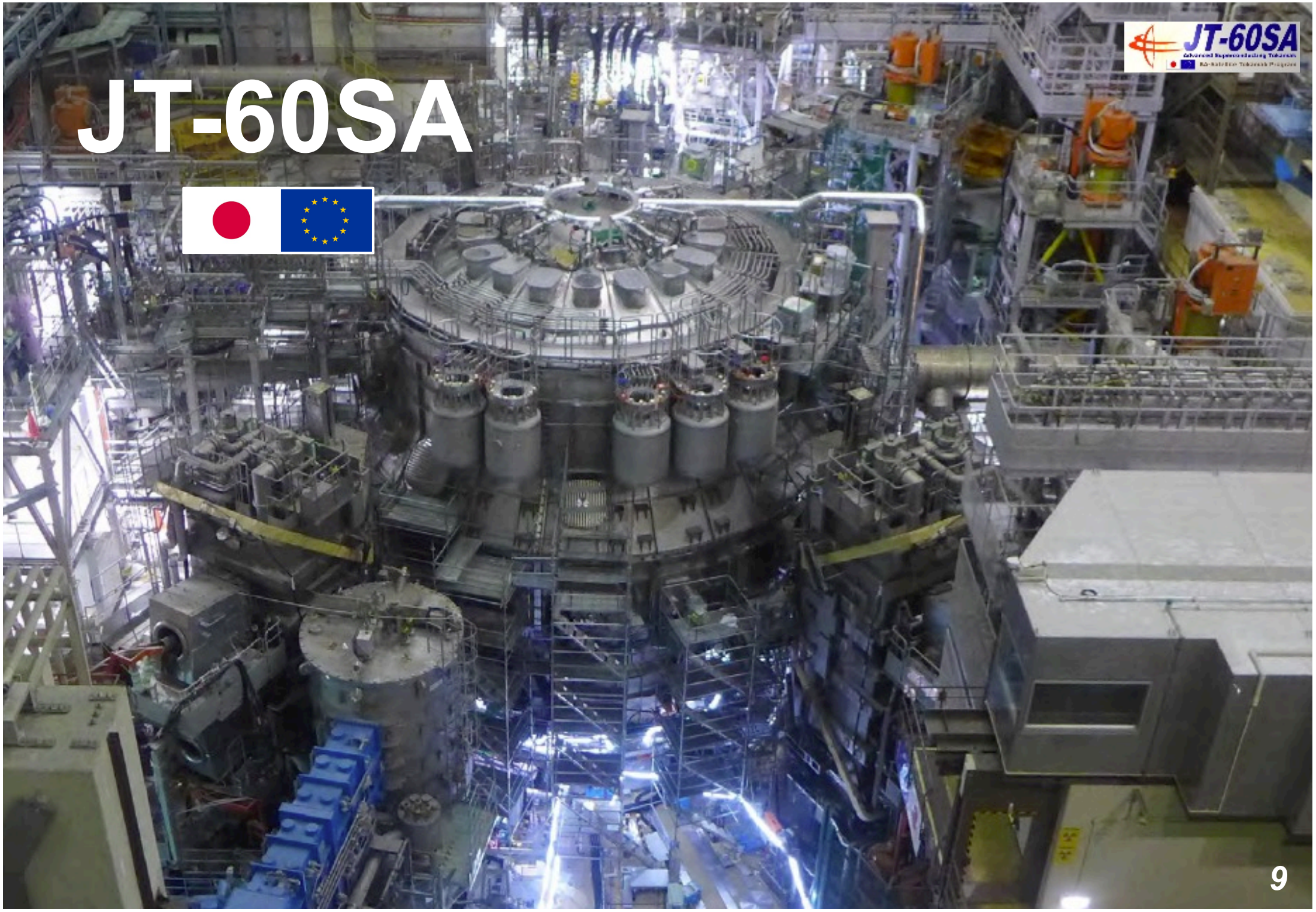


Future Direction: Multiple Frequency Gyrotron

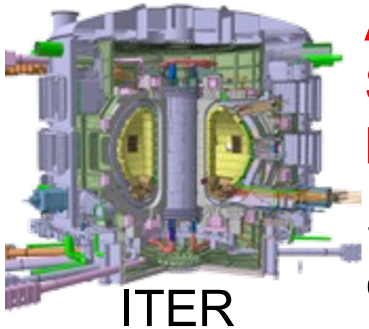
'Four Frequency'






