FIRST JT-60SA PLASMA OPERATION AND PLANS IN VIEW OF ITER AND DEMO

J. Garcia on behalf the JT-60SA integrated project team

JT-60SA Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

QST
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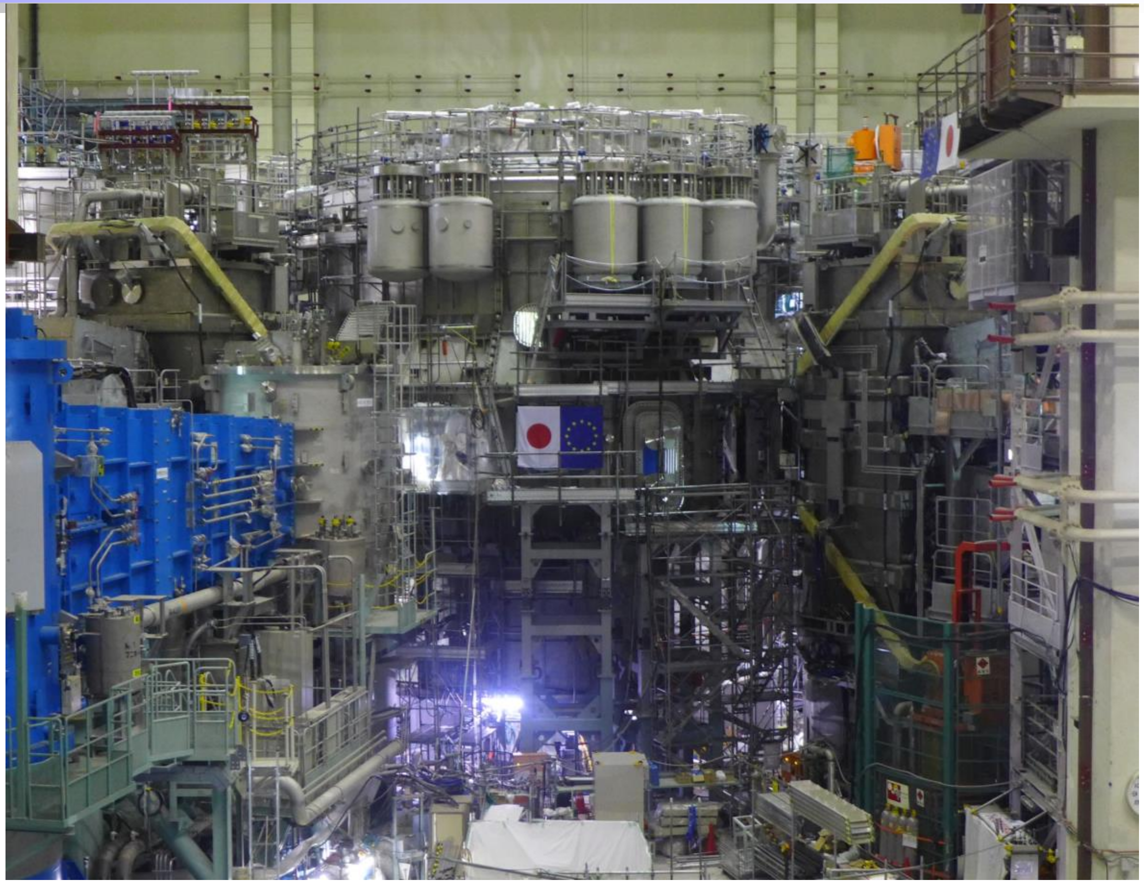
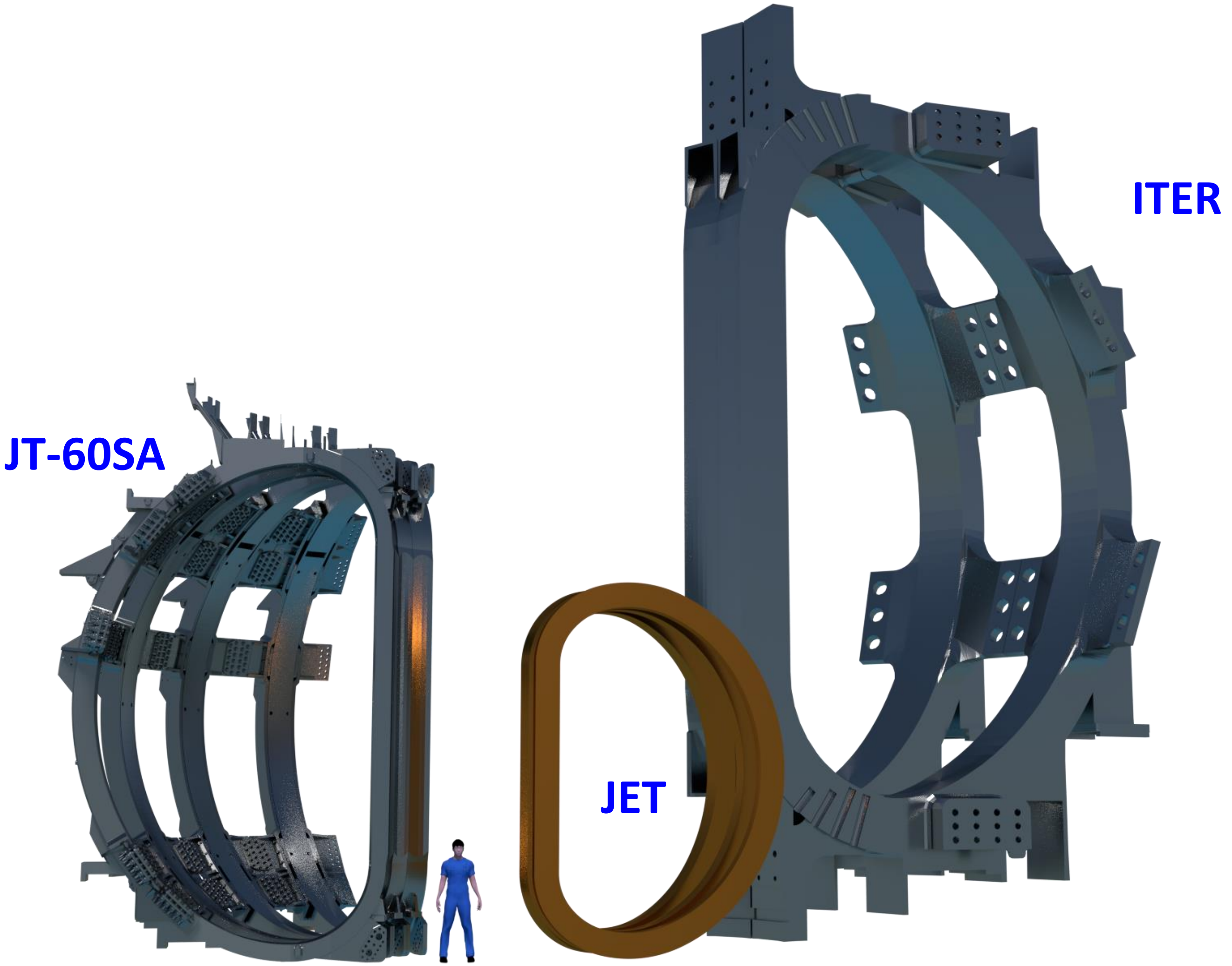
Outline

- The JT-60SA tokamak
- Integrated commissioning and OP-1 results
- Status of the JT-60SA project, timeline and scientific priorities
- Preparation for future campaigns
- Conclusions

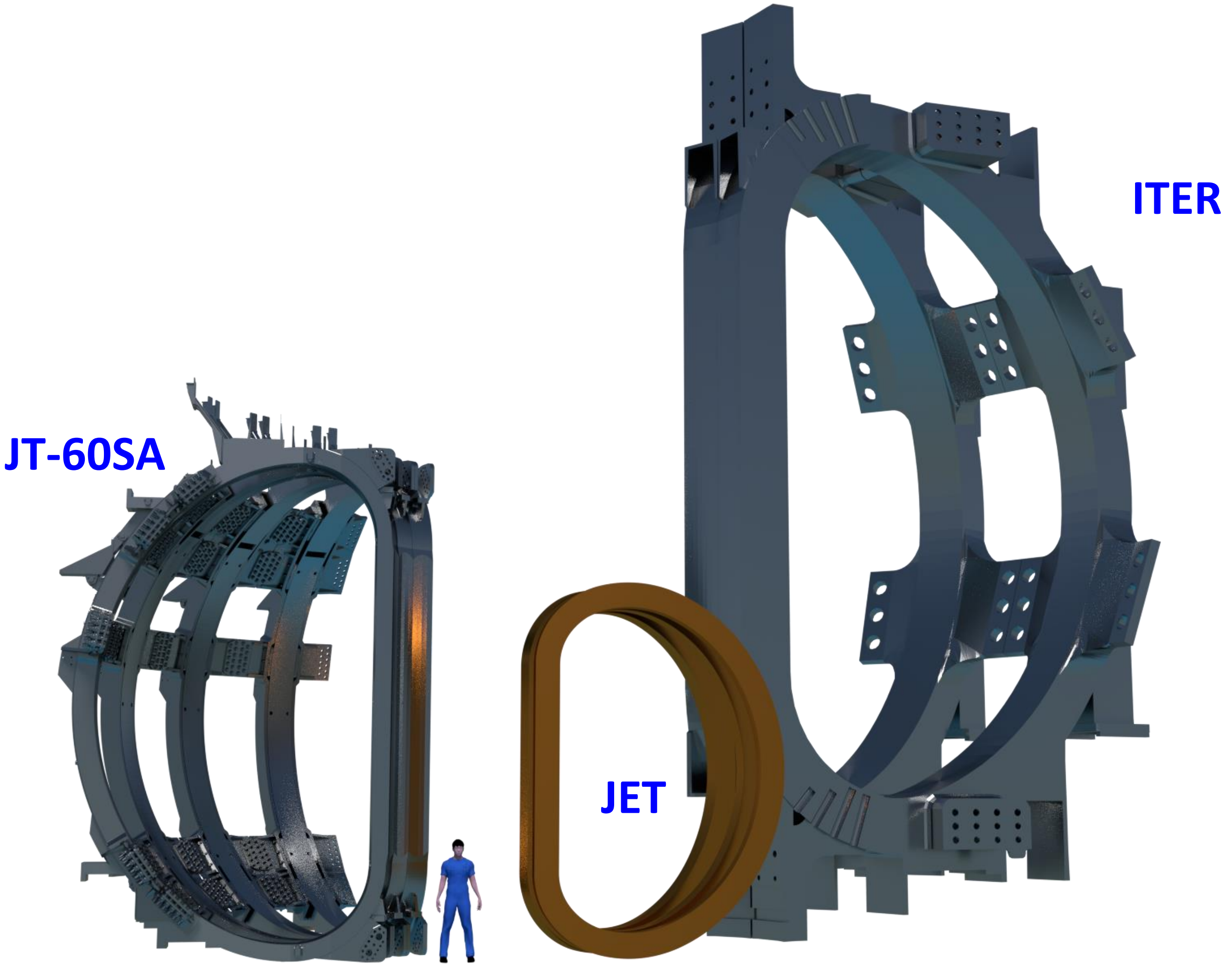


JT-60SA: large step beyond JET towards ITER



- JT-60SA is the **largest** tokamak before ITER
- JT-60SA represents an intermediate step between JET and ITER

