Welcome to ITER

2022 European HDF5 User Group -
May 31 – June 2, 2022

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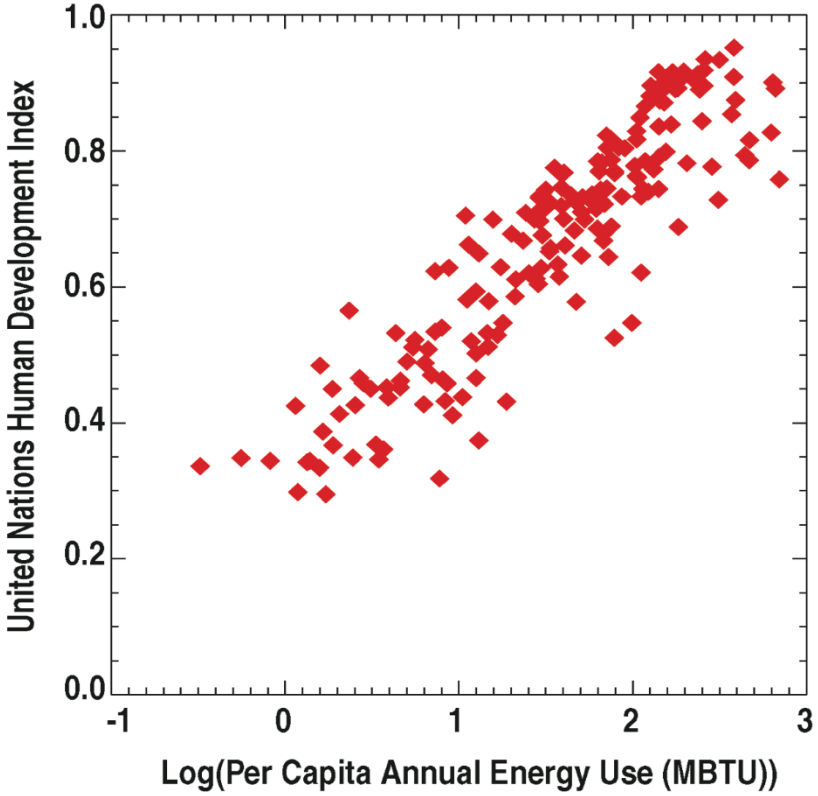
Head of Controls Division
ITER Organization Central Team

Outline

- What is ITER about?
- What is needed to get a burning plasma?
- Role of the Control System
- Data
- Project status – construction, commissioning, operation
- Summary

Standard of Living Is Related to Energy Use

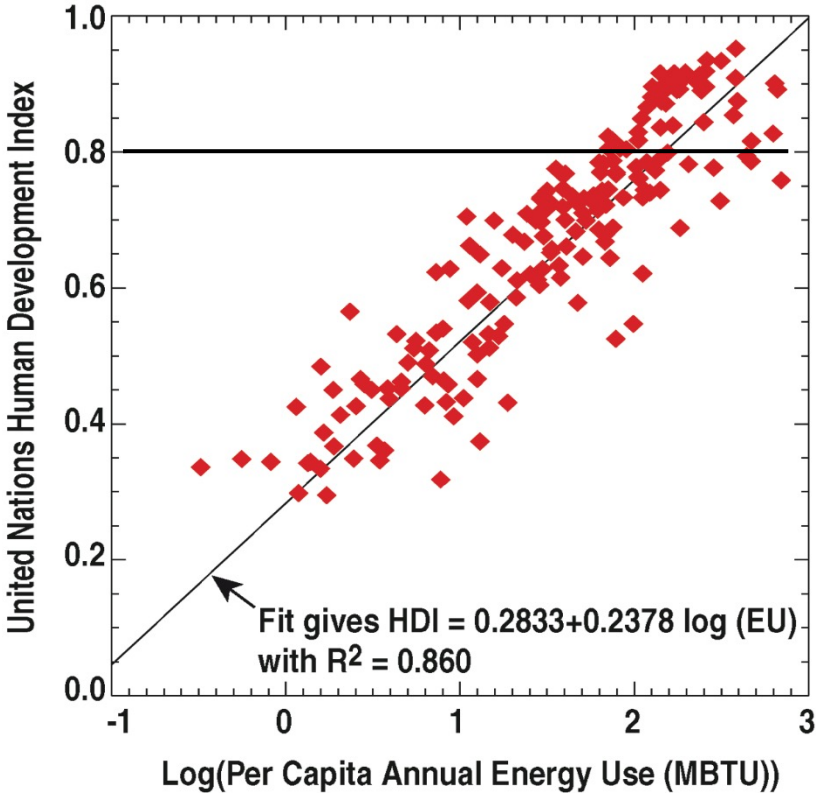
- **For standard of living, use the UN Human Development Index (HDI)**
  - Combines three metrics: life expectancy at birth, a measure of the expected education level, and per capita national income
  - http://hdr.undp.org
- **For energy use, use US Energy Information Administration statistics for national energy consumption**
  - http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=44&pid=44&aid=2



Standard of Living Is Related to Energy Use

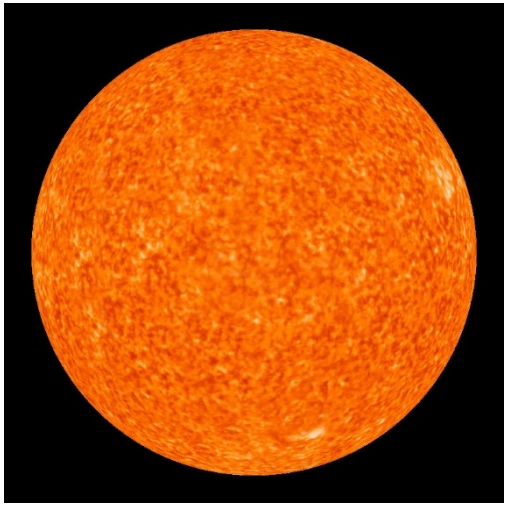
- **How much energy does the world need for a "reasonable" standard of living?**
  - Use the slope of the correlation of HDI and Log(EU) to project the energy associated with the whole world at HDI ≥ 0.8
  - The resulting <u>incremental</u> energy is >800 10^{18} J/yr or more than 1.6x the present energy use (~500 10^{18} J/yr)
  - This does not take into account population increase

If we want to increase the standard of living of the world population we need to increase the production of energy (in addition to use it more efficiently)



The Role of Fusion

Why is fusion energy attractive?

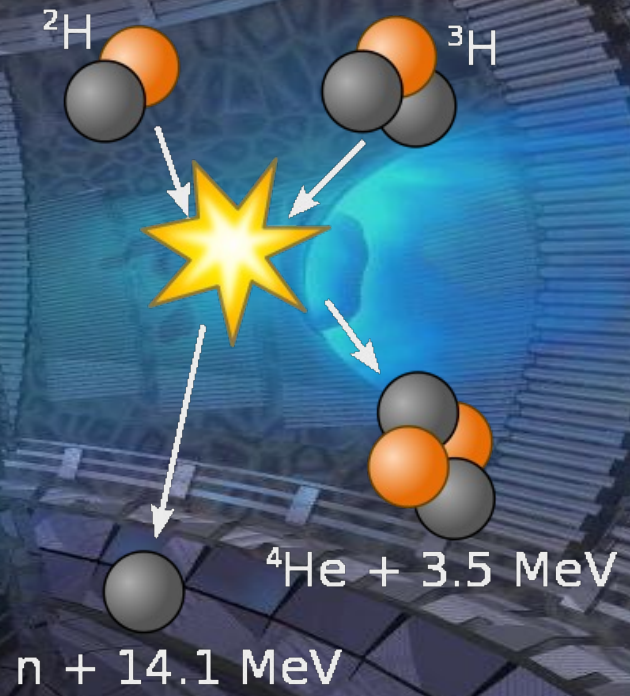


- Fusion fuels are widely available and nearly inexhaustible
- There is no risk of any fission type accident
- Fusion reactors produce no CO_2 and no high activity, long-lived nuclear waste (the rest product is non toxic Helium)

Fusion on Earth

Energy from fusing 1 gram of fusion fuels = Energy from burning 8 tons of oil

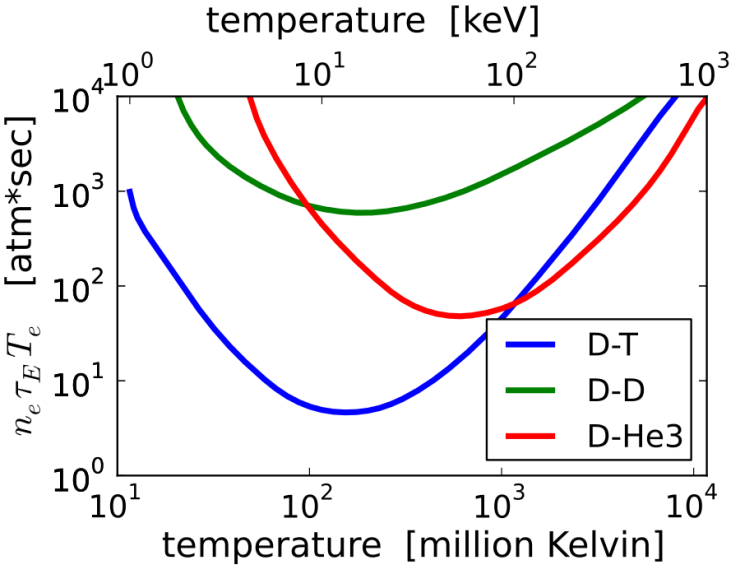
- A plasma of Deuterium + Tritium is heated to more than 100 million °C (set by fusion cross-section)
- The hot plasma is shaped and confined by strong magnetic fields
- Helium nuclei sustain burning plasma
- Neutrons transfer their energy to the Blanket
- In a fusion power plant, a conventional balance of plant will transform the heat into electricity



What are the technical challenges?