JT-60SA

Roles of JT-60SA in Fusion Research



ITER

Achievement & Long Sustainment （Q=10）of Burning Plasmas

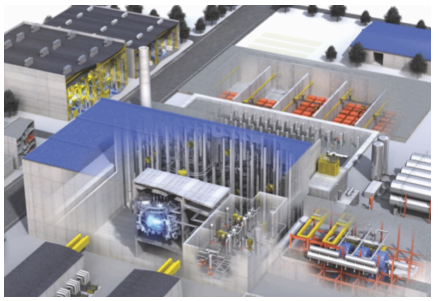
Steady-state operation at Q=5

Achievement of high Integrated Performanance

Reduced Divertor heat load
Disruption & ELM avoidance & mitigation

Establishment control schemes

DEMO



support

Understandings of Self-regulating combined system

Theory & Modeling

Long sustainement of break-even class plasmas

JT-60SA

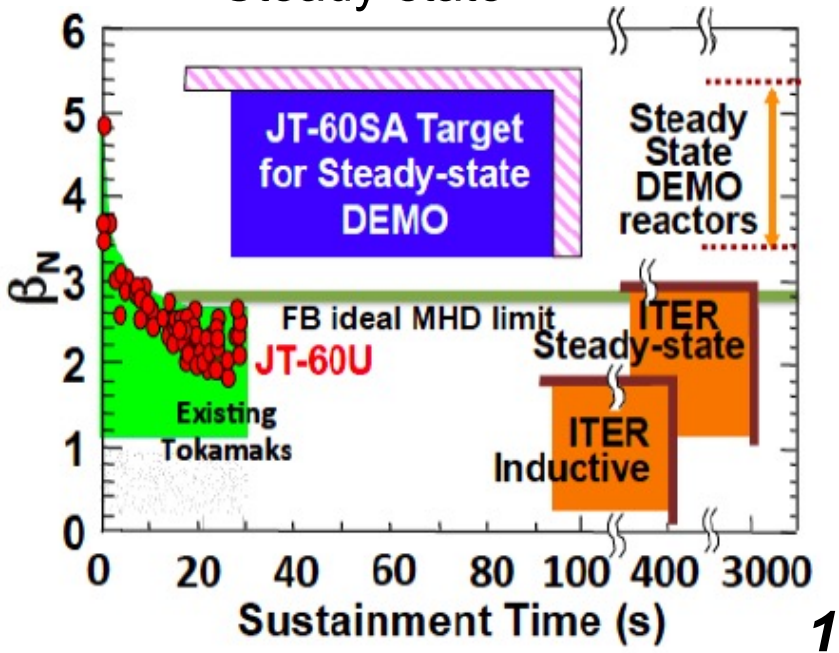
Steady-state high pressure (high β & high bootstrap fraction ）

Engineering R&D
divertor, blanket

Foster next generation

Collaboration with world tokamaks

Economically Attractive, Steady-state



Achievements of JT-60SA in assembly and commissioning

◆ **Assembly of JT-60SA was completed in March 2020 with high accuracy**

Manufacture & assembly tolerance ≈ 0.01%:
< 1 mm for 10 m-sized components => Satisfied

→Contributed ITER by lessons learned.