JT-60SA: large step beyond JET towards DEMO

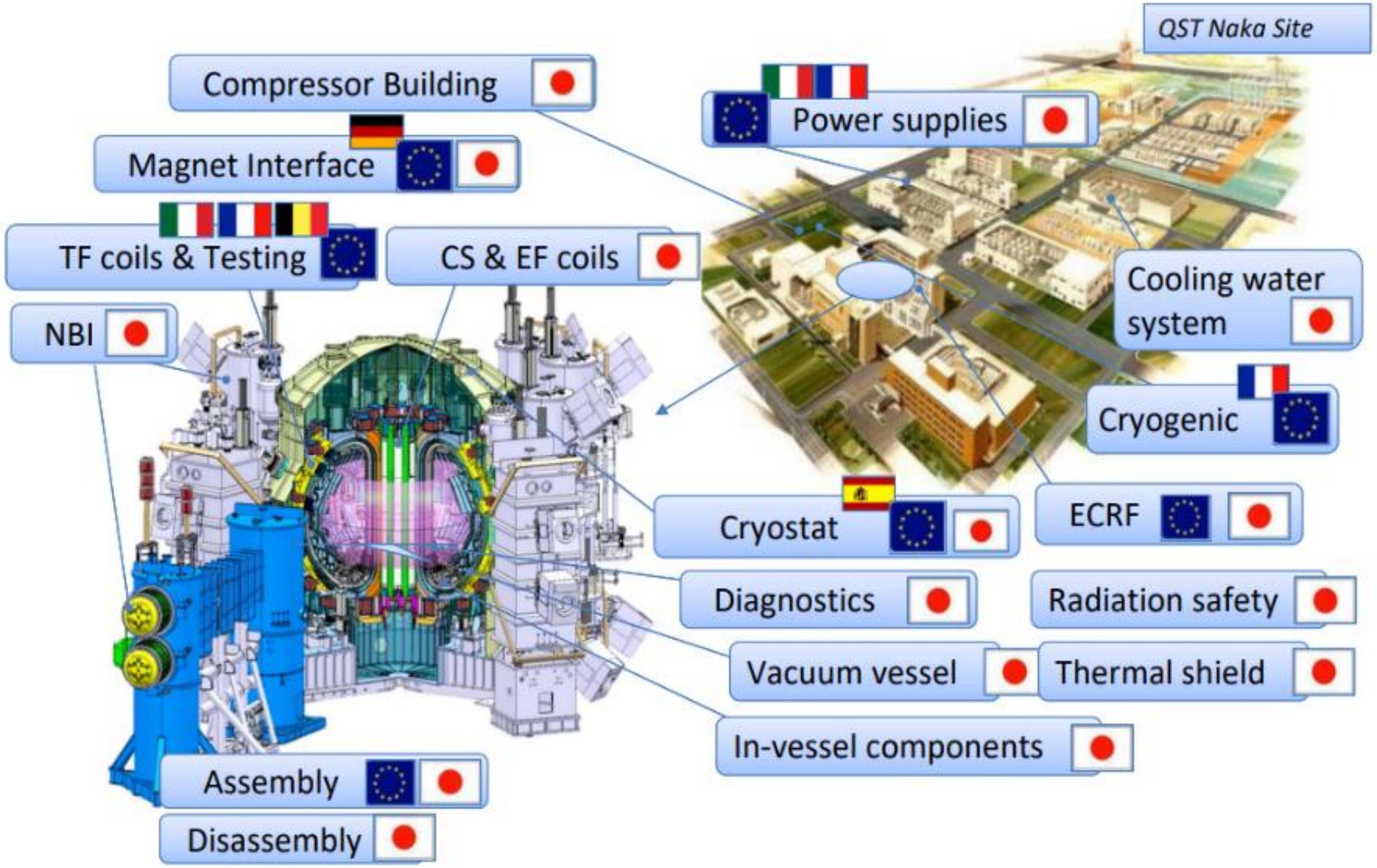


- JT-60SA is the **largest** tokamak before ITER
- JT-60SA represents an intermediate step between JET and ITER
- Unlike JET, JT-60SA can address long pulse steady-state operation
- Continuous operation is important for DEMO

The JT-60SA tokamak: an international platform

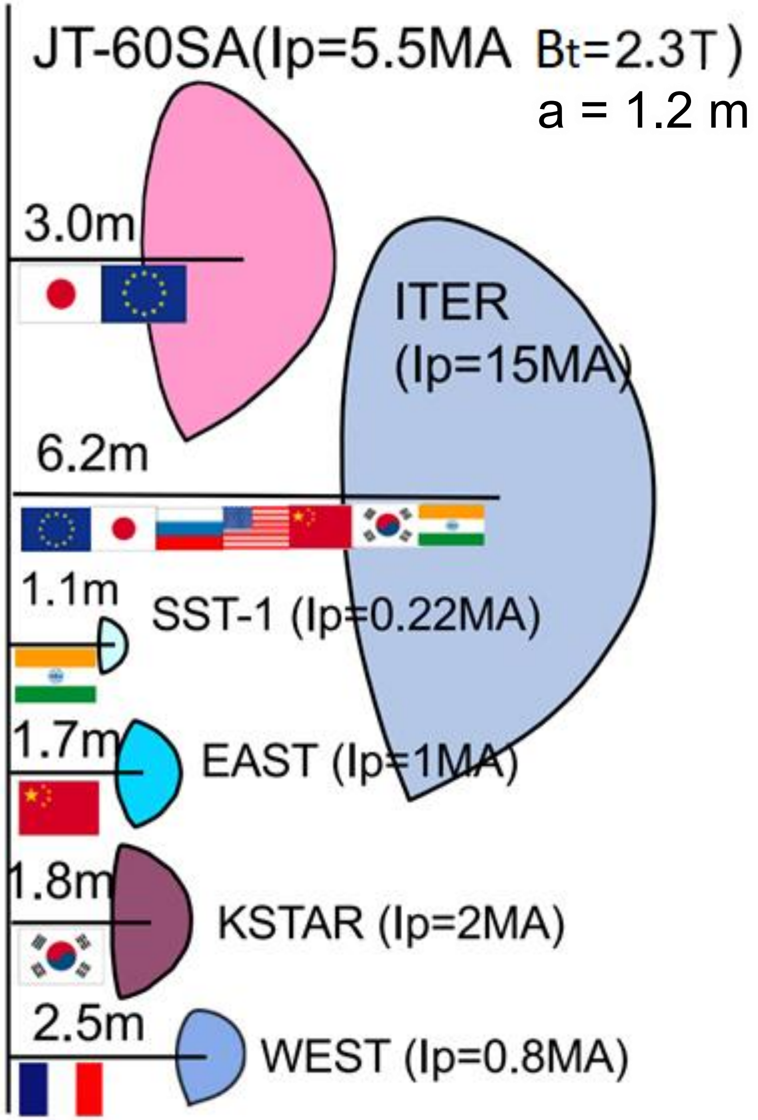
- Designed and built **jointly** by **Japan** and **EU** at the Naka site under the Broader Approach agreement

[Y. Kamada, NF 2022] [H. Shirai, NF 2024]



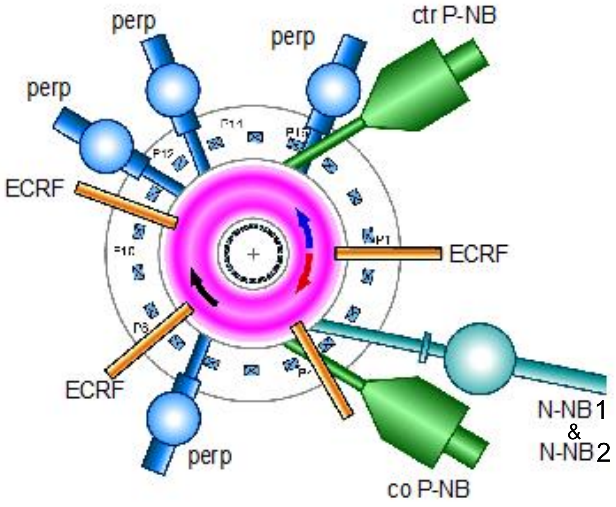
The JT-60SA tokamak configuration

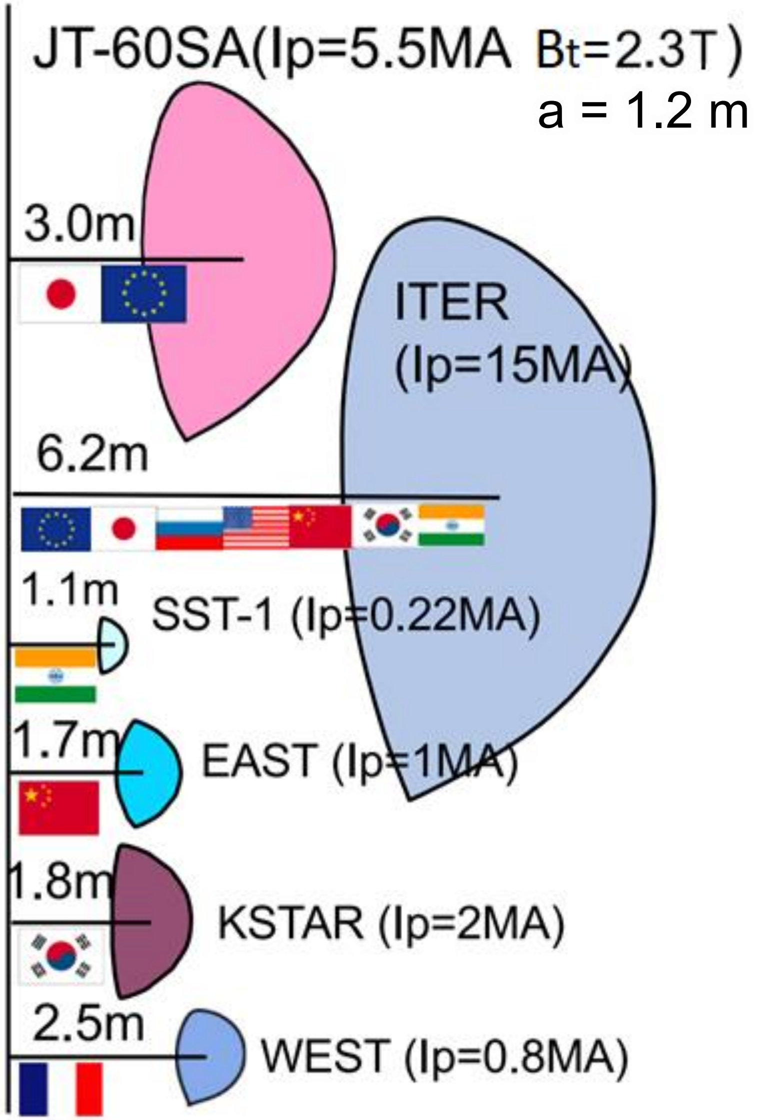
- Designed and built **jointly** by **Japan** and **EU** at the Naka site under the Broader Approach agreement
- Fully **superconducting**, high **current**, highly **shaped**



The JT-60SA tokamak configuration

- Designed and built **jointly** by **Japan** and **EU** at the Naka site under the Broader Approach agreement
- Fully **superconducting**, high **current**, highly **shaped**
- **High input power flexibility, ECRH (7MW) and NBI (34MW)**
- **Jointly exploited** by Japan and EU