- **Lawson triple product**
  - Temperature
  - Density
  - Confinement time

- DT fusion reaction has been proven by TFTR (US) and JET (UK) in the 1990's and again by JET in 2021, but without break-even P_{fus}/P_{in} ($\equiv$ Q) = 0.65 < 1



ITER mission

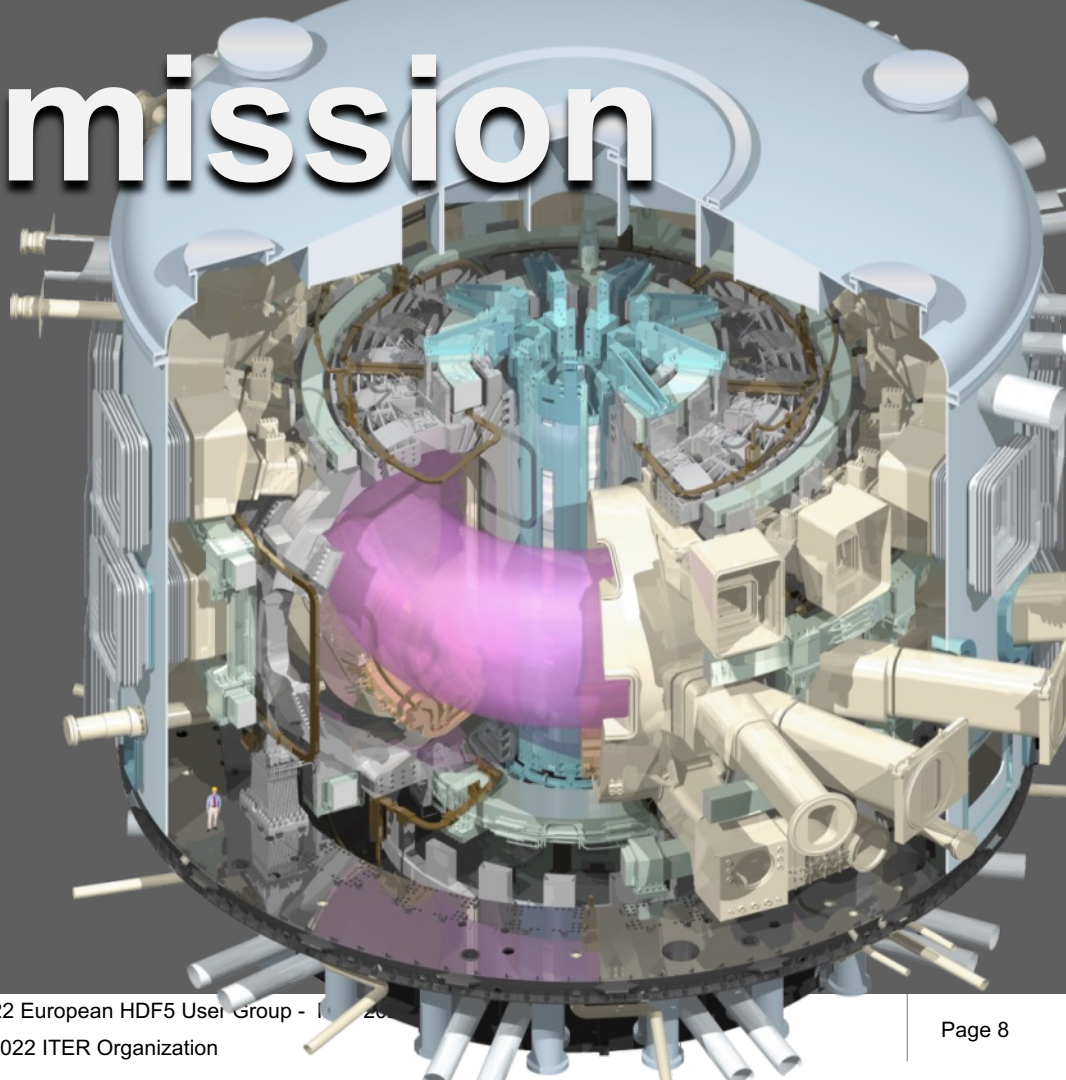
To demonstrate the scientific and technological feasibility of fusion power for peaceful purposes

Achieve fusion power of 500 MW with P_{fus}/P_{in} (≡ Q) ≥ 10 for 300-500 s (i.e., stationary conditions)

Input (heating power): 50 MW

Output (fusion power): 500 MW

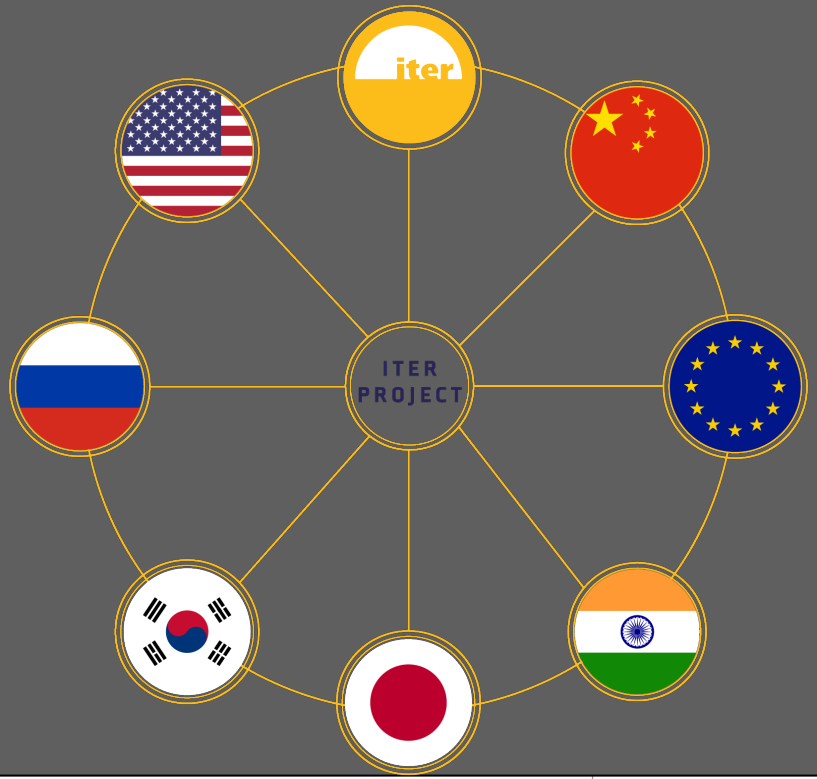
The output of ITER is DATA



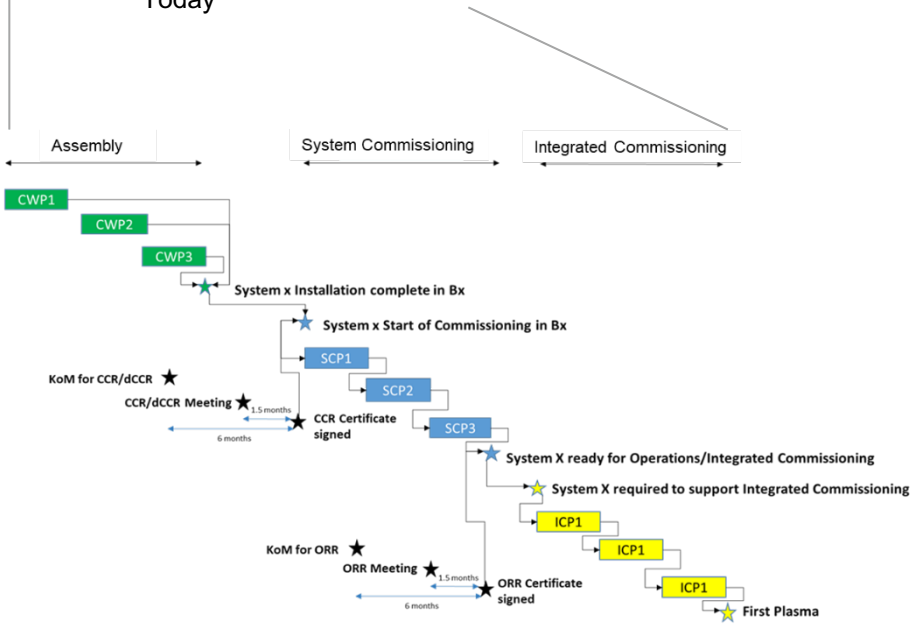
An integrated project:

Central Team & Seven Domestic Agencies

- The 7 ITER Members make cash and in-kind contributions (90%) to the ITER Project. They have established Domestic Agencies to handle the contracts to industry.
- The ITER Organization Central Team manages the ITER Project in close collaboration with the 7 Domestic Agencies.
- The ITER Members share all intellectual Property generated by the Project.