Cryostat Base

Lower EF coils

Vacuum Vessel

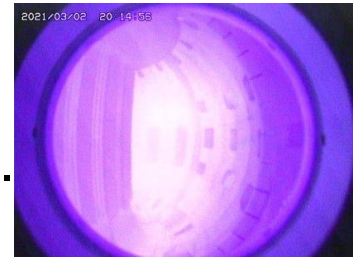
TF coils

Central Solenoid


Cyrostat

◆ **Integrated commissioning started from April 2020.**

- Cool down of the super conducting coils and cryostat : completed.
- Transition into the super conducting state : confirmed for all the coils.
- Coil energization test has started.
  - Function of the quench protection confirmed for TF and PF.
  - TF coils tested up to 25.7kA (100%)
  - All the PF coils tested up to 5.0kA (25%)
  - Voltage control test up to ± 5kV and ±5kA finished all but EF1.
- ECRF plasma at 2.25T (TF current of 25.7kA) successfully.



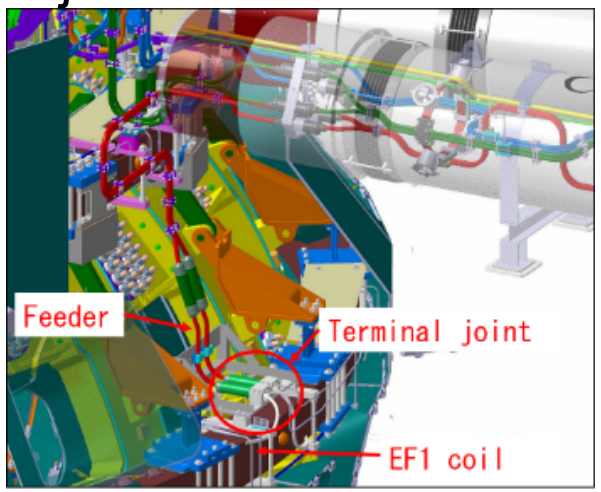
ECRF plasma at 2.25T

Incident : current feeder for a Superconducting coil

Over current was detected in the voltage control test at 5kV on EF1 coil in Mar. 2021.

- •Marc of arc was found at both positive and negative terminal joint of EF1
- •No damage on super conducting coil itself

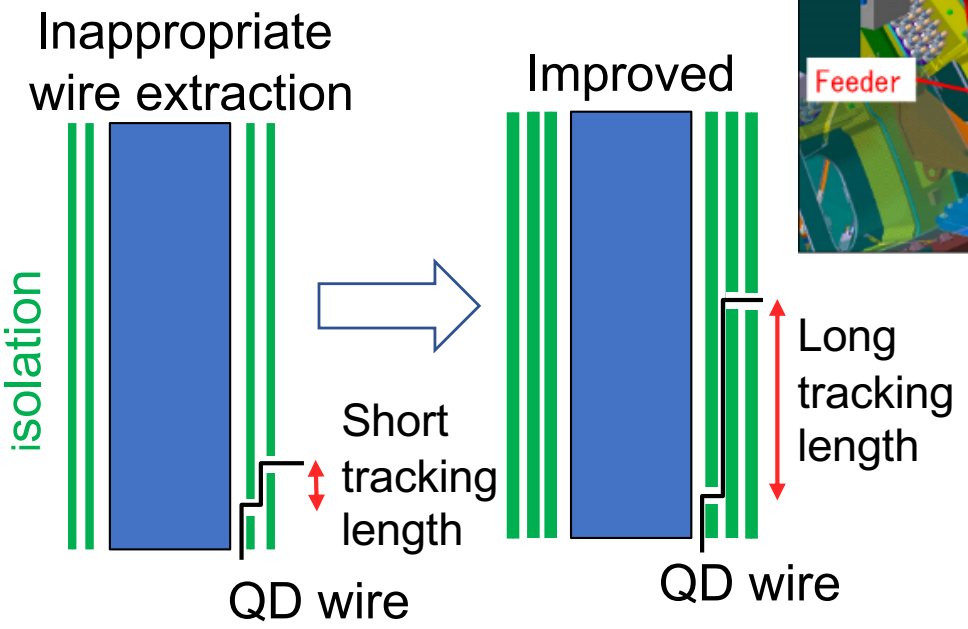
Root cause : Insufficient voltage holding capability of the insulation at the terminal joint.