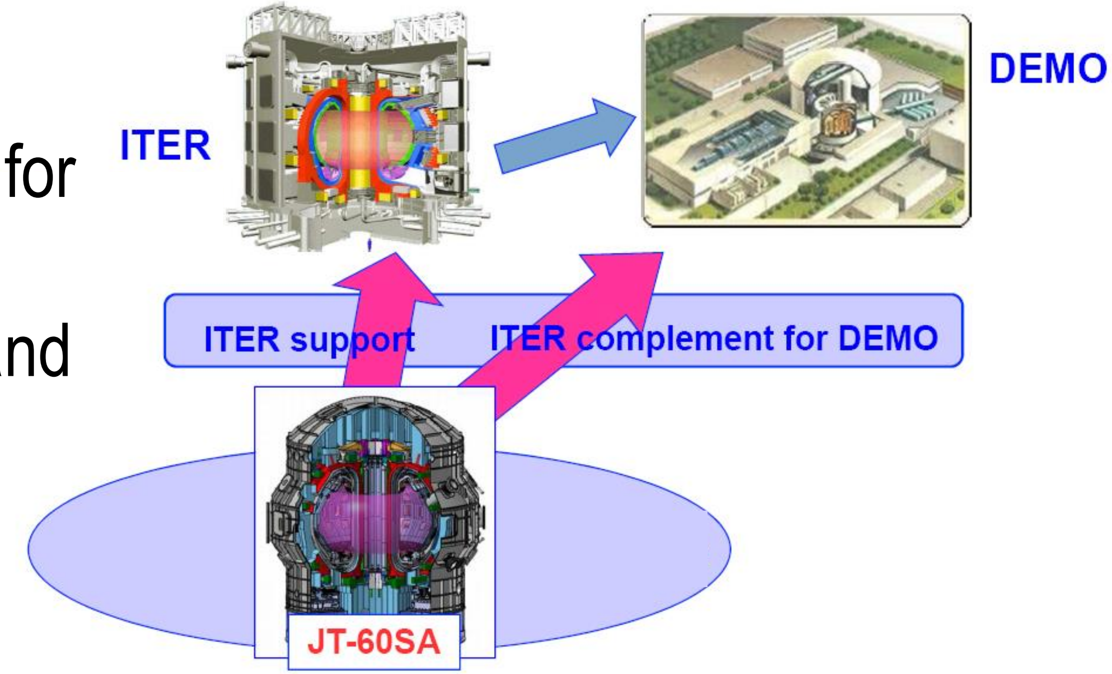




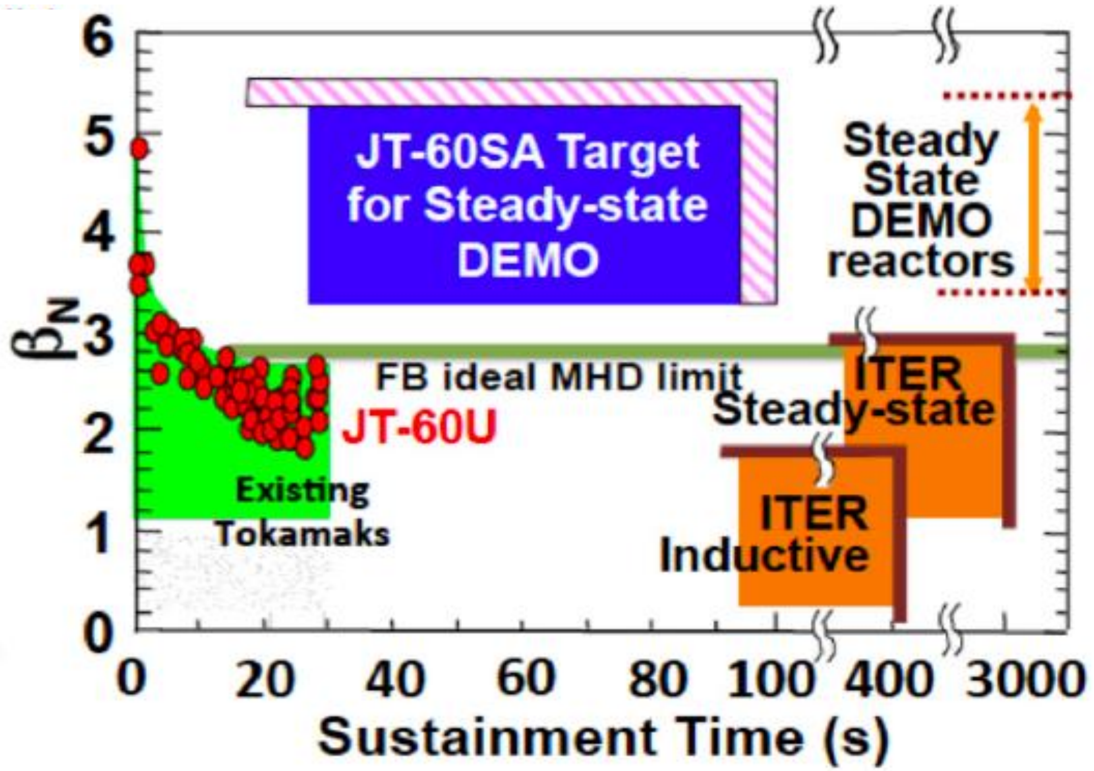
The JT-60SA project objectives

- Contribute to early realization of fusion energy by:
  - **supporting** the comissioning, start-up and exploitation of ITER
  - **complementing** ITER in resolving key issues for DEMO
  - **train** the next generation of fusion physicists and engineers

- The most important goal of JT-60SA is:
  - to **decide** the practically acceptable DEMO plasma design
  - including practical and reliable **plasma control** schemes

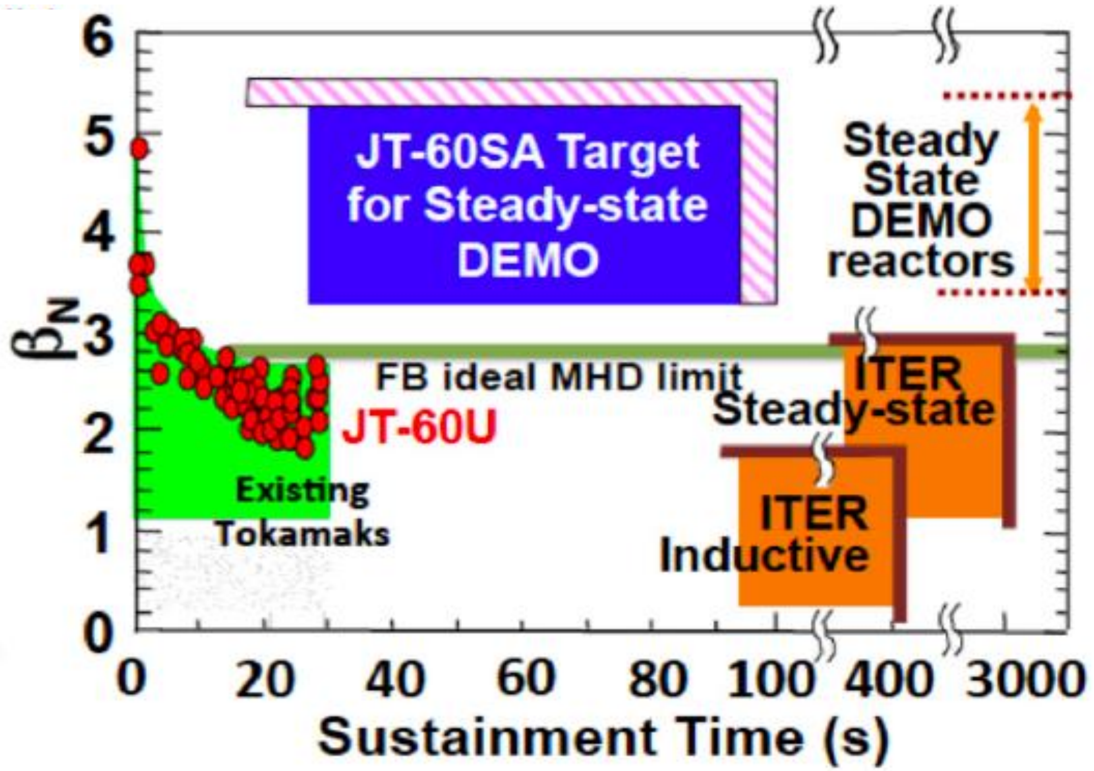


JT-60SA: a scientific and operational challenge



- JT-60SA aims at challenging normalized plasma parameters
  - High: beta, non-inductive current fraction, normalized density, confinement

JT-60SA: a scientific and operational challenge



- JT-60SA aims at challenging normalized plasma parameters
  - High: beta, non-inductive current fraction, normalized density, confinement

- While working at high absolute plasma parameters:
  - Ip=5.5MA
  - Peak Thermal Energy ~20MJ
  - Peak DD Neutron rate ~1e17s^{-1}
  - Sustained period ~100s

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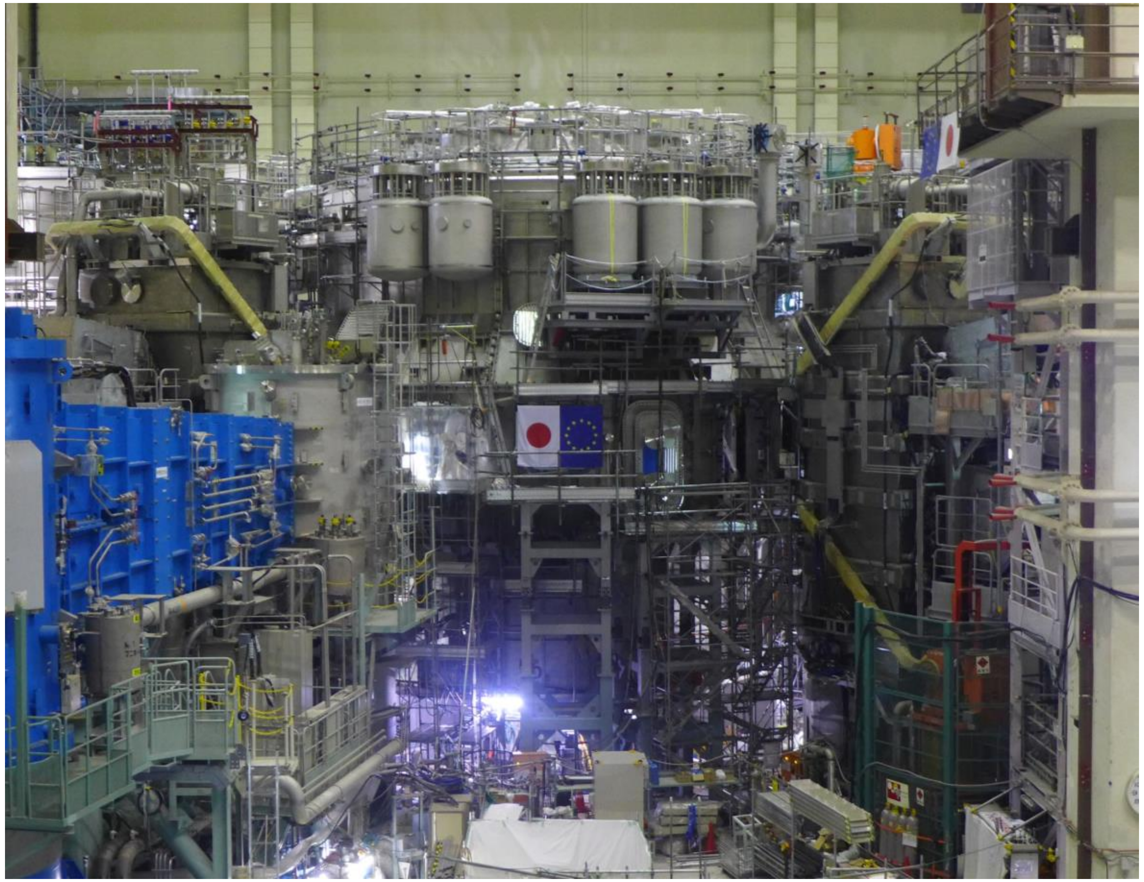


End of 2023: Integrated comissioning and OP1

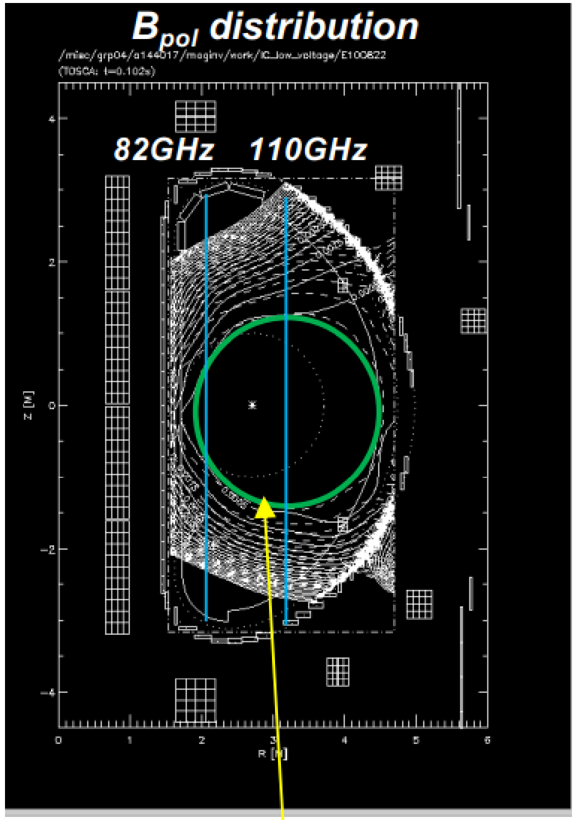
[M. Yoshida, PPCF 2025]

- Hardware integrated comissioning:
  - Purpose is to commission each sub-system and confirm machine readiness for plasma operation
  - Designed technical requirement is satisfied? each sub-systems works as designed?