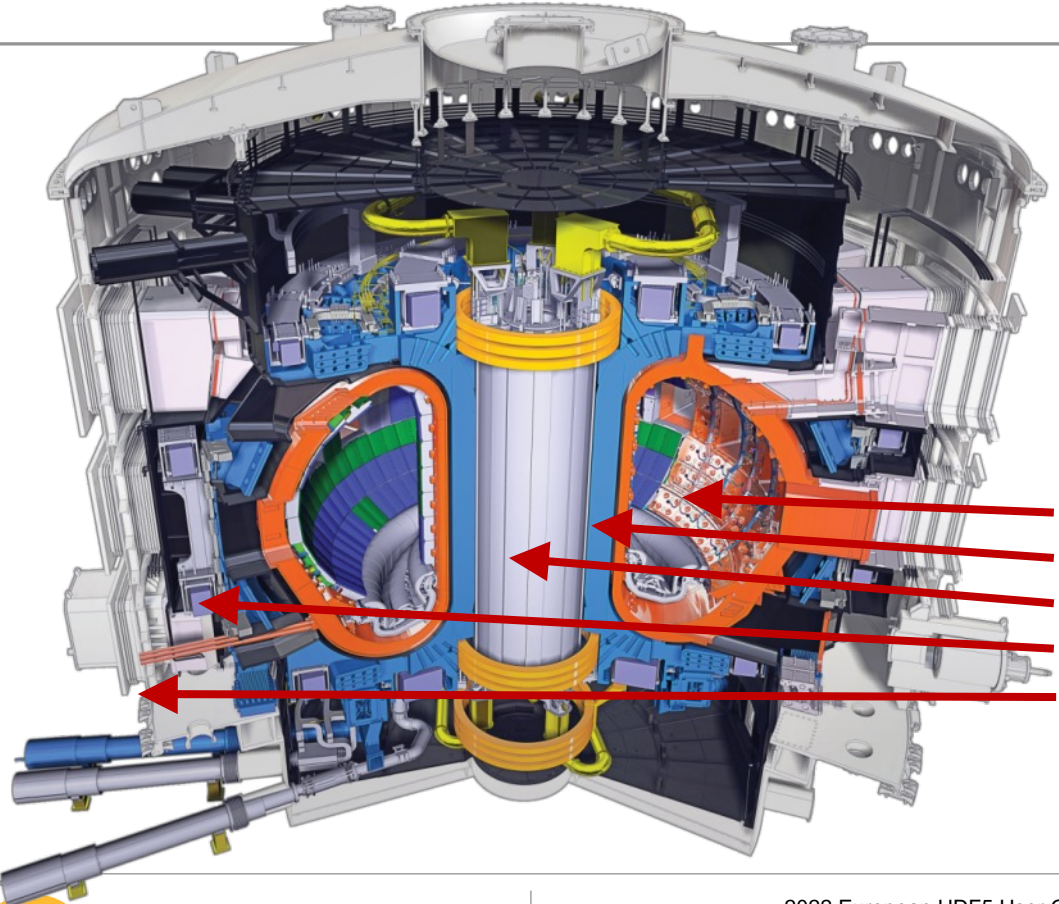
A staged approach to DT plasma



- Each stage consists of assembly, system commissioning, integrated commissioning and operation
- Each stage adds more hardware and systems
- Assembly and system commissioning can be executed partly in parallel (different locations, different systems)

- Work is broken down in construction working package (CWP), system commissioning packages (SCP) and integrated commissioning packages (ICP).
- Each package details all the steps (and procedures) required to reach the next milestone
- Gate reviews guarantee the acceptance for readiness of the systems (construction completeness review - CCR, operation readiness review - ORR)

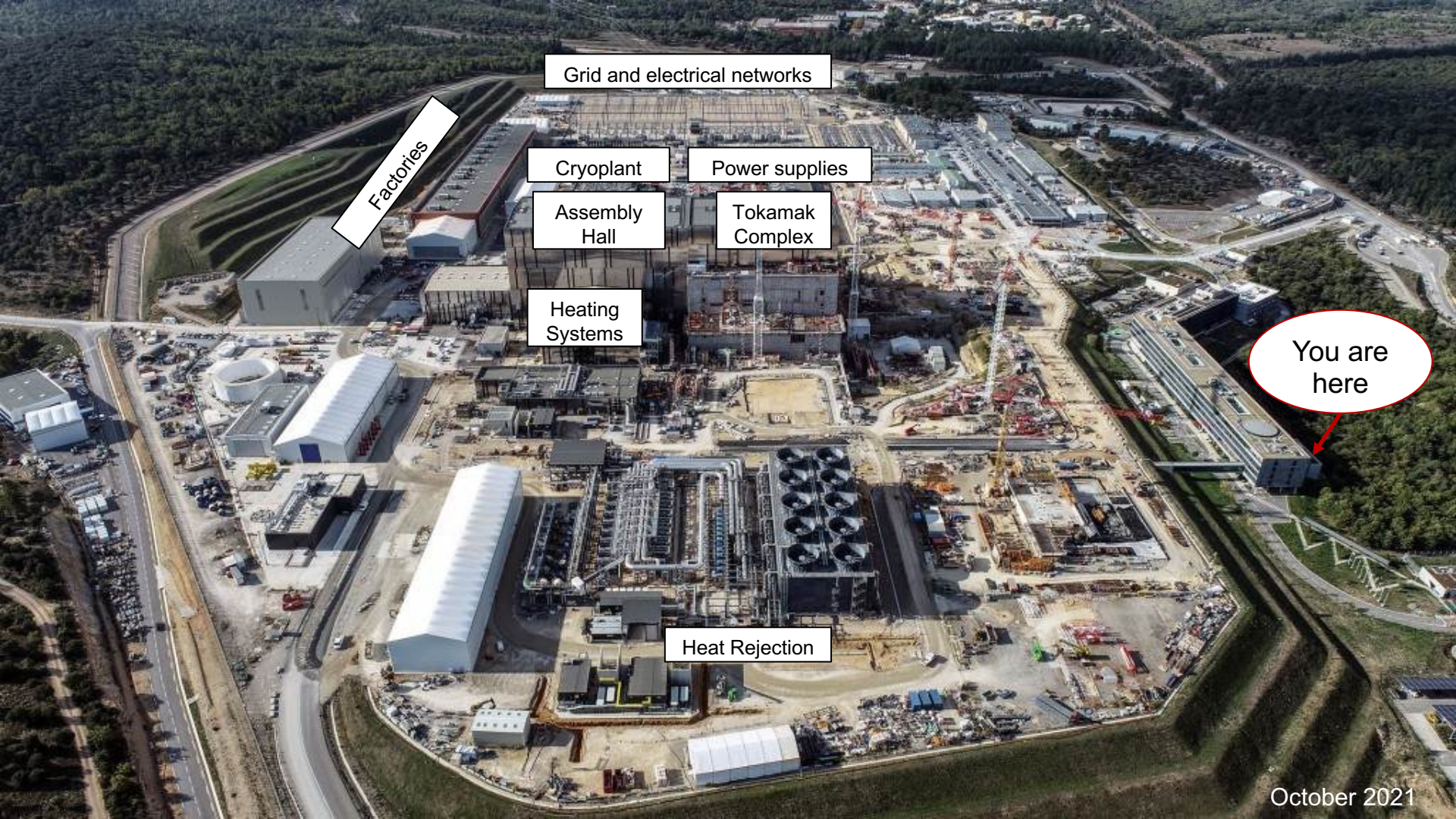
The ITER Tokamak



An intense magnetic field, generated by powerful superconducting magnets shapes and confines the hot plasma, and keep it away from the vacuum vessel wall.

- Vacuum Vessel: 8 000 t. 850 m^3
- 18 TF Coils: 360 t. 17-m high
- 1 Central Solenoid: 1 000 t. 13-m high
- 6 PF Coils: 200-400 t. 8 to 24 m diameter
- Cryostat: 30 x 30 m

October 2021

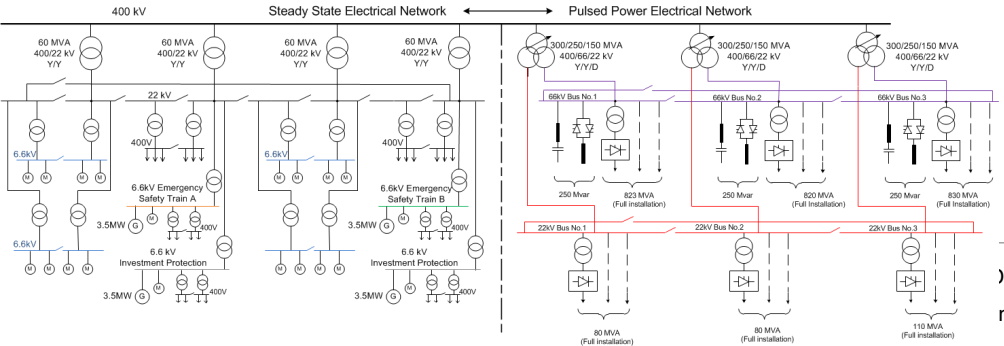

Grid and electrical networks
Factories
Cryoplant
Power supplies
Assembly Hall
Tokamak Complex
Heating Systems
You are here
Heat Rejection
October 2021

What do we need to get plasma …

Electricity

- Take the power from the grid, transform and distribute
- Control System to ensure the right currents are flowing in the right places and take actions if faults appear or configurations are changed

- Started operation in 2019 and adding more and more load centers



CAS CSS Pulse ID 1289
CODAC CIS SUP ###

ELECTRICAL POWER SUPPLY AND DISTRIBUTION

2022-04-12T08:15:06.