Improvements

- Correct QD wire extraction
- Enhance isolation method
- Confirm by Paschen test

Not only for inappropriate wire extraction, but also for all joints



The JT-60SA shares the analyses of the incident, recovery actions and their results with the fusion community to support ITER, DEMO and any future tokamaks.

◆ **IC will restart from February 2021 toward first Tokamak plasma.**

JT-60SA Plans

- Resume of the Integrated Commissioning (IC) in 2022

Works on SC-coils: January => Evacuation of VV & Cryostat: from Feb.
⇒Cool down => Coil energization re-test => Complete the IC
(First Plasma, MA class diverted plasmas until the summer)

- Longer term plan

–Machine Enhancement
lower divertor,
stabilizing plate,
In-vessel coils,
NB (P-NB & N-NB) 23MW
Additional ECRF 3MW,
Diagnostics,
– High power exp. 2024, for ITER risk mitigation & enhanced efficiency
–Actively cooled carbon divertor: 2027-8 for long pulse high β for DEMO.
–W divertor & the total power 41MW.

	Phase	Expected operation schedule		Annual Neutron Limit	Remote Handling	Divertor	P-NB Perp.	P-NB Tang.	N-NB	NB Energy Limit	ECRF 110 GHz & 138 GHz	Max Power
Initial Research Phase	phase I	2020-2021 (5M)	H	-	R&D	USN Carbon	0	0	0	0	1.5MWx5s	1.5MW
		2023 (2M)				LSN Carbon Div. Pumping	3MW	3MW	10MW	23MW x 14s duty = 1/30	1.5MWx100s + 1.5MWx5s	19MW
	phase II	2023 (6M)	D	3.2E19			6.5MW	7MW				26.5MW
		2024-2025										
	phase III	2025-2027								Real Injection : ~ 26MW x 2-3 sec limited by divertor cooling		
Integrated Research Phase	phase I	2029 - 2031	D	4E20		LSN monoblock-Carbon Div.Pumping	13MW			20MW x 100s 30MW x 60s duty = 1/30	7MW x 100s	37MW
	phase II	2033 -	D	1E21	Use	LSN monoblock-Tungsten-coated Carbon Div.Pumping						
Extended Research Phase		>5y	D	1.5E21		DN/SN monoblock-Tungsten-Coated Carbon Advanced Structure	16MW	8MW		34MW x 100s		41MW

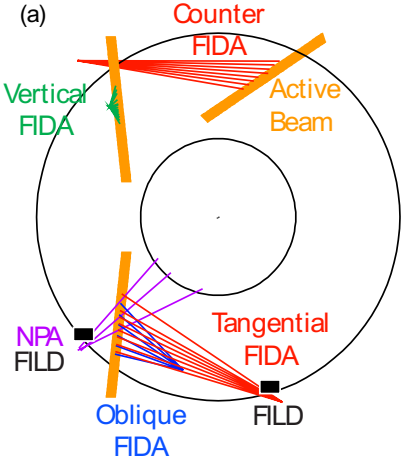
Upper Divertor (open divertor, inertia cooling) is always ready

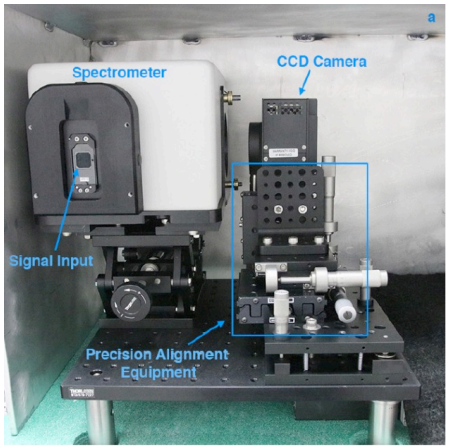
JT-60SA Diagnostics from US: deep appreciation

- US-DOE, F4E and QST agreed in 2020, at the technical level, to propose a participation of US research Institute in JT-60SA with the following diagnostics:
- **FIDA (Fast–Ion D-Alpha Spectroscopy) by GA and Univ. of California Irvine**
- **XICS (X-Ray Imaging Crystal Spectrometer) by PPPL**