- OP1:
  - Achieve a MA-class divertor plasma
  - Demonstrate stable plasma control from current-up to ramp-down
  - Electron Cyclotron Resonance Heating (ECRH) assisted start-up in low parallel electric field ($E_{||}$) conditions

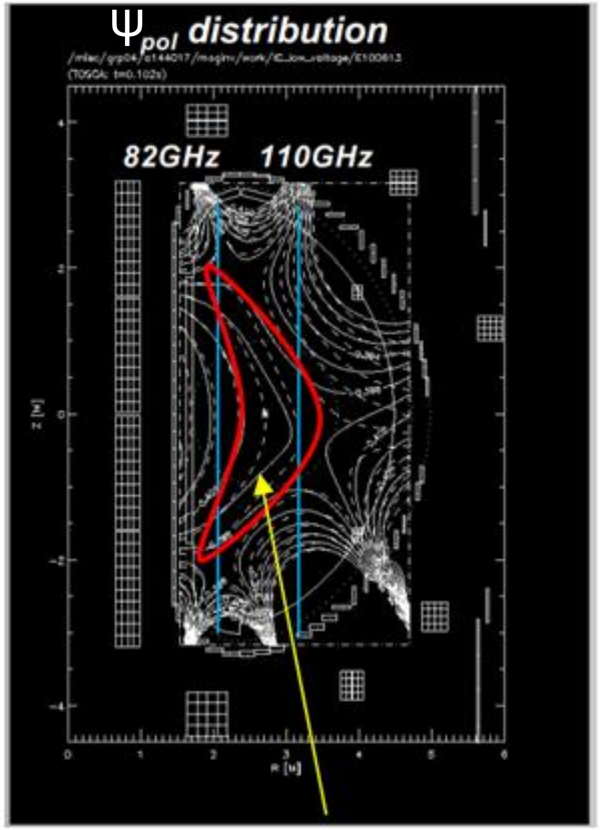
Predict first modeling for first plasma

Field Null Configuration (FNC)



Region of $B_{pol} \leq 10G$.

Trapped Particle Configuration (TPC)

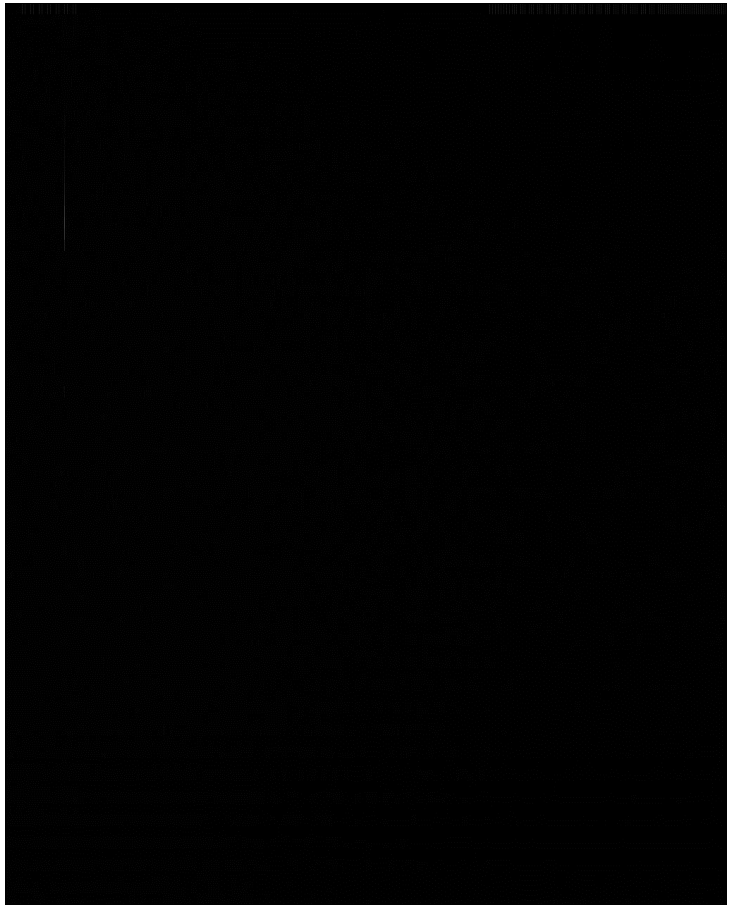


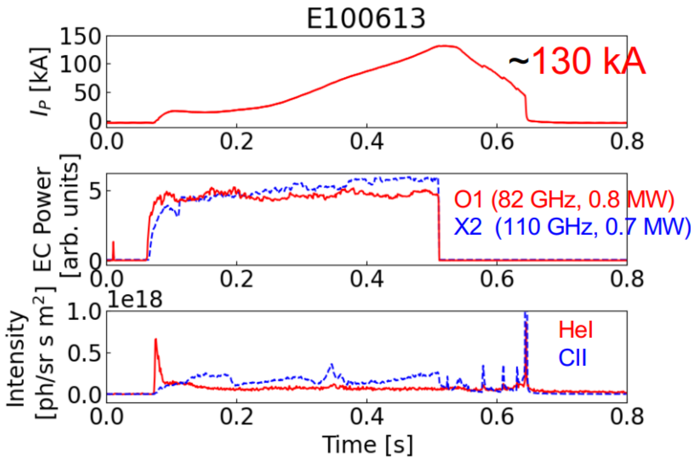
Trapped orbit of electron accelerated perpendicular to B_t by ECRF

- Predict first simulations showed easier start-up with TPC and ECRH

T. Wakatsuki, EX/7 2689

First Plasma Was Obtained on 23rd October 2023





- Predict first simulations showed easier start-up with TPC and ECRH
- After several FNC attempts, first plasma achieved at first trial using TPC

T. Wakatsuki, EX/7 2689

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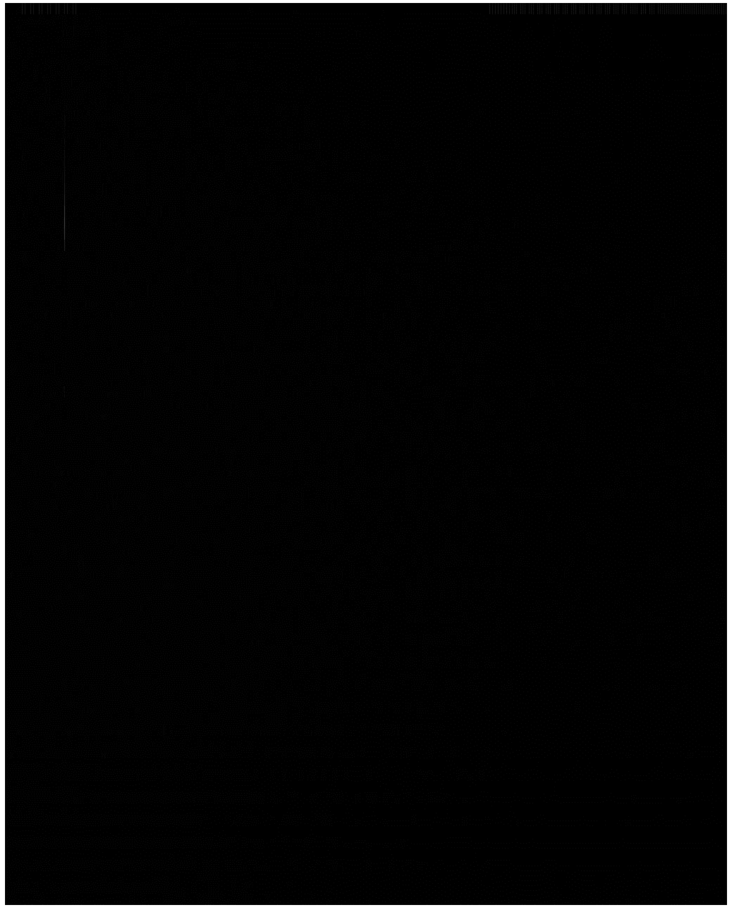
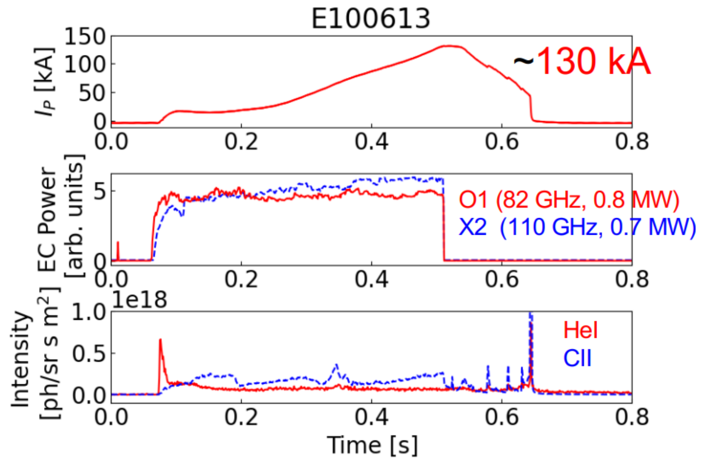
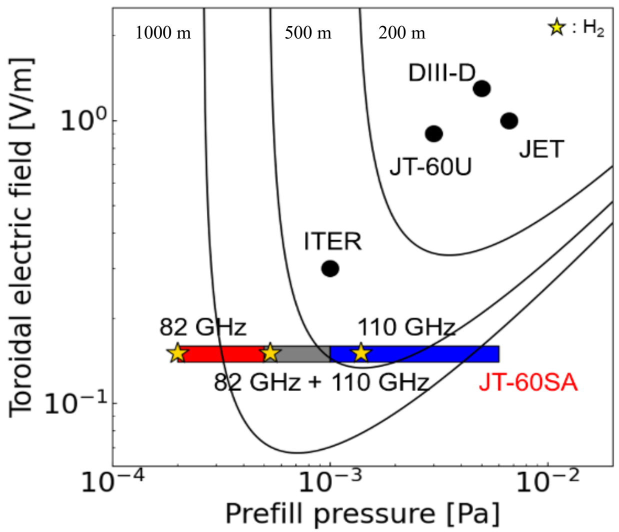




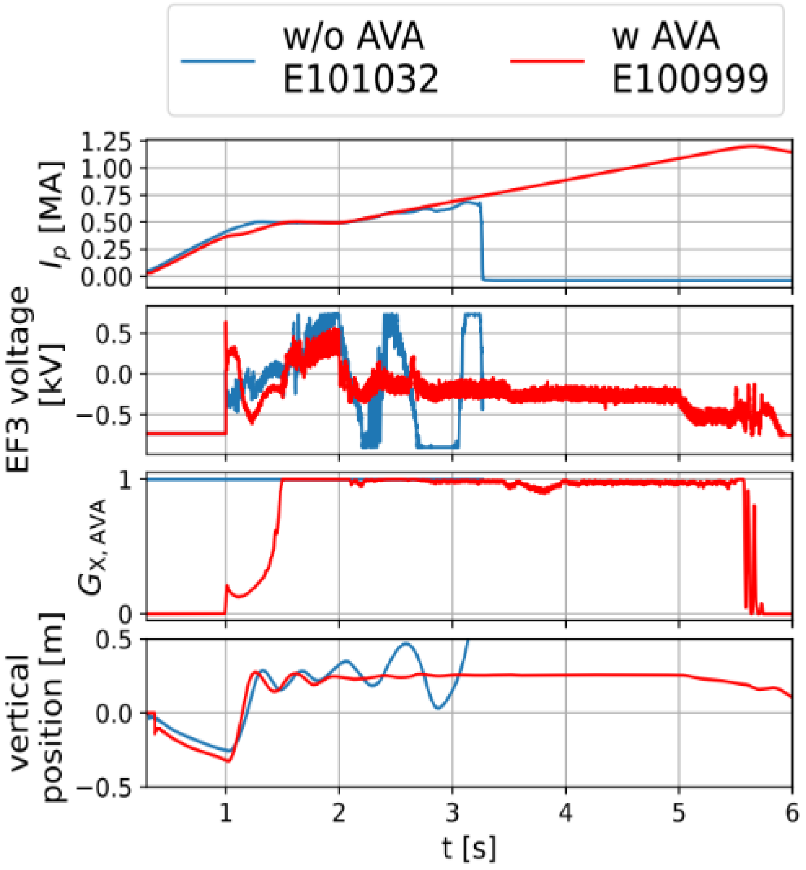


- Predict first simulations showed easier start-up with TPC and ECRH
- After several FNC attempts, first plasma achieved at first trial using TPC

Even lower $E_{//}$, 0.15 V/m, than expected in ITER→ Encourage ITER low $E_{||}$ start-up