Show Info

COS = EXECUTING

ALARMS HISTORY PV WRITE TREE

Current Alarms (3 of 4791 Selected)

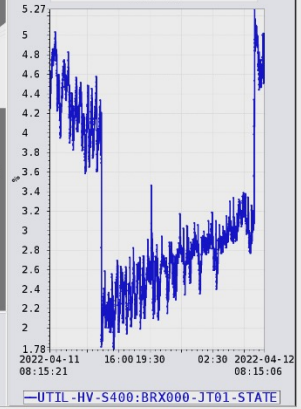
Acknowledged Alarms (0 of 429 alarm

Ac	Description	Alarm Ti
	ELC T0 MAJOR Fault	07:40:24
	ELC T5 MAJOR Fault	15:12:45
	ELC T4 MAJOR Fault	15:12:45

B36

Status Trends

4.49 MW



S6 T6 T2 B07 0.1 MW

B40 0.3 MW B42 0.3 MW

S4 T9 0.0 MVA L15 L09 LC13 LC04

TLC01 LC02 LC08 MV4 MV6 LC01

LC06 0.0 MVA MV5 MV2 0.0 MVA

B91 0.2 MW RTE 0.0 MVA MV3 0.0 MVA LC10 0.0 MVA

1.07 MW 1.87 MW 1.43 MW 0.12 MW B36 4.49 MW LC16

B92 0.2 MW LC11 0.2 MVA MV1 0.0 MVA LC03 0.0 MVA LC05 0.2 MVA

T0 0.0 MVA T5 LC14 0.9 MVA LC17

T4 LC12 0.8 MVA T8 0.0 MVA TLC3 0.4 MVA S2

B62 S5 T3 0.0 MVA T1

S1

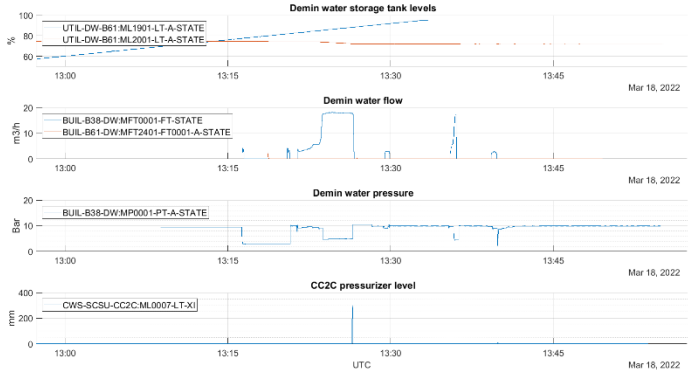
HOME ELC HV IP LV MV PHV PMV S15 SPA SPB

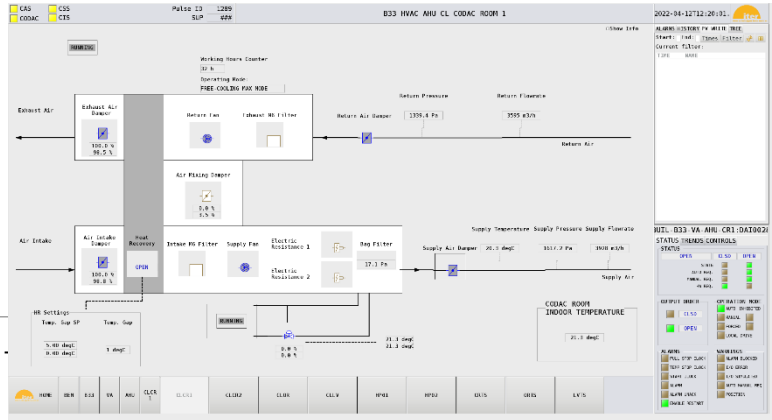
What do we need to get plasma …

Buildings and Site Services

- Control the environment (temperature, pressure, humidity) and provide services like fire protection, compressed air, demineralized water, etc. in all ITER buildings
- Control System to ensure environment is correct and services are provided and take actions if faults appear or configurations are changed

- Started operation in 2020 and adding more and more buildings



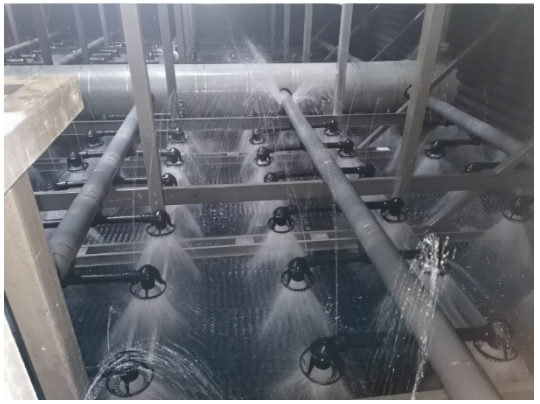


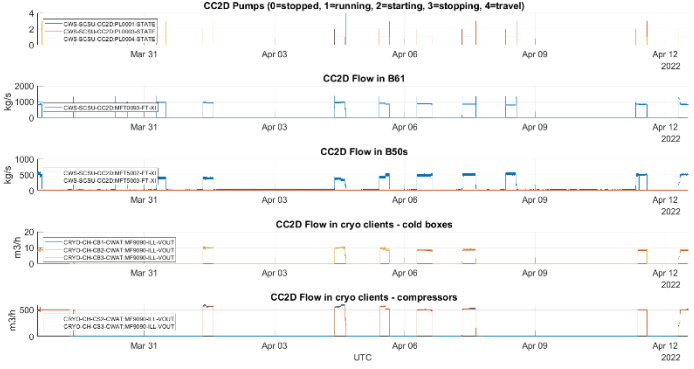
What do we need to get plasma …

Cooling Water

- Cool equipment around the site and reject the heat through cooling towers
- Control System to control valves, pumps etc., regulate flows, pressures and temperatures and take actions if faults appear or configurations are changed

- Started commissioning in 2020 and starting to serve first clients now

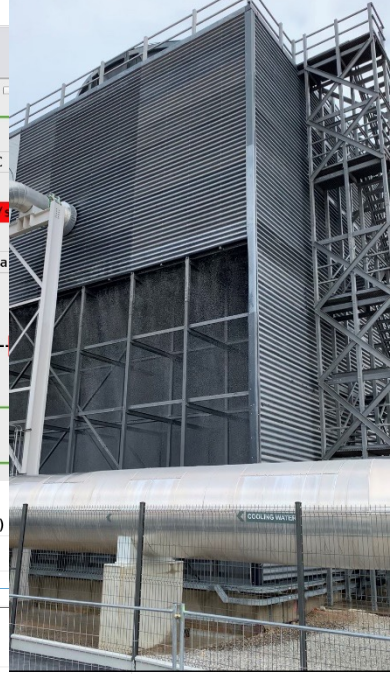


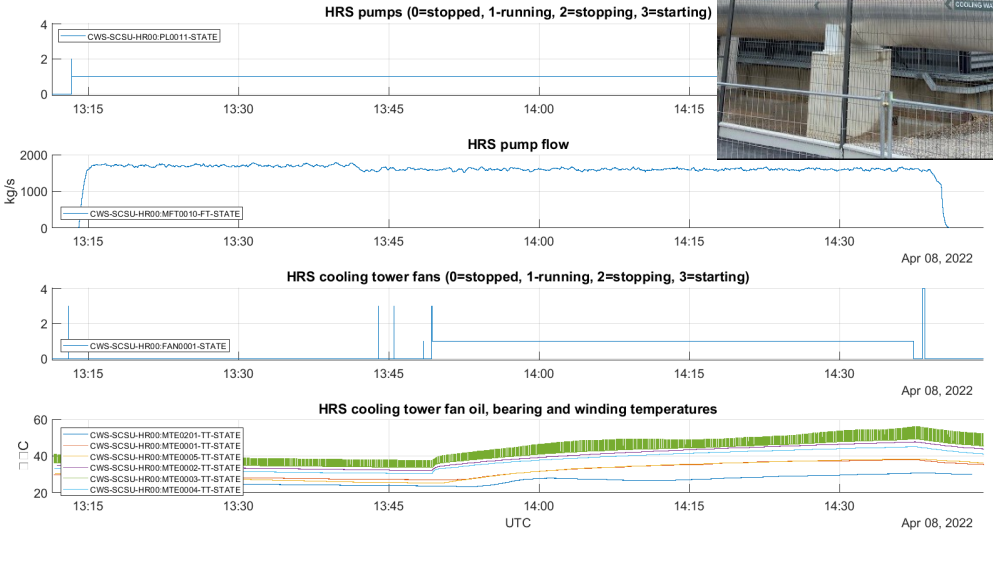


CAS
CODAC
CSS
CIS
Pulse ID 1289
SUP ###

HRS: COOLING TOWERS, BASINS AND PUMPS

CCWS-2 HEX
14.8 °C
7.5 °C
CTBP
CTOP
PMPG 1
SFU-0001
CCWS-2 VENTURI SKID
SFU-0001
12.6 °C
CCWS-1 VENTURI SKID
CCWS-1 HEX
CCWS-1 VENTURI SKID
SFU-0002
SFU-0003
HBBP
PMPG 3
1609.1 kg/s
HWFC
245.7 kPa
7.5 °C
22.0 %
21.7 %
ML-0204(V)
3831.0 mm
0.0 rpm
0.0 rpm
0.0 rpm
0.0 rpm
0.0 rpm
0.0 rpm
0.0 rpm
0.0 rpm
0.0 rpm
0.0 rpm
PMPG 2
12.3 °C
20.6 kg/s
74.1 kPa
115.7 kPa
HOME
SCW
HRS
PFD
P1:HREJ_CPMP_W VM
P3:HEX