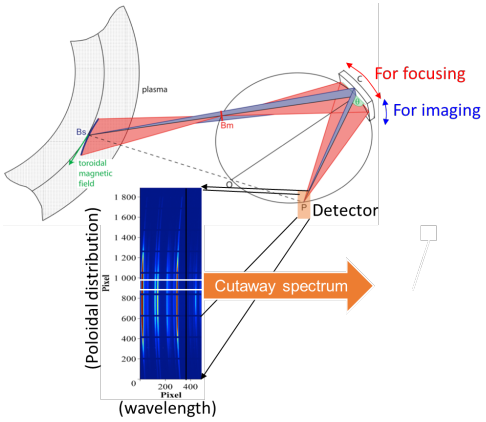
- *According to the "Guidelines on participation of other ITER Parties in BA activities at the level of Research Institutes," "Expression of Intention" by the US research Institute was submitted to the Secretariat of the BA Steering Committee.*
- *BASC asked both IAs to start negotiations with these institutes.*
- *The STP Project Team started preparation and the Design review is on going.*

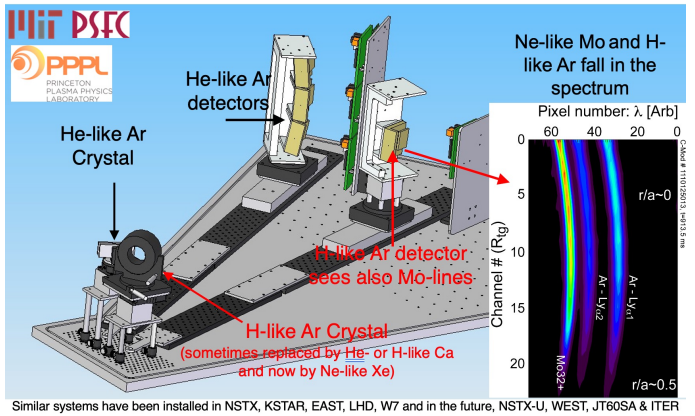
Fast–Ion D-Alpha @GA





X-Ray Imaging Crystal Spectrometer @PPPL





Similar systems have been installed in NSTX, KSTAR, EAST, LHD, W7 and in the future, NSTX-U, WEST, JT60SA & ITER