T. Wakatsuki, EX/7 2689

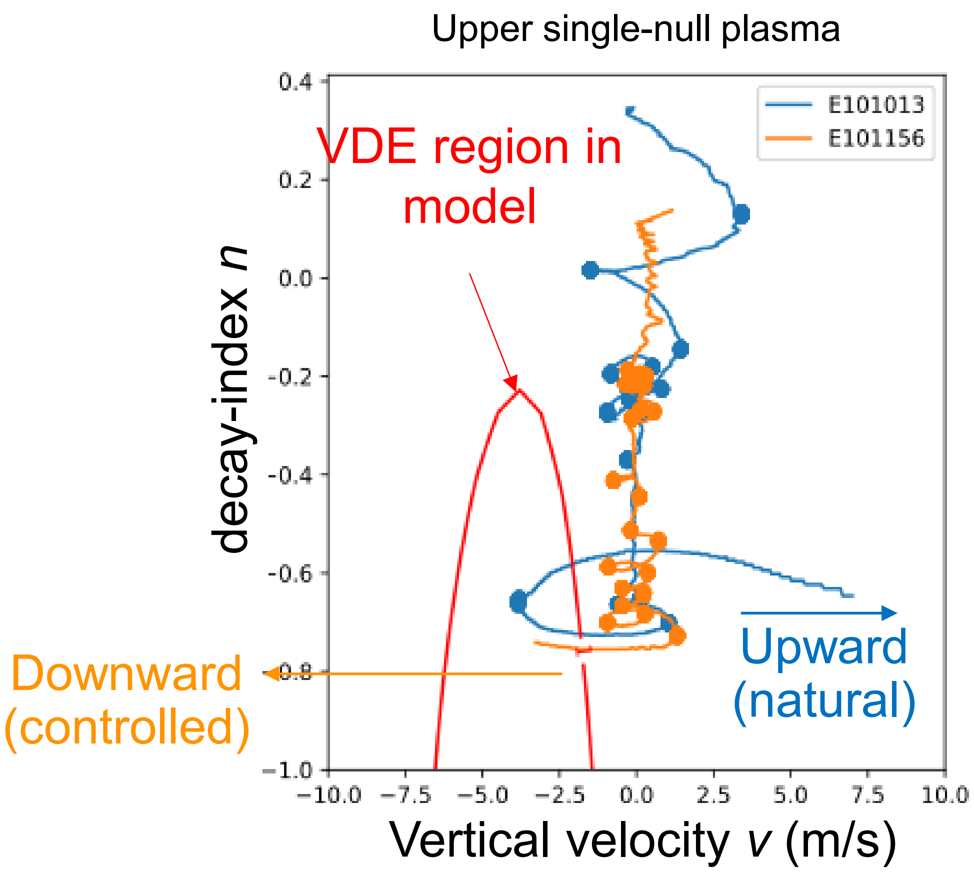
Adaptive voltage allocation (AVA): a key plasma control scheme



S. Inoue, EX/7 2898

- Potential saturation of poloidal coils voltage found in predict-first simulations
- AVA: adjusts the balance between the position and shape control and the Ip control
- Successfully tested during OP-1 with pre-optimized gains from the nonlinear simulator MECS
- Importance of predict-first modelling

VDE Prediction and Control Scheme Were Demonstrated

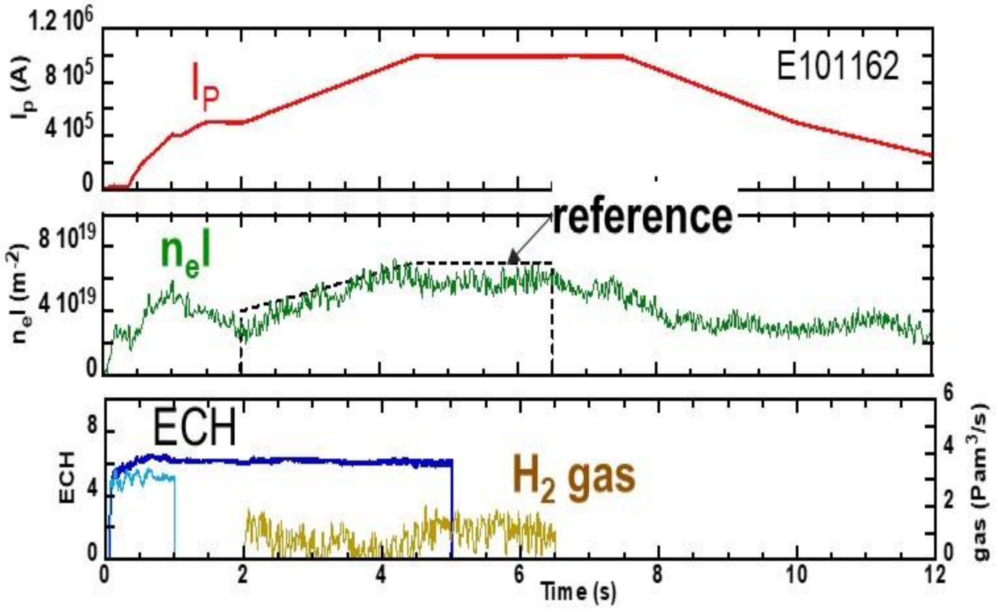


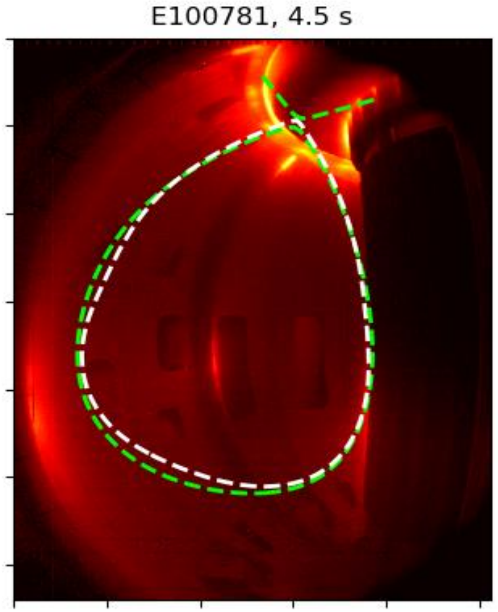
[S. Inoue, NF2024]

- **VDE predictor and control algorithm were developed using machine learning**
  - Vertical velocity *v*, decay-index *n*, used for VDE prediction
- **Deliberate downward VDE was demonstrated**
  - Coil voltage set to 0
- **Machine learning and AI techniques being developed during the start-up with limited input data**

Important development for future large superconducting tokamaks → ITER

JT-60SA is a MA class tokamak



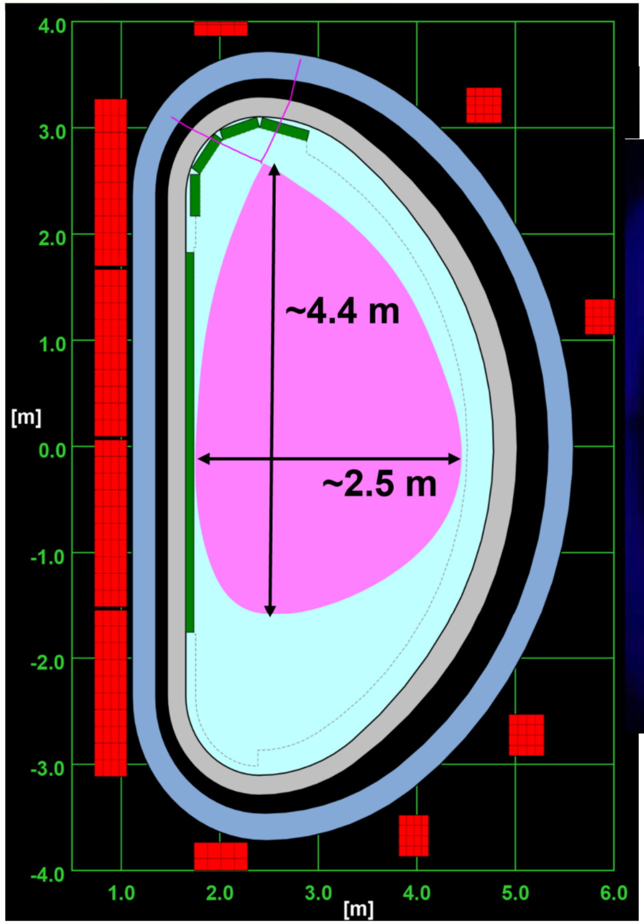


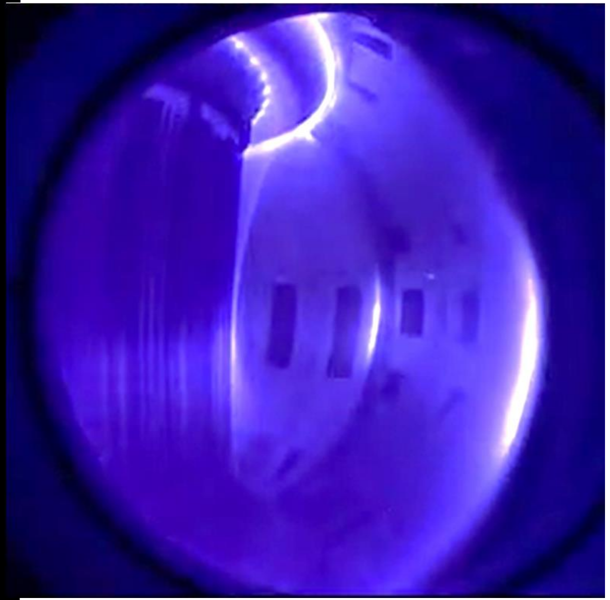
T. Szepesi, P1 2811

[M. Yoshida, PPCF 2025]

- I_P=1 MA is obtained with well controlled diverted plasma in H_2 and optimized breakdown/build up scenario.
- Density feedback control was a success.
- Strike points clearly identified with visible camera EDICAM

Record plasma volume → going beyond JET





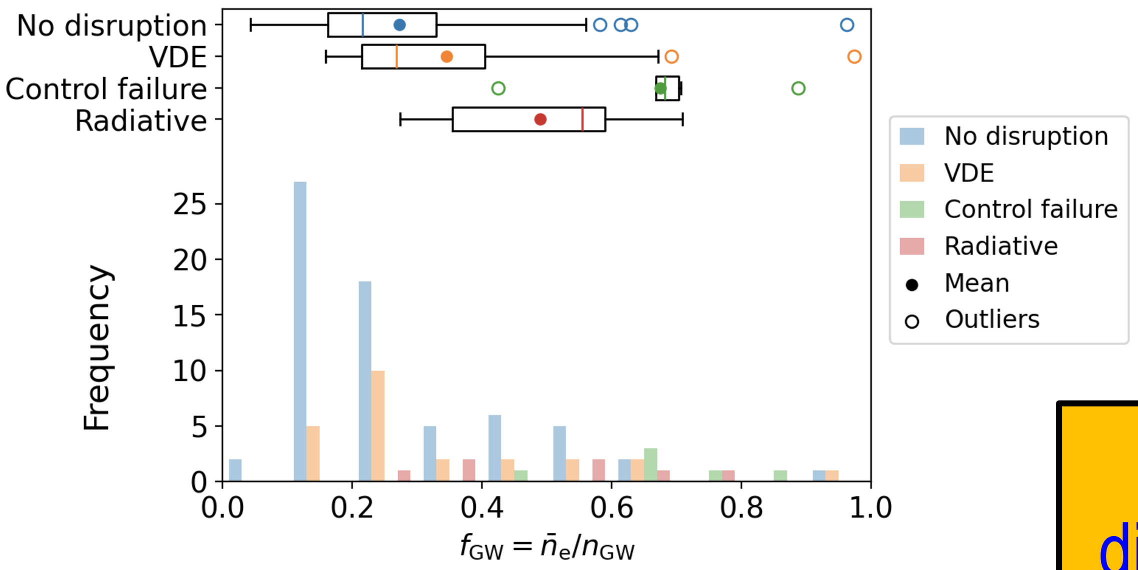
S. Inoue, EX/7 2898

- JT-60SA produces largest plasma volume, 160 m^3, beyond JET plasmas, ~100 m^3
- Record plasma current up to 1.2 MA in a superconducting tokamak