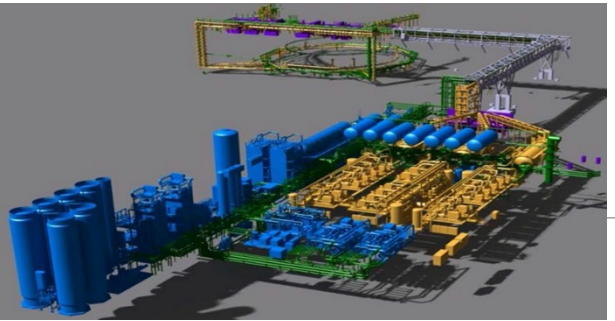


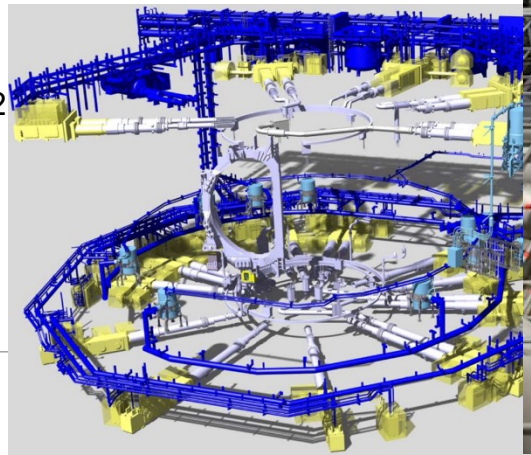


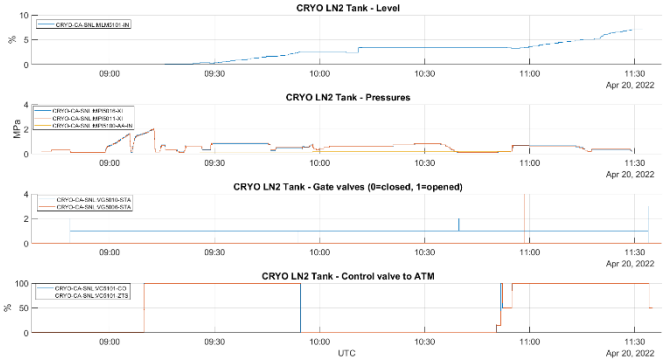
What do we need to get plasma …

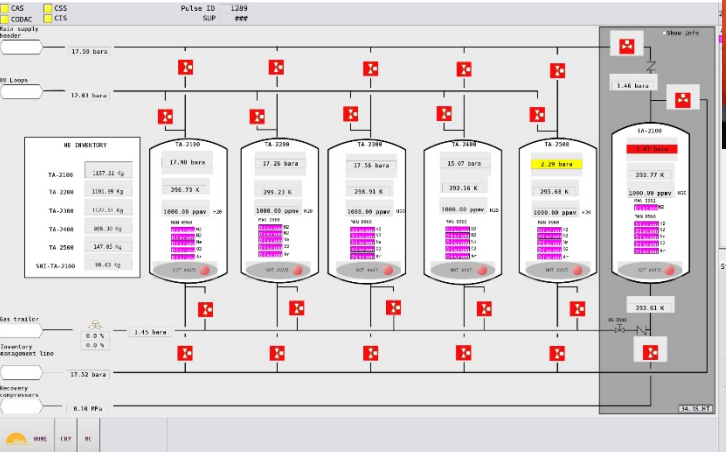
Cryogenic Cooling

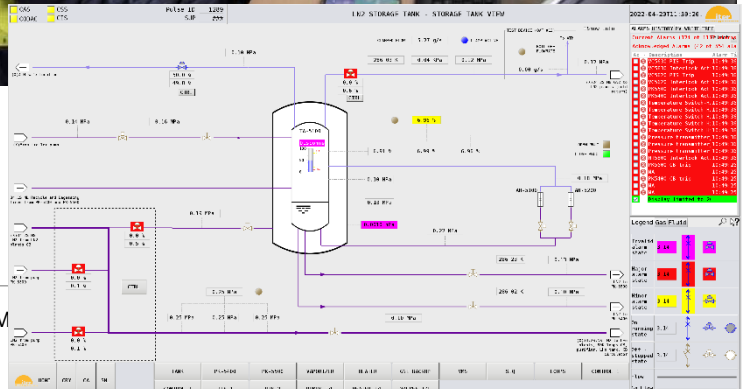
- Generate and distribute coolant (80K LN_2 and 4K LHe) to magnets, cryopumps, current leads and thermal shield
- Control System to control and monitor the production (cryoplant) and distribution to all clients, regulate and monitor flow rates, pressures and temperatures and take actions if faults appear or configurations are changed (e.g. high power pulsing)
- Started commissioning in early 2022











22 European HDF5 User Group - M

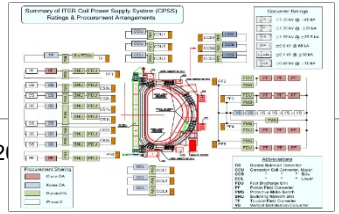
2022 ITER Organization

What do we need to get plasma …

Coil Power Supplies

- The magnets need well controlled currents to generate the required magnetic fields.
- Control System to control and monitor the AC/DC converters to produce the right current at the right time to the magnets and take actions if faults appear or configurations are changed
- Control System to control and monitor the switching networks, busbars, protection circuits, all current and voltage measurements, etc. and take actions if faults appear or configurations are changed.

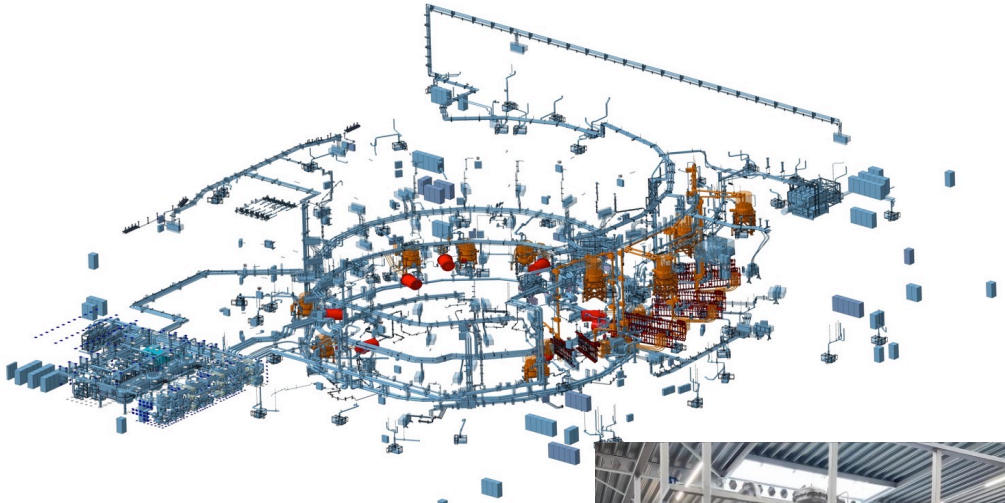
- In construction. Commissioning starts in summer



What do we need to get plasma …

Vacuum

- The torus vessel, cryostat, neutral beam, ECH and some Diagnostics need to operate in vacuum.
- Control System to control and monitor many different types of pumps, valves, cryopump regeneration, pressures etc. and take action if faults appear or configurations are changed



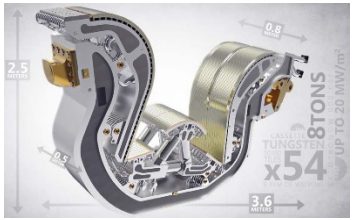
- In manufacturing and construction

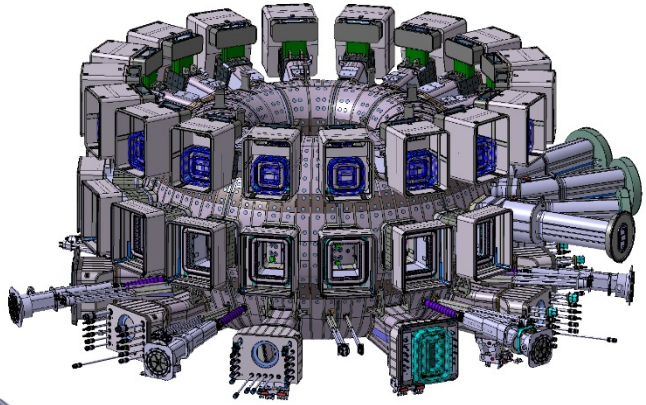
What do we need to get plasma …

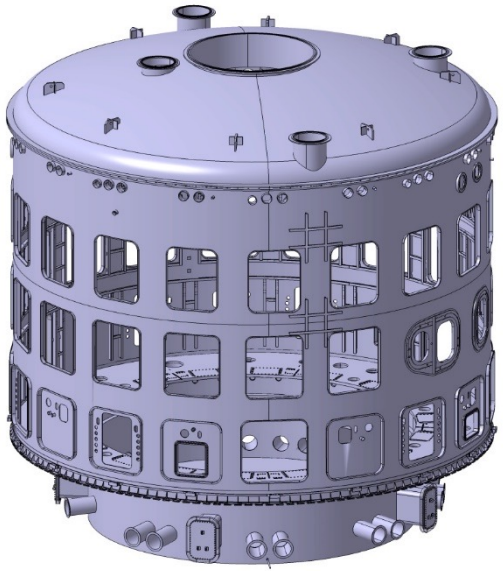
Structures

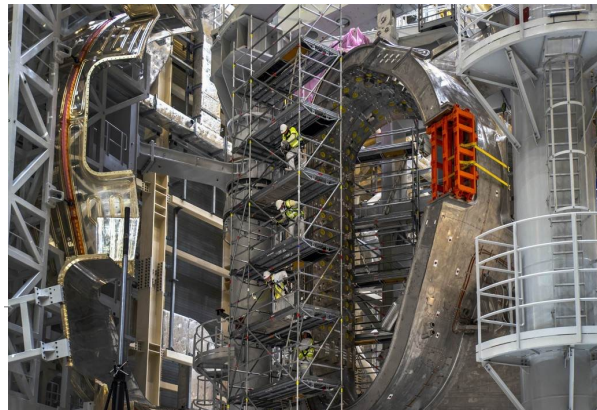
- Vacuum vessel, cryostat, thermal shield, port plugs and first wall (blankets, divertors and breeding test blankets)
- Control System to monitor the structure (temperatures, mechanical deformation and stress) and take actions if fault appears
- Control System to control and monitor all functions of the test blankets

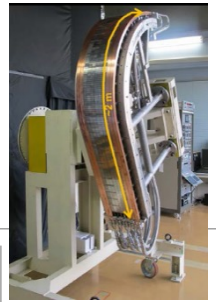
- In design, manufacturing and construction









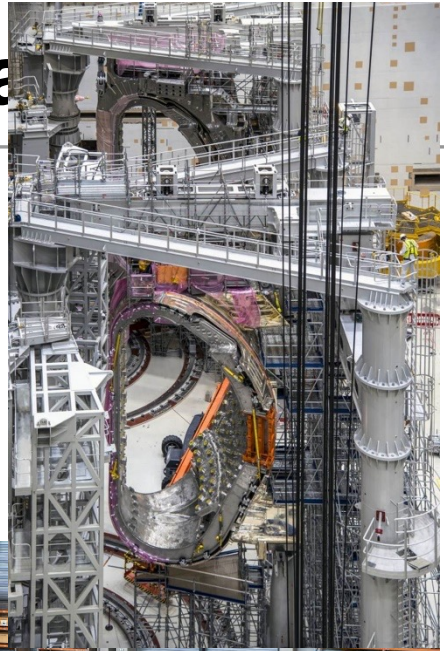


What do we need to get plasma

Magnets

- Superconducting magnets and conventional in-vessel coils to confine and control the plasma.
- Control System to monitor the temperatures, coolant flow and mechanical integrity of the superconducting magnets and feeders, to detect fault, in particular quenching, and take corrective actions.