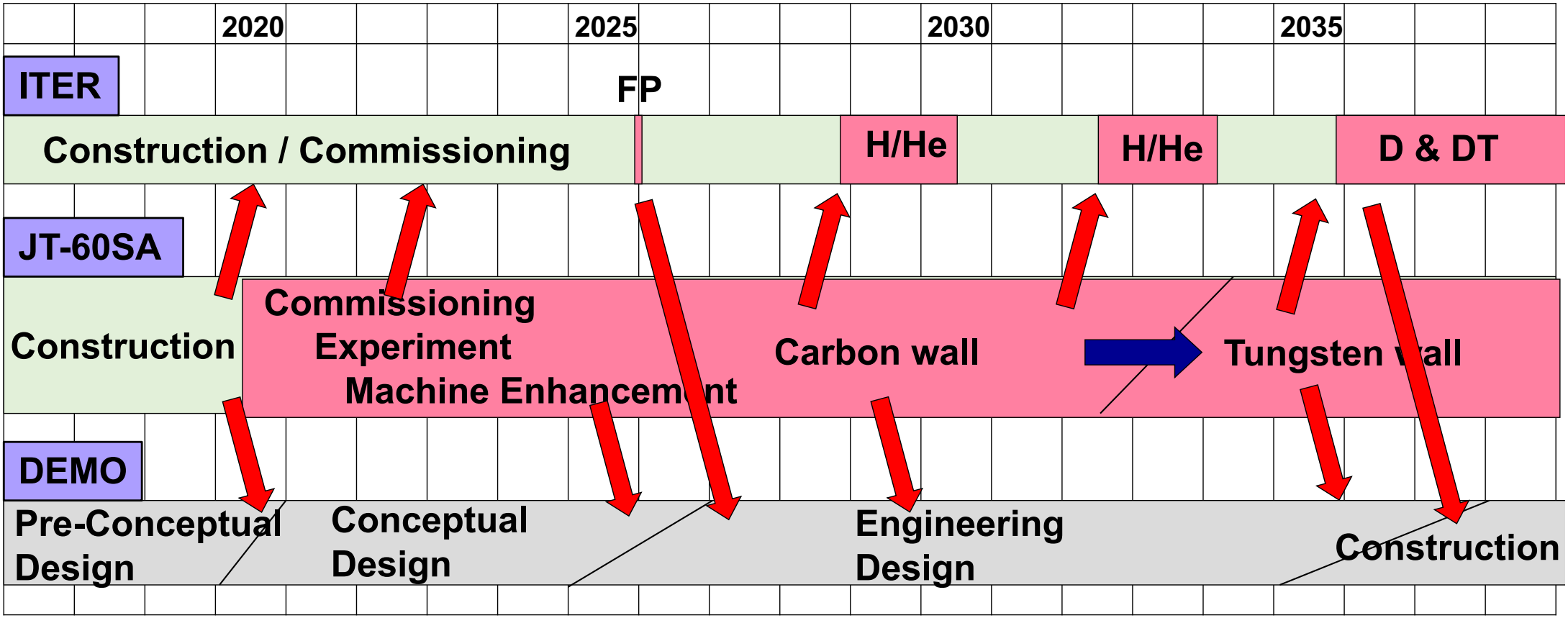
JT-60SA + ITER => DEMO

Manufacture & Assembly
Experiments/ Analyses/ Modeling

=> ITER, and DEMO

ITER & JT-60SA Collaboration Arrangement was Signed on Nov. 20, 2019

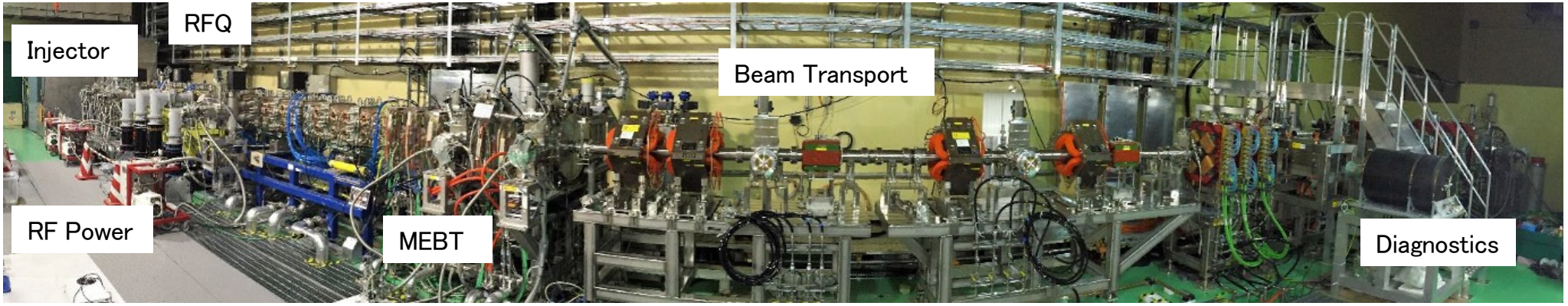
On-site Laboratory Agreements with 6 JA Universities have been signed, and soon the laboratory rooms will be prepared for student stay in Naka site in 2021.