Classification of the causes for disruptions

I_P = 0.28-1.07 MA

	Total	In flat-top	In ramp-down
Disruptions	82	37	45
VDE	58	24	34
Control failure	8	6	2
Radiative	16	7	9
No disruptions	69	-	-



Y. Yokoyama, P5 2690

Disruption database has been constructed

VDE: Vertical Displacement Event

at high elongation and/or large gap between plasma surface and wall

Control failure caused by n=1 mode

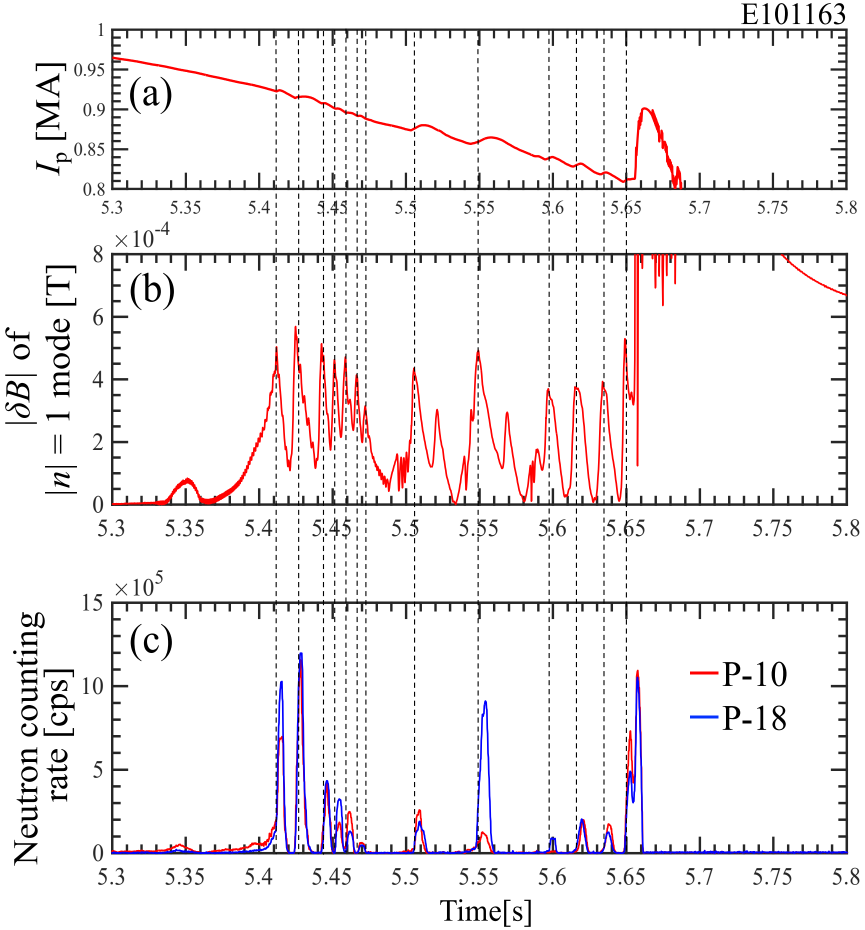
at relatively high $f_{GW} = n_e/n_{GW}$

Radiative disruption

imbalance between heating and radiative power when excessive gas injection

JT-60SA data being included in multi machine disruption database→ Essential for extrapolations

Focus during OP-1 for Run Away electrons generation→ role of MHD



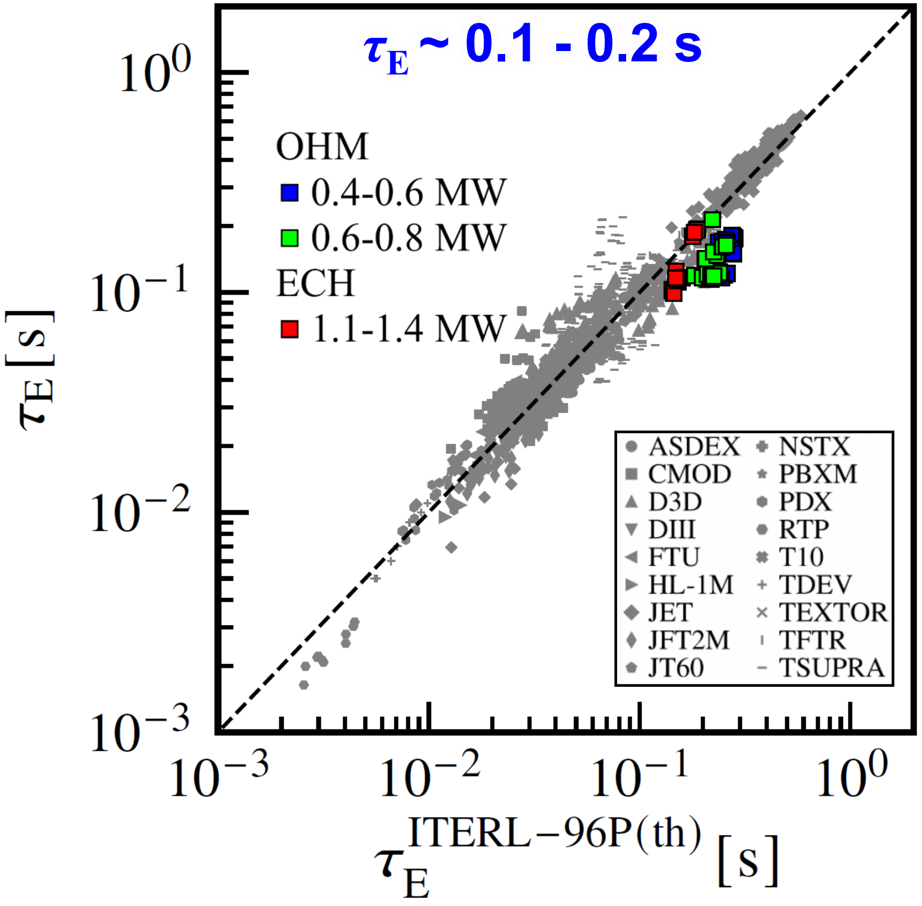
S. Sumida, P5 2692

- Neutron flux monitors (NFMs) are used to indirectly detect the RE loss on PFCs
- Correlation between REs and n=1 MHD activity, caused by tearing modes→ Necessity of MHD control even during start-up
- Hard X-Ray (HXR) dosimetry for the evaluation of REs done with visible camera EDICAM

T. Szepesi, P1 2811

REs generation detected at low $E_{||}$→ mitigation techniques necessary even in the start-up

Plasma energy time confinement during OP-1



Y. Ohtani, P1 2851

[M. Yoshida, PPCF 2025]

- **Energy confinement ~100-200 ms in I_P=1 MA plasmas**
  - Consistent with expo. time-decay of W_{sto}~130ms
  - Generally consistent with the ITERL-96P scaling
  - Dependent on LOC or SOC plasma regime

Initial JT-60SA plasmas show general agreement with expectations from tokamak databases

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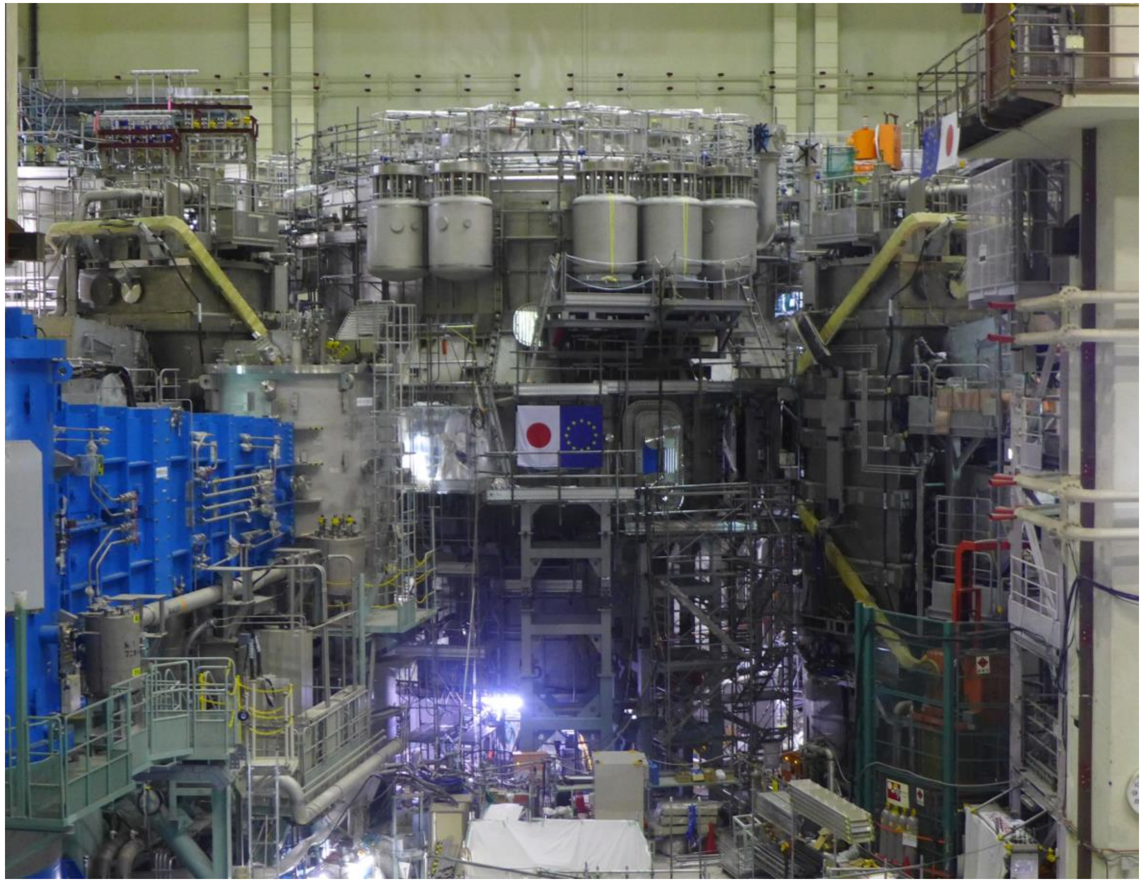
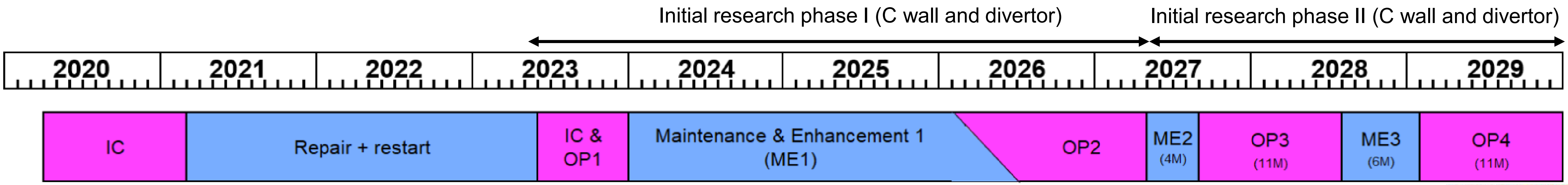


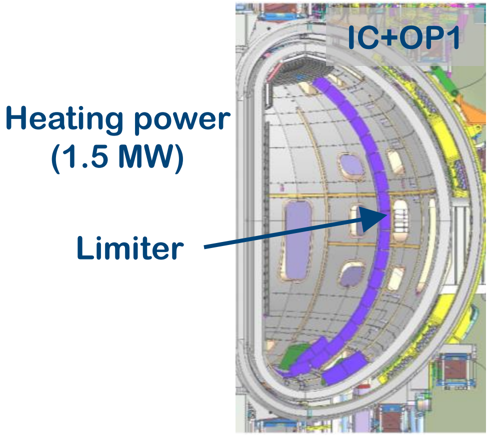
Timeline for JT-60SA

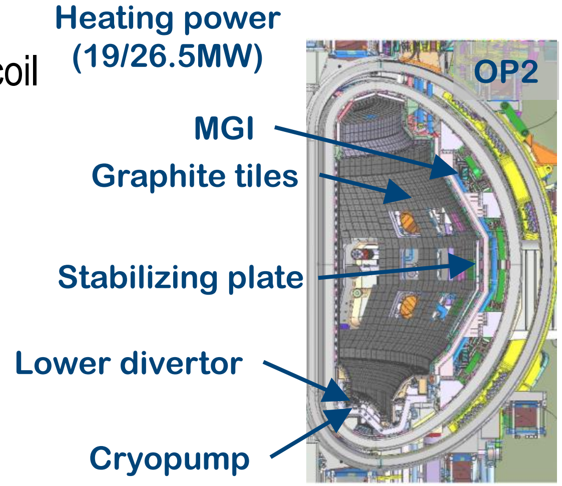


- JT-60SA is in a phase of maintenance and enhancement (ME1):
  - **Input power upgrade:**
    - EC: 1.5 MW → 3 MW (82, 110, 138 GHz)
    - NB: 0 MW → 16 MW(H) / 23.5 MW(D): 10 MW of 500 keV negative-ion NBI
  - Lower divertor
  - Several plasma control coils
    - Error Field Correction coil (EFCC), Resistive Wall Mode coil (RWMC), First Plasma Position Control coil (FPPCC)
  - Upgraded Diagnostics (Thomson Scattering, ECE, CXRS, etc…)
  - Massive gas injection for disruption mitigation
  - Stabilizing plate : CuCrZr heat sink + Carbon tiles
- Transition from ME1 to OP2 in 2026