- In manufacturing and construction

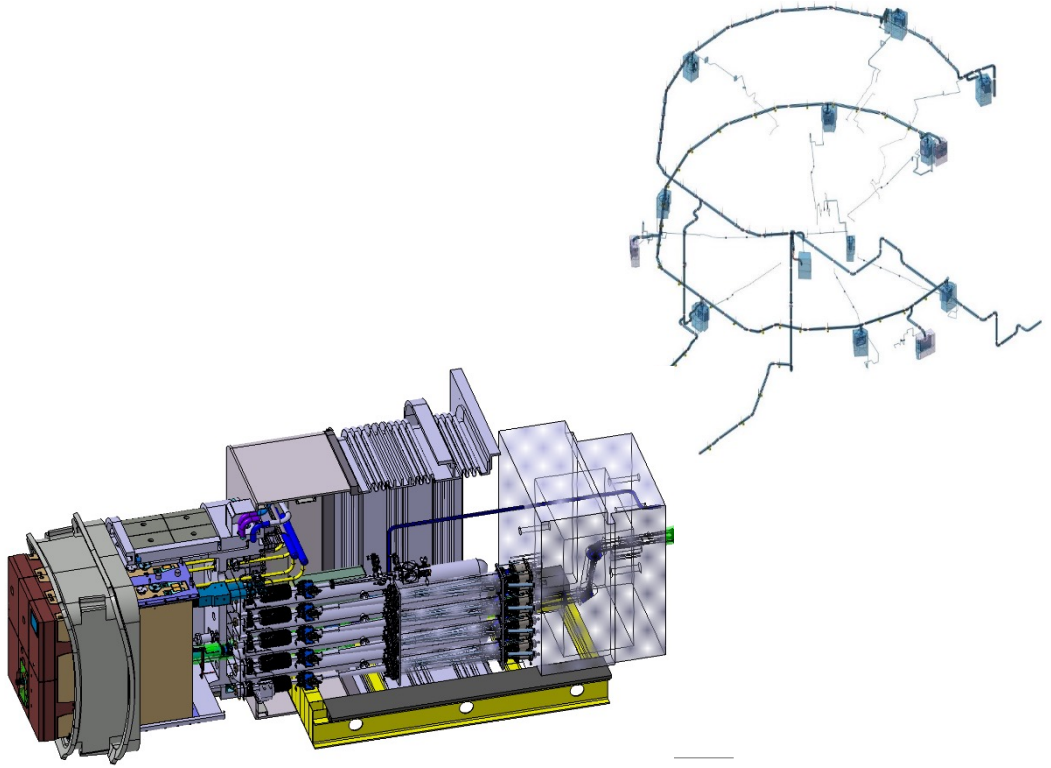


What do we need to get plasma …

Fueling

- Inject fuel in vacuum vessel to create and maintain the plasma
- Control System to control the injection of the right amount of fuel, gas or pellets, at the right time
- Control System to control the plasma density by providing fuel in real-time based on feedback control
- Control System to mitigate disruptions by massive injection of impurity fuel

- In design, manufacturing and construction

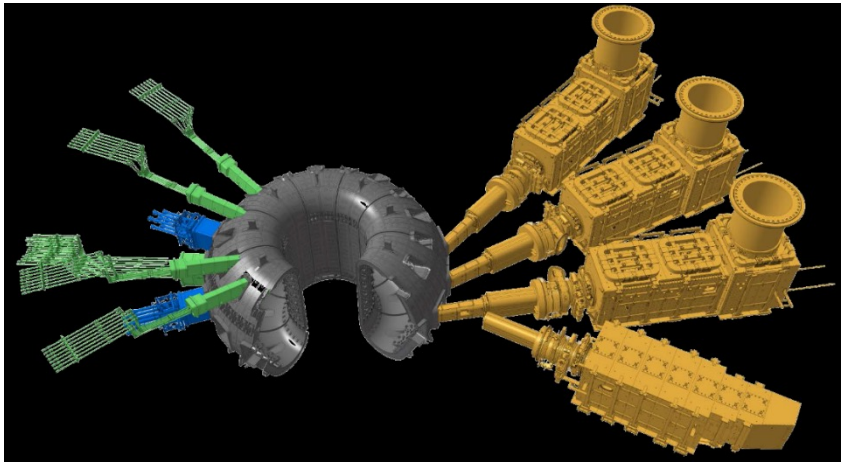


What do we need to get plasma …

Additional Heating

- Kick-start the plasma, heat it and drive the current by injecting additional energy
- Control System to control and monitor the three heating systems (ICH – Ion Cyclotron Heating, ECH – Electron Cyclotron Heating and NBH – Neutral Beam Heating)

- In design, manufacturing and construction

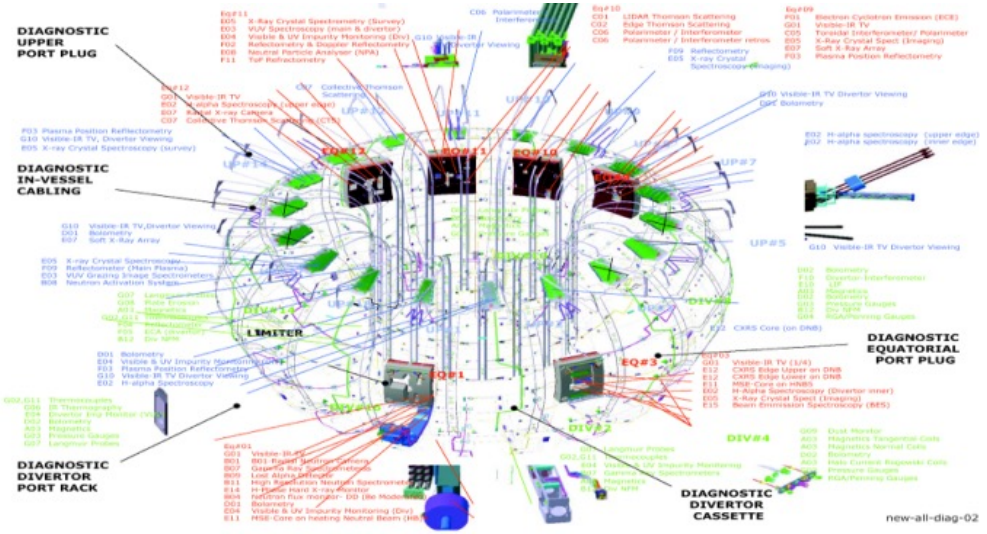


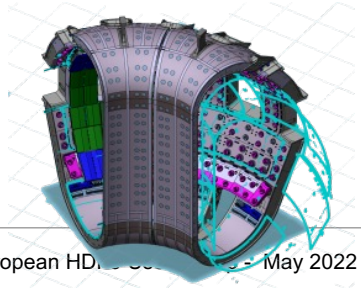
What do we need to get plasma …

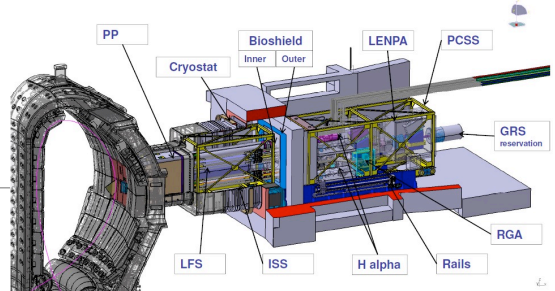
Diagnostics

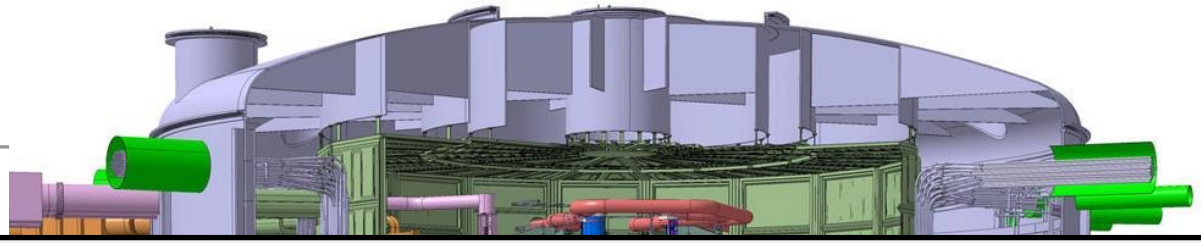
- Measure the plasma (current, density, temperature, shape, position, confinement time, fusion power, impurities…) by more than 50 different Diagnostics
- Control System to control and monitor the diagnostics so they can provide the required measurements
- Control System to treat the produced measurement (data) to be used for protection, plasma control and scientific exploration