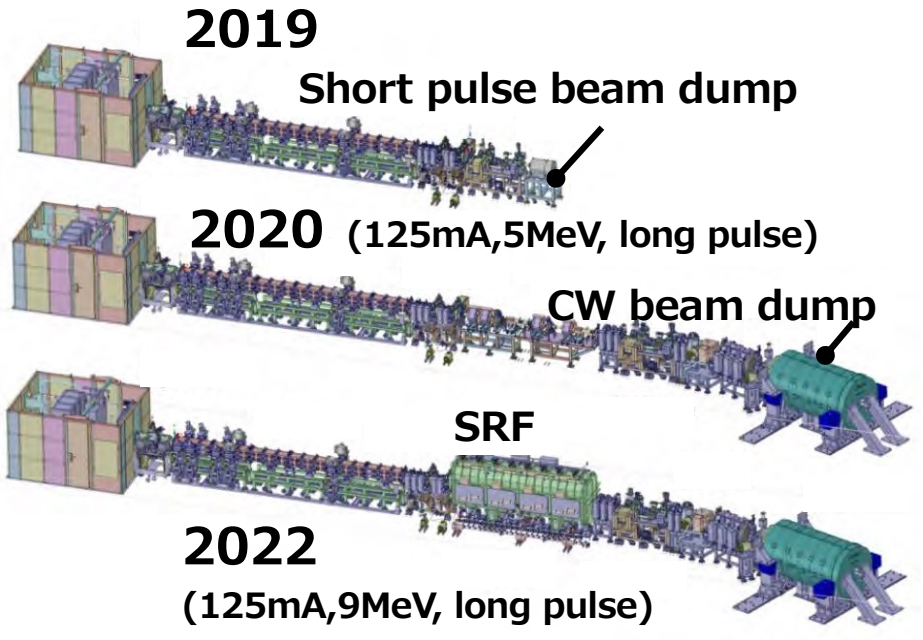
IFMIF/EVEDA Project: going well

Development of Linear IFMIF Prototype Accelerator (LIPAc)

D^+ accelerator: 125 mA LIPAc 9MeV (IFMIF 40MeV)



RFQ: Radio Frequency Quadrupole Acc. SRF: SC RF Linac MEBT/HEBT: Medium/High Energy Beam Transport Lines



- 2019: On RFQ, 125mA, 5MeV D- beam was achieved.
- 2020: Assembly of the CW beam dump was completed.
- 2021: A Long pulse operation has started with a CW-BD.
- 2022: Assembly of SRF (SC RF linac) for 9MeV will be installed.

Beam Operation using CCR and Data Transfer System

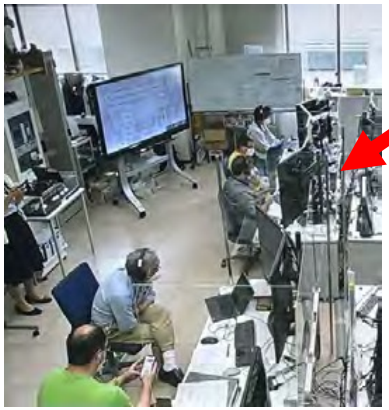
- EU experts are not easy to enter Japan (Covid-19).
- To participate the LIPAc experiments from EU, the LIPAc data transfer system was made based on the REC (ITER Remote Experimentation Center) technology.
- The Central Control Room (CCR) was fully commissioned as the core site of beam operation.
- The beam operation for a long pulse has been started by using these systems.

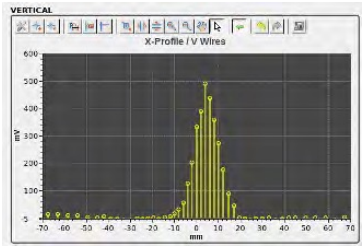
EU (Garching, F4E)

Central Control Room

Remote Monitoring

Local Control Room (LIPAc Rokkasho)





Data examples of Beam Profile, Beam Currents, etc.