S. Kojima, P7 2716

C. Sozzi, P6 2827





JT-60SA scientific priorities in the initial phase

Initial research phase I & II (C inertial divertor and C wall)

Integrated research phase (W actively cooled divertor and W wall)

OP2 (P_{in}=26.5MW)

Stable operation at high current heated plasma

H-mode access

First high beta plasma attempt

OP3 (P_{in}=26.5MW)

High confinement H-mode plasmas at high current including ELM control

Physics of energetic particles

Study of high beta plasmas

OP4 (P_{in}=33MW)

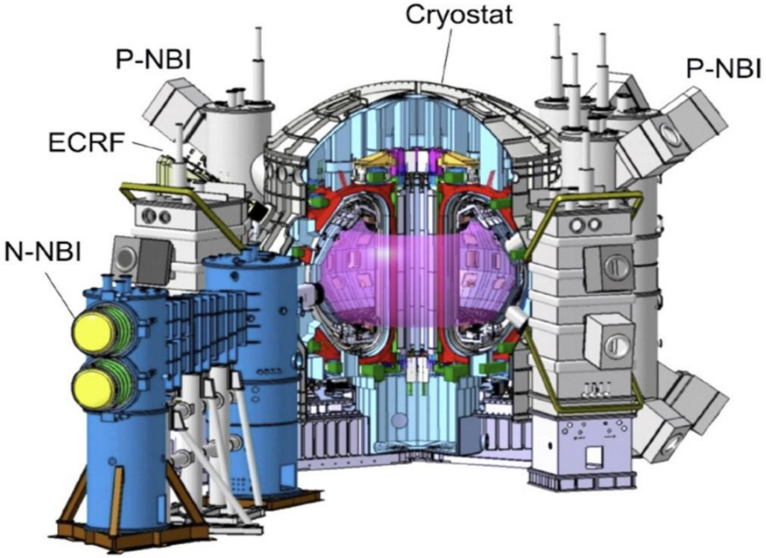
Disruption mitigation and avoidance at high current in H-mode

Heat load to divertor mitigation

High beta plasmas compatible with radiative divertor

OP5- (P_{in}=41MW)

Long pulse operation in W environment



Including scientific and operation preparation for the W phase

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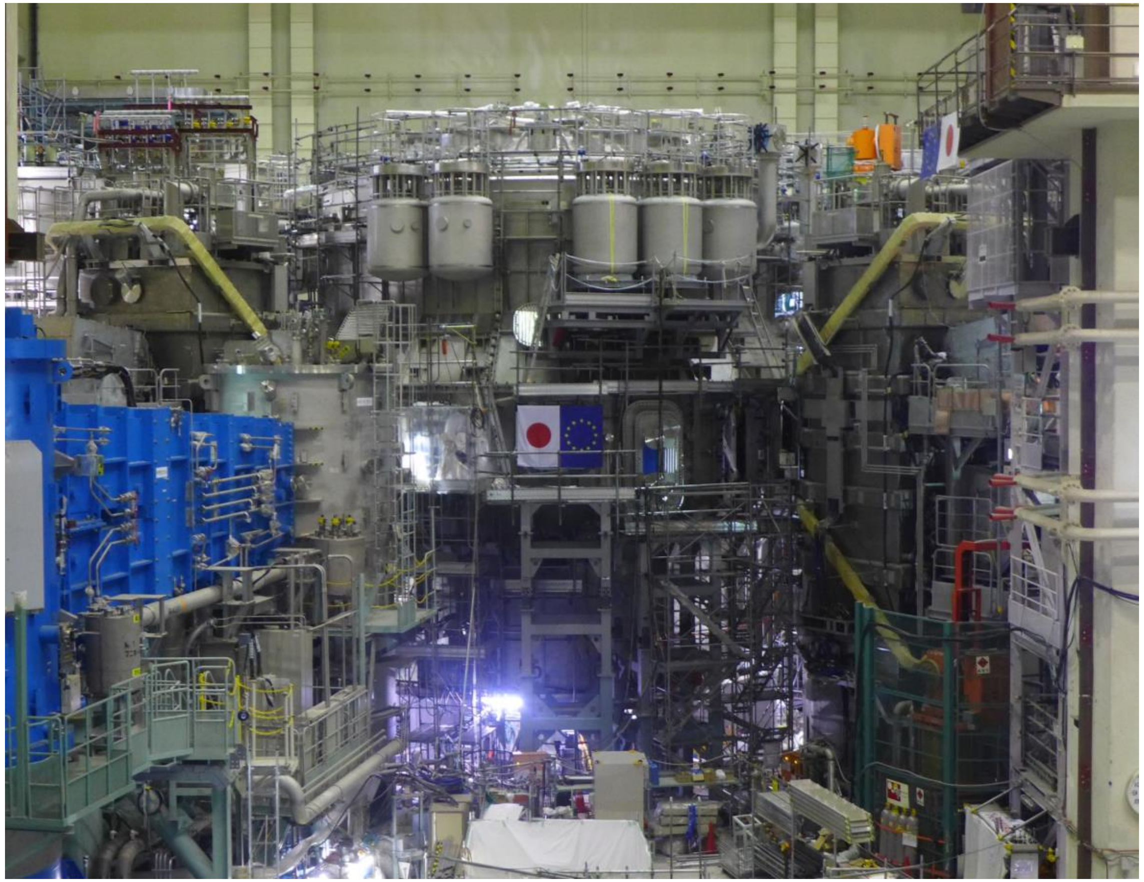
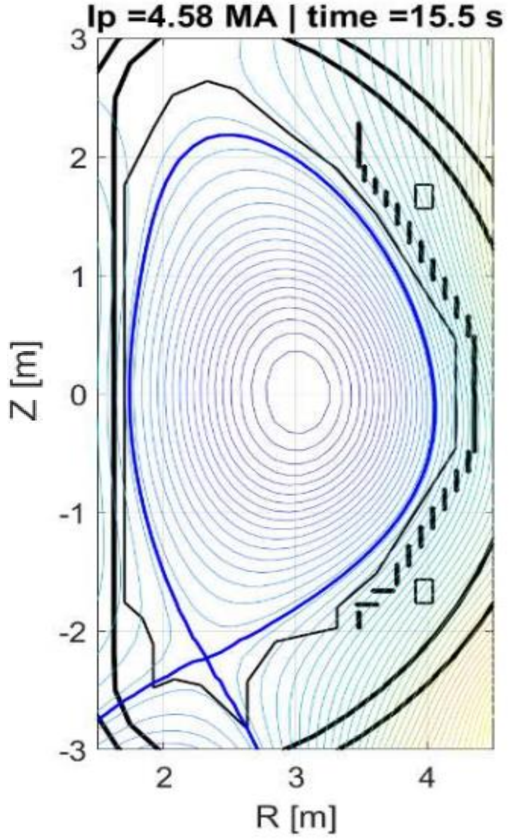


Scenario preparation for OP2

	Ip/Bt (q_{95})	β_N/β_p
Baseline	4.6 MA/2.28 T (q_{95} ~ 3)	~1.8/<1
Hybrid	2.7 MA/1.70 T (q_{95} ~ 4)	~ 2-3/~1
Internal Transport Barrier	1.7-2.0 MA/1.70 T (q_{95} > 6)	> 3.5/>>1

- Three typical scenarios for OP2 have been investigated
- New pulse design simulator being developed



E. Joffrin, P1 2720

Scenario preparation for OP2

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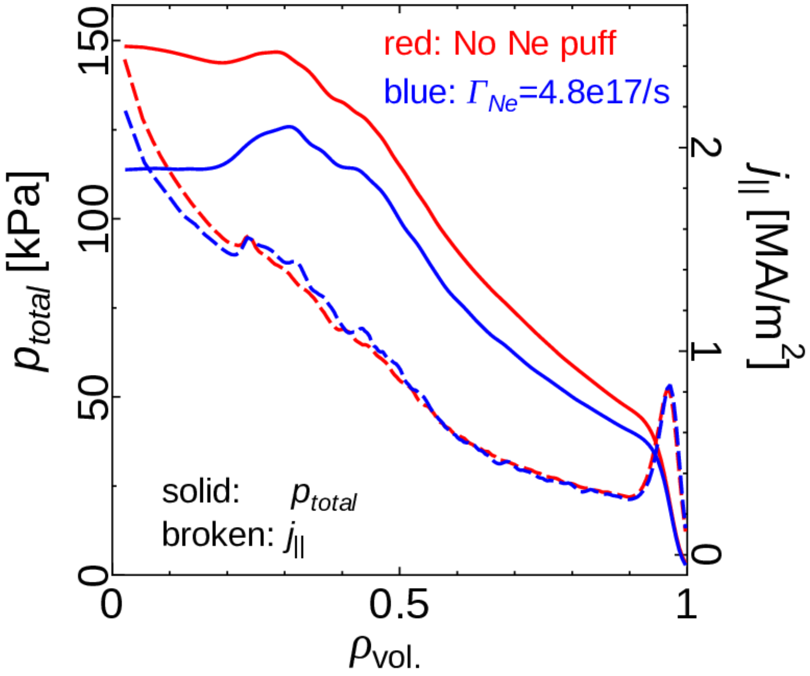

- Three typical scenarios for OP2 have been investigated
- SOL-PEDESTAL-CORE integrated simulations performed with GOTRESS+
- Target scenarios are possible with OP2 conditions
- Control of heat flux q_{flux}<~10MW/m^2 to divertor can be obtained with impurity injection