- In design, manufacturing and construction









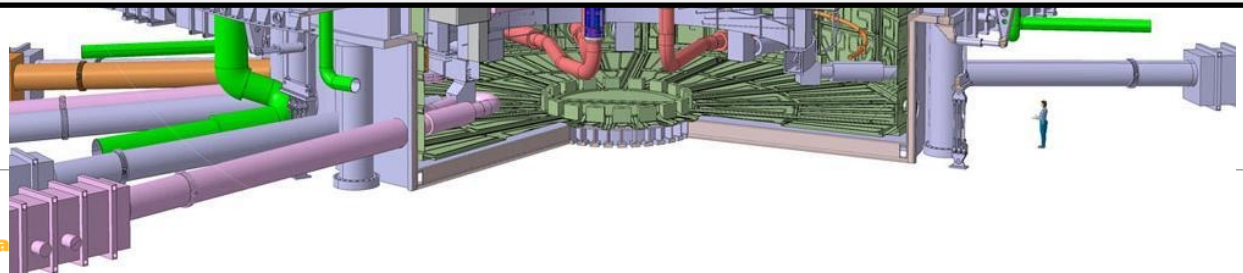
The ITER Control System

performs the

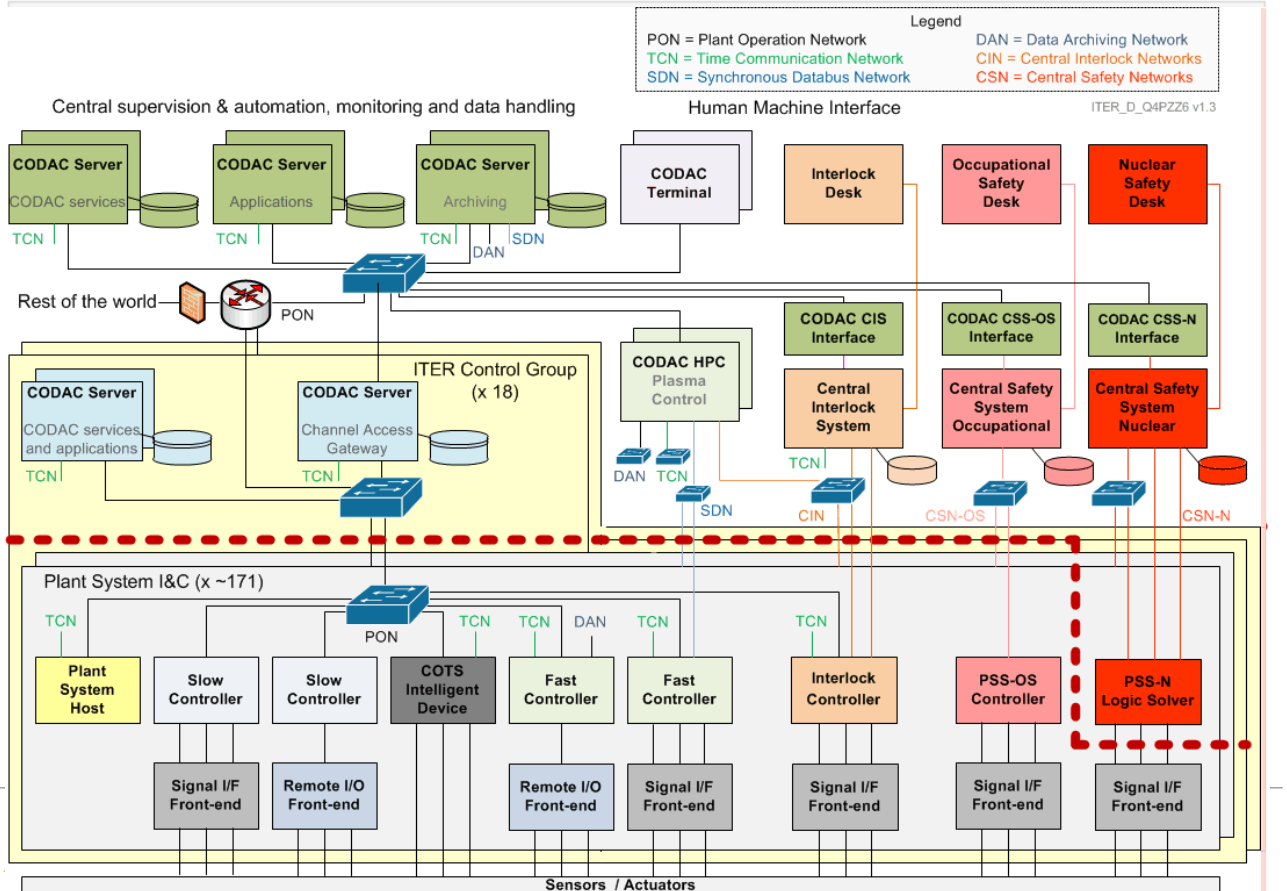
functional integration of the ITER plant

and enables

integrated and automated operation



ITER Control System Architecture



Pulse Operation Dataflow

ITER is operated in pulse mode, with a pulse duration between 100 ms and one hour.

All configuration parameters for a pulse are defined in advance by the scientist using the Scheduler system.

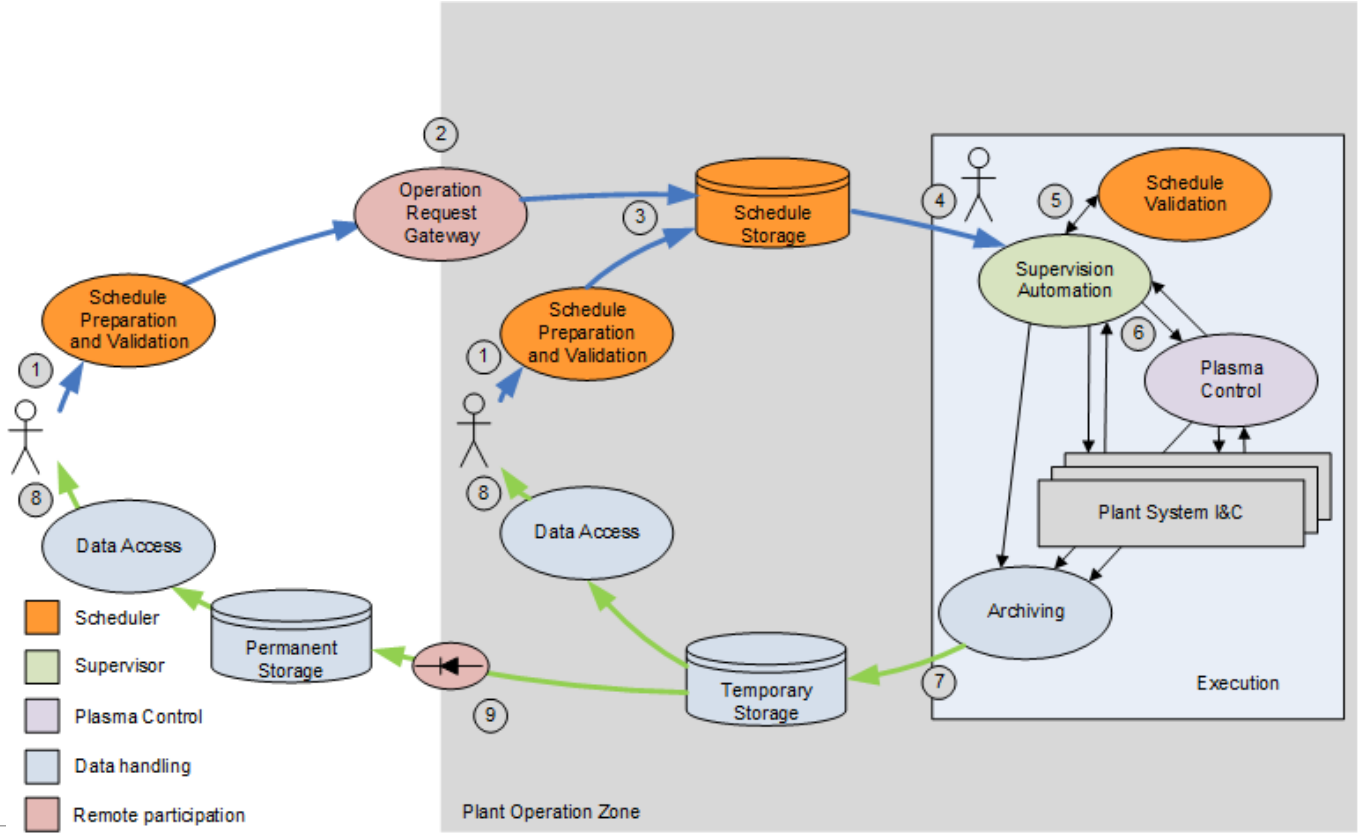
The Shift Operation Manager fetches a schedule from the storage for execution (validation, configuration of systems and pulse countdown)