Video Communication among operators and experts in EU and JA

Japanese Special Design Team for Fusion

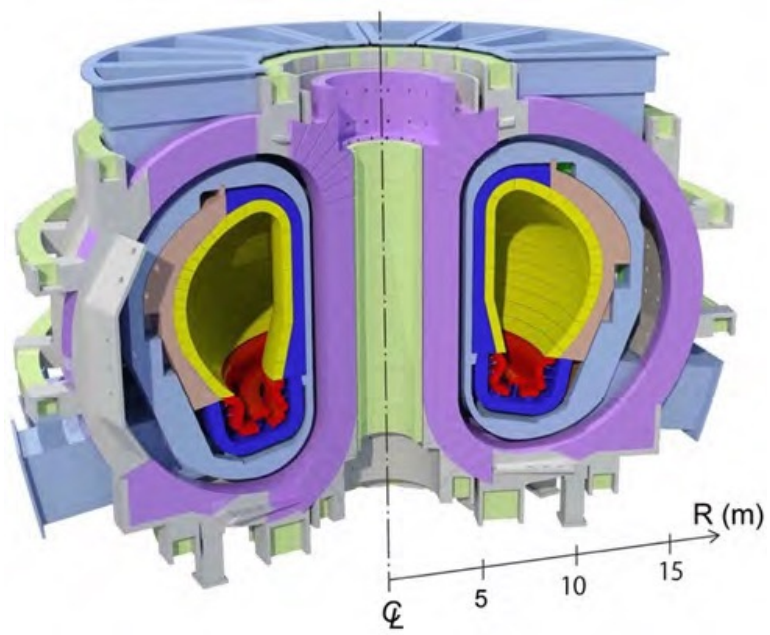
- **Developing a Japanese DEMO concept by the All-Japan design team** involving QST, 16 Industries, 3 Institutes and 23 universities
  => **130 experts in total**

Basic concept design of JA DEMO

Design principle and Basic specification

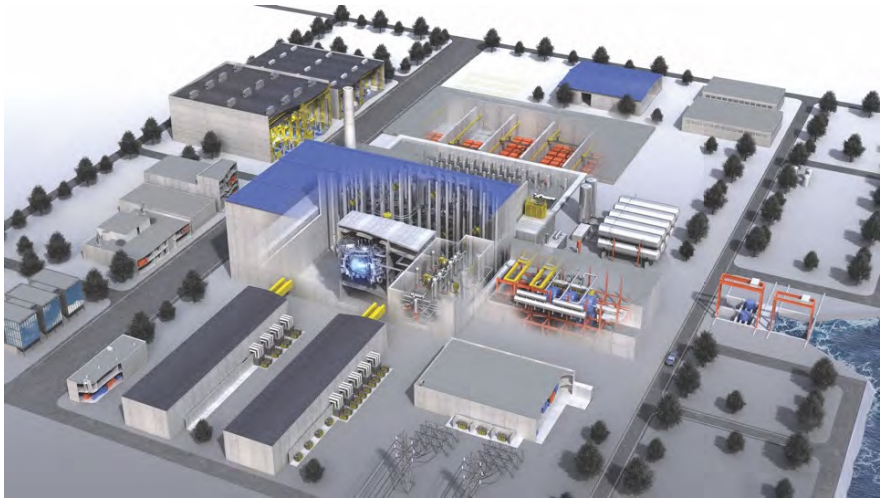
- Conceptual design of the main components - toroidal field coils, breeding blanket and divertor - as an extension of the ITER technology base.
- For technologies beyond ITER, industry's experience in power plant and universities' knowledge will be utilized.
- Plasma concept will be developed based on the envisaged outcomes of ITER and JT-60SA.

JA DEMO "Steady-State"



R_p: 8.5m
a_p: 2.42m
P_{fus}: 1.5GW
P_{gross}: 0.64GW
B_{T0}: 6T
I_p: 12.3MA
b_N: 3.4
n_e/n_{GW}: 1.2
HH_{98y2}: 1.3

Overview of fusion power plant



Site area: 1000m x 1000m

Summary

Projects are progressing along All-Japan Strategy toward DEMO

(1) ITER Procurement: going well
TFC, NBTF, Gyrotron, Blanket Remote Handling, Divrtor, Diagnostics

(2) **JT-60SA**
Construction completed => Commissioning.
Under recovery from Incident => re-start Commissioning in Jan 2022

(3) IFMIF/EVEDA (prototype accelerator (LIPAc))
Operation toward a Long pulse has started
Successful operation using a new data system for EU-remote participation.

(4) **DEMO Design**
JA Demo design ongoing by the All-Japan design team.