N. Aiba, TH/4 2890

Scenario preparation for OP2

	Ip/Bt (q_{95})	β_N/β_p
Baseline	4.6 MA/2.28 T (q_{95} ~ 3)	~1.8/<1
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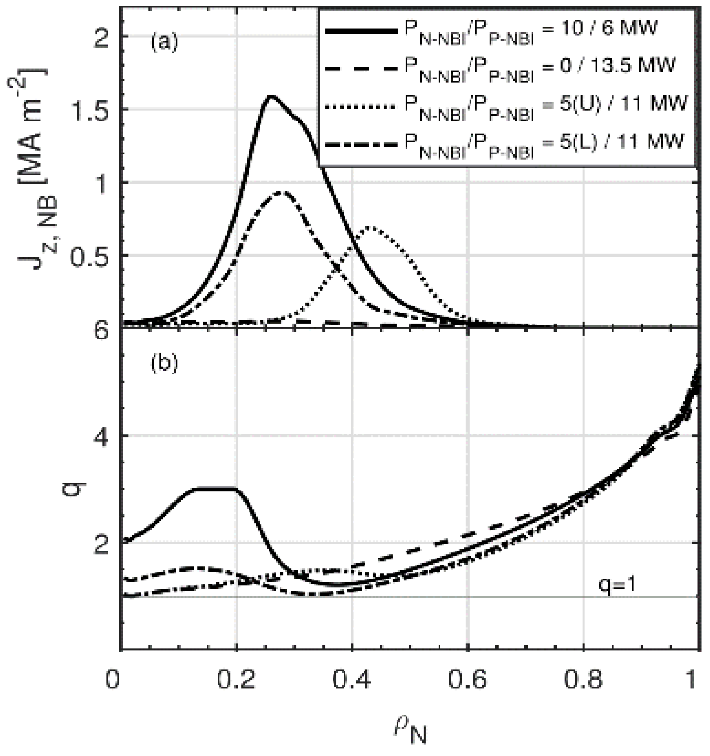
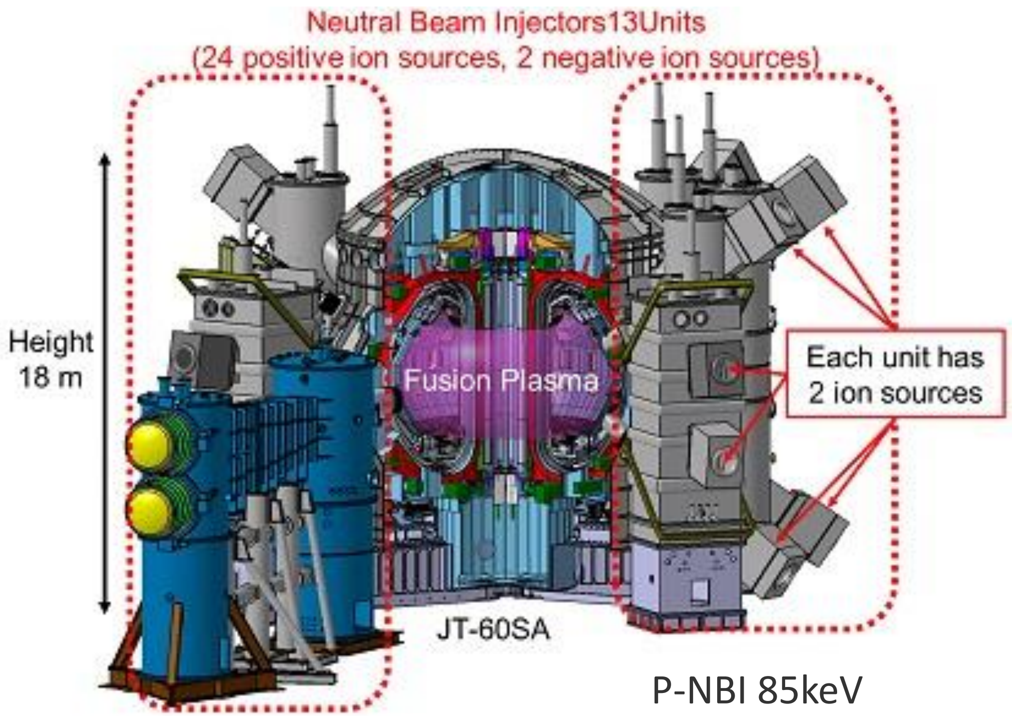
- Three typical scenarios for OP2 have been investigated
- JINTRAC simulations show strong impact of N-NBI current drive on q profile
- Flexibility for tailoring of the q profile with ECCD and NBI



[S. Gabriellini, NF 2025]

Fast ions studies possible with N-NBI

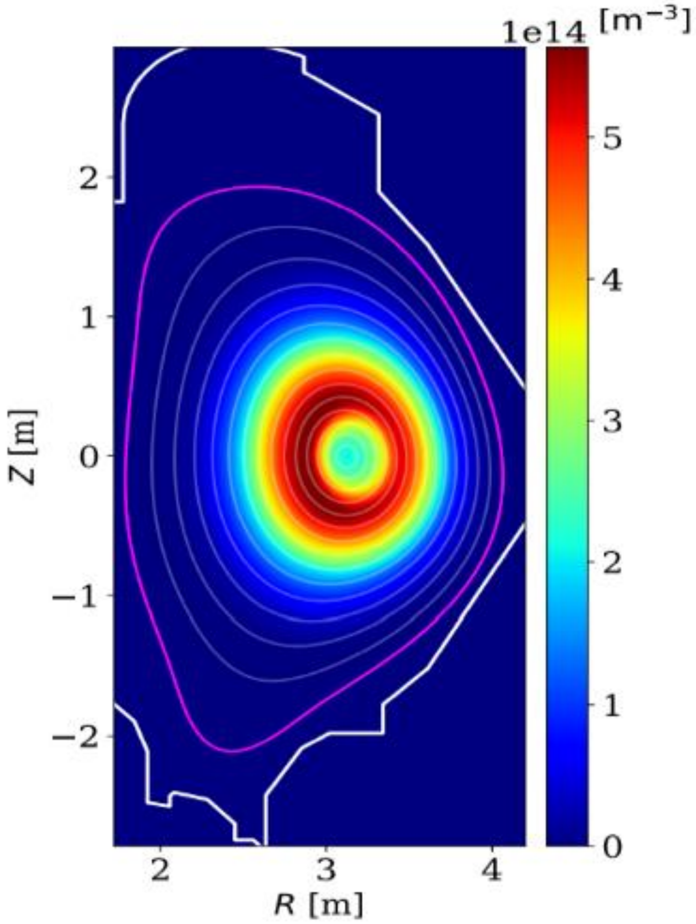
- Fast ion physics studies area a priority with N-NBI at 500keV and P-NBI 85keV
- Interaction between fast ion driven modes and turbulence found [A. Iantchenko, NF 2024]



P-NBI 85keV

N-NBI 500keV

α particle physics studies with ^{3}He plasmas



Y. Kazakov, P4 3333

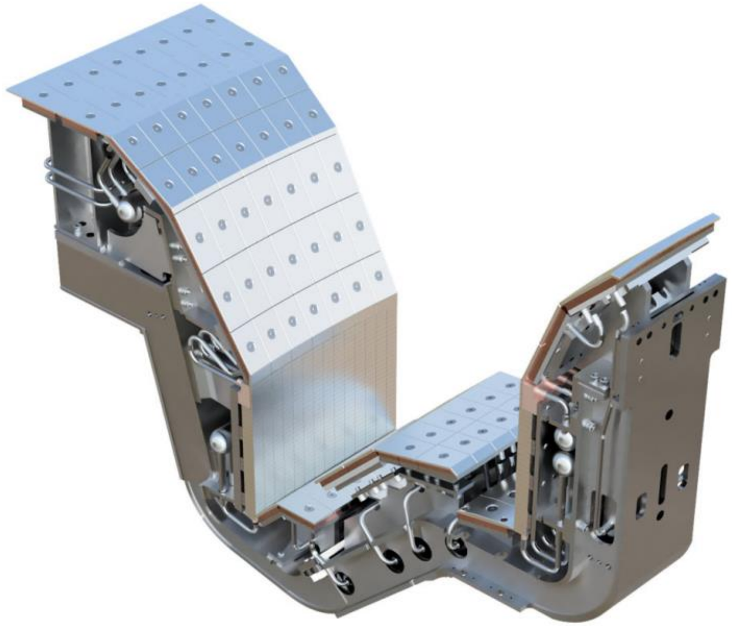
R. Coelho, P2 3269

S. Nowak, P6 3171

- Fast ion physics studies area a priority with N-NBI at 500keV and P-NBI 85keV
- Interaction between fast ion driven modes and turbulence found [A. Iantchenko, NF 2024]
- α particle physics can be studied with N-NBI injection
- $D_{beam}+^3He \rightarrow ^4He$ (3.6MeV) + p (14.7 MeV), which has its maximum cross-section close to 500keV for fast D
- Significant off-axis α particle production in reversed q profile→ interplay between α and MHD

Transition to W PFCs

- Long pulse operation will be carried out in the integrated research phase with W PFCs→ ITER support and DEMO design
- Tungsten divertor under development
  - Monoblocks for inner and outer vertical targets
  - Solid tungsten bolted tiles elsewhere
- Design starting for first wall
- Predict first modelling ongoing for assessing:
  - optimized divertor design M. Richou, TEC/2 3023 [G. Rubino, EPS 2024]
  - additional ECRH heating and W screening [C. Angioni in preparation]
  - boronization system
  - additional diagnostics



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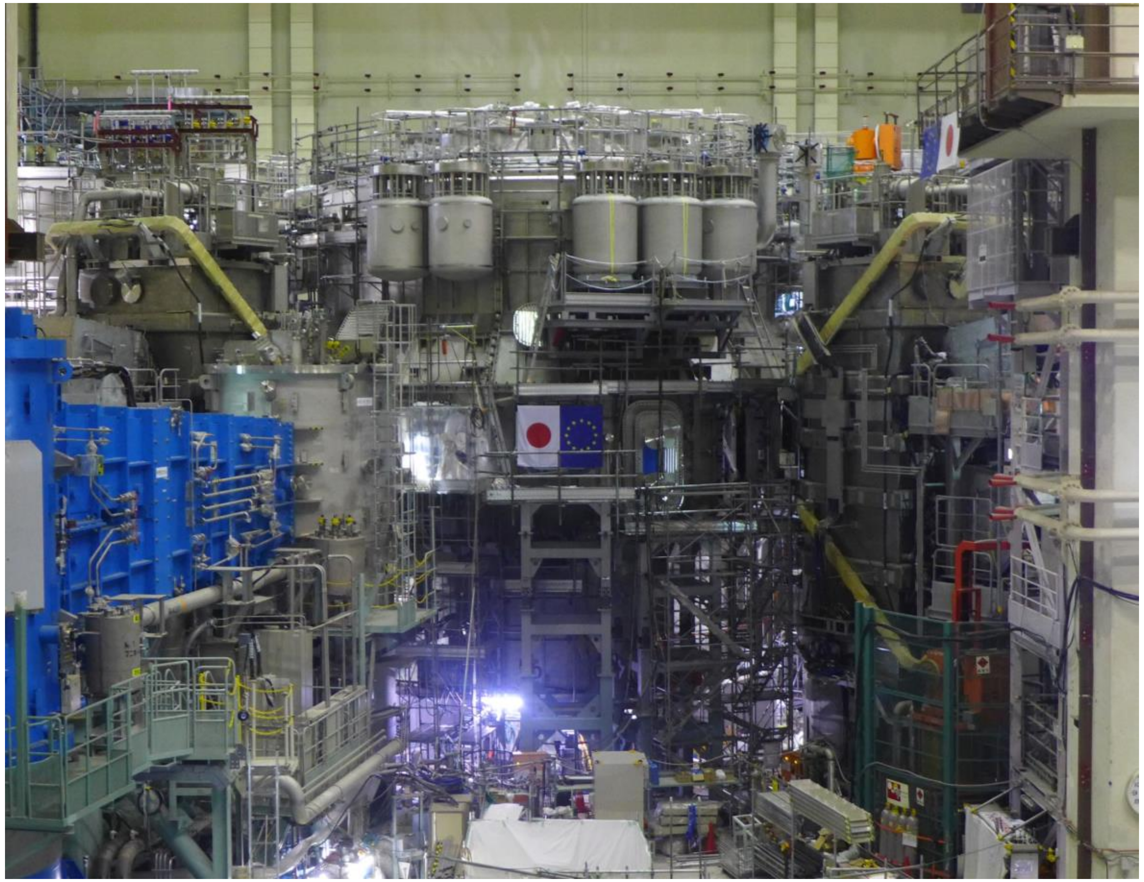

Conclusions

- JT-60SA was jointly constructed and is jointly funded and exploited by Japan and EURATOM
- First plasma was achieved in 2023
- OP1 has demonstrated the importance of predict first and machine learning activities even for start-up phase
- Now implementing major enhancements to in-vessel components, heating systems & plasma diagnostics
- Operation restarts in 2026 targeting high plasma current and H-mode
- Experimental programme being developed by the Experiment Team
- Aim to transition to a tungsten environment in time to provide results to support ITER and DEMO in the early 2030s

JT-60SA contributions in the 30th IAEA-FEC

DISRUPTIONS AND MHD INSTABILITIES OBSERVED IN THE INITIAL OPERATION PHASE OF JT-60SA **T. YOKOYAMA** P5 2690

CHARACTERISTICS OF RUNAWAY ELECTRON LOSS IN THE INTEGRATED COMMISSIONING OF JT-60SA **S. SUMIDA** P5 2692

CONFINEMENT PROPERTY IN THE JT-60SA PLASMA IN THE FIRST OPERATIONAL PHASE **Y. OHTANI** P1 2851

DEVELOPMENT OF EQUILIBRIUM CONTROL SIMULATOR AND EXPERIMENTAL DEMONSTRATION OF ADVANCED ISO-FLUX EQUILIBRIUM CONTROL DURING THE FIRST OPERATIONAL PHASE OF JT-60SA **S. INOUE** EX/7 2898

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