The plasma control system executes the pulse

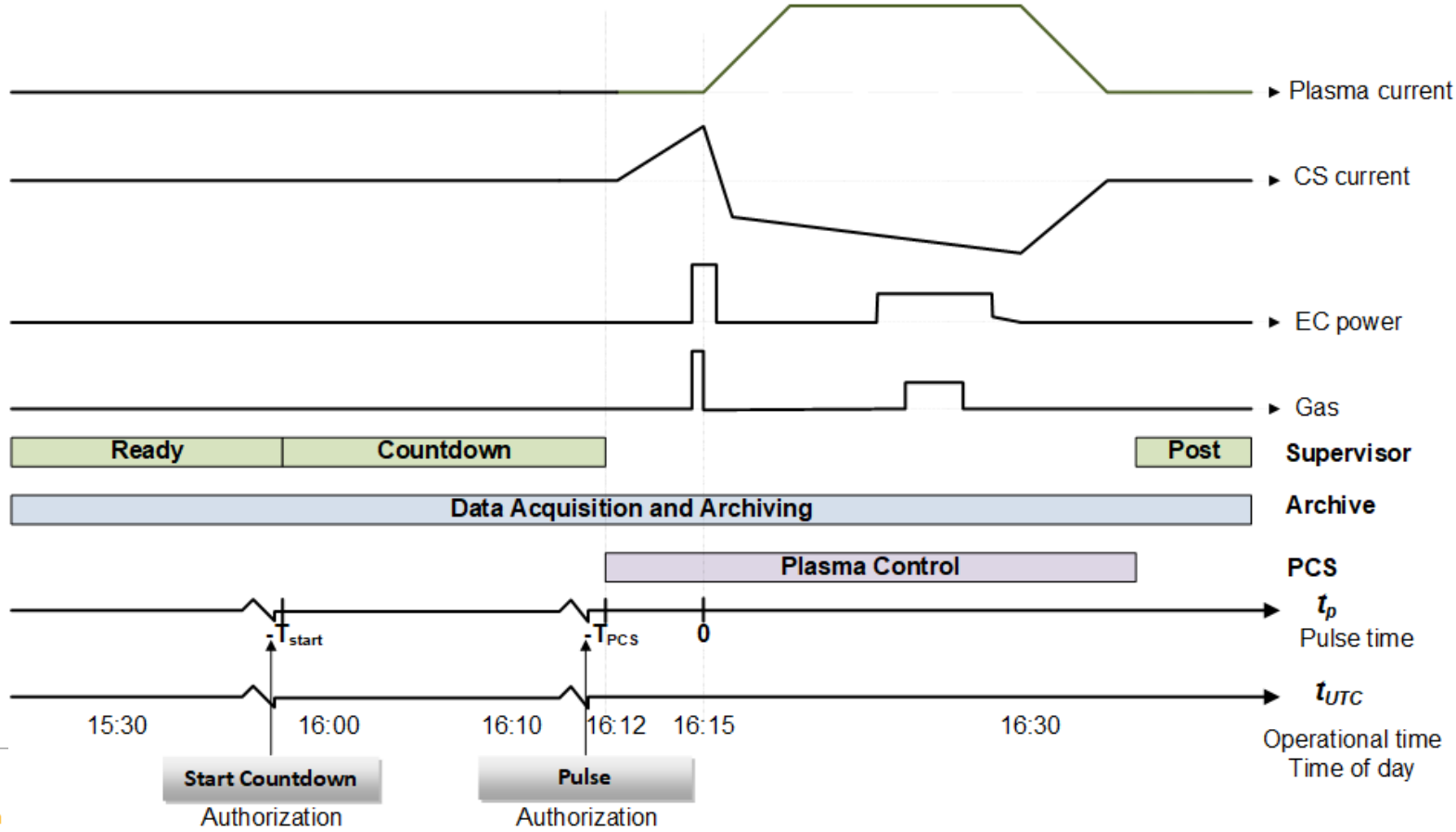
The data handling system acquires, streams, pipelines and archives the data.

The scientist access and analyze the data

Support for remote participation is provided by the operation gateway and data diode.



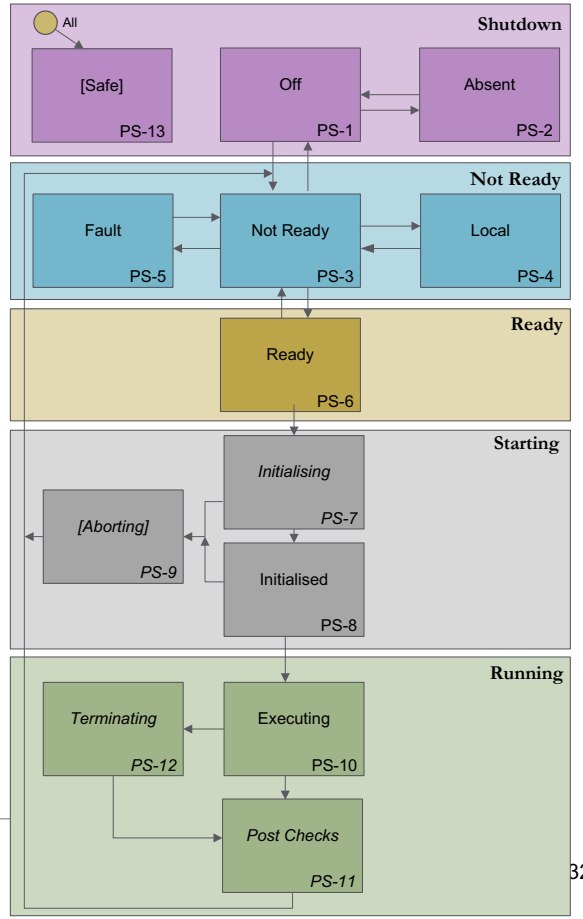
Pulse Operation Timing Diagram



Control System Functions

Coordination

- Coordinate all systems described previously to operate in an integrated fashion
- Control System to ensure every system reports its synthetic state using one of the following five states (Common Operation State)
  - **Shutdown**
  - **Not Ready**
  - **Ready**
  - **Starting**
  - **Running**
- The composite of all states from required systems allows the operator to know the ITER state at a glance and to allow the system to decide if the next actions are permissible or not

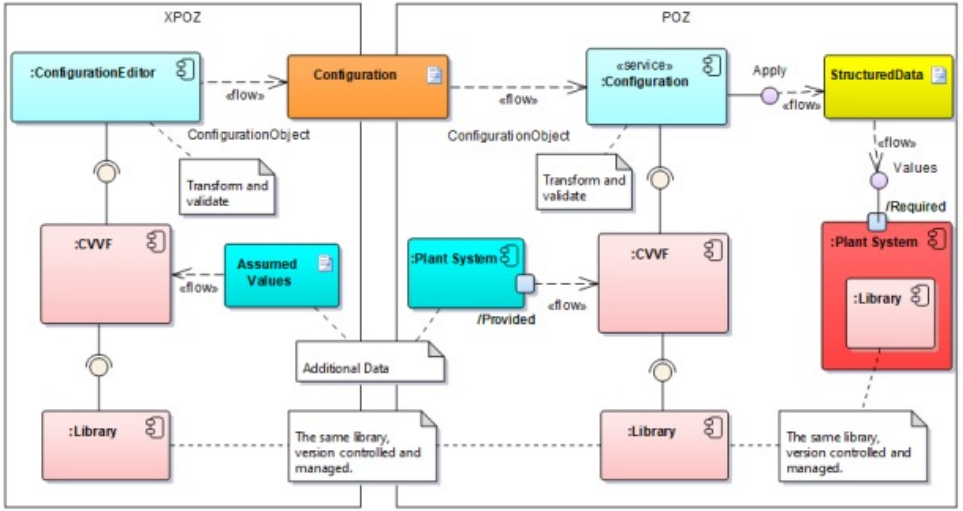


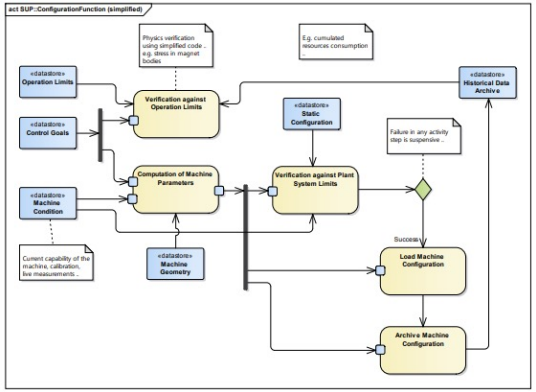
Control System Functions

Configuration

- Configure all parameters required to perform an experiment

- Control System must
  - Provide interface to scientist to specify the experiment information
  - Derive machine parameters from planned experiment information in the schedule
  - Conduct multi-stage engineering verification
  - Load machine parameters in the plant systems as part of the experiment preparation

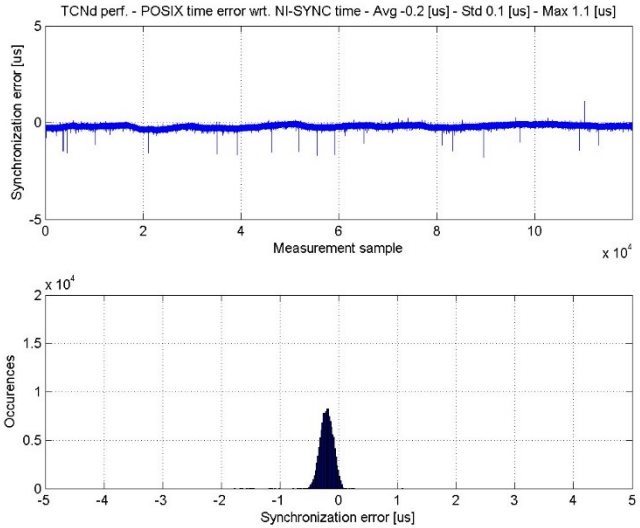


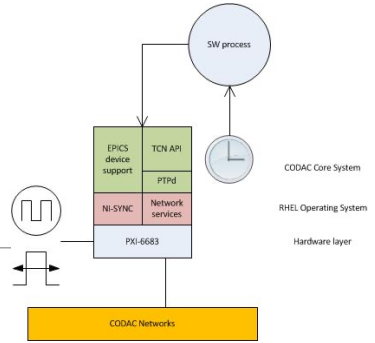


Control System Functions

Synchronization

- Synchronize all systems to start actions at the right time and to time stamp data consistently
- Control System must ensure actions on different systems are synchronized, distributed feedback control loops are synchronized and data from different systems can be correlated
- The ITER timing system distributes absolute time to all systems on the platform with an accuracy in the sub µs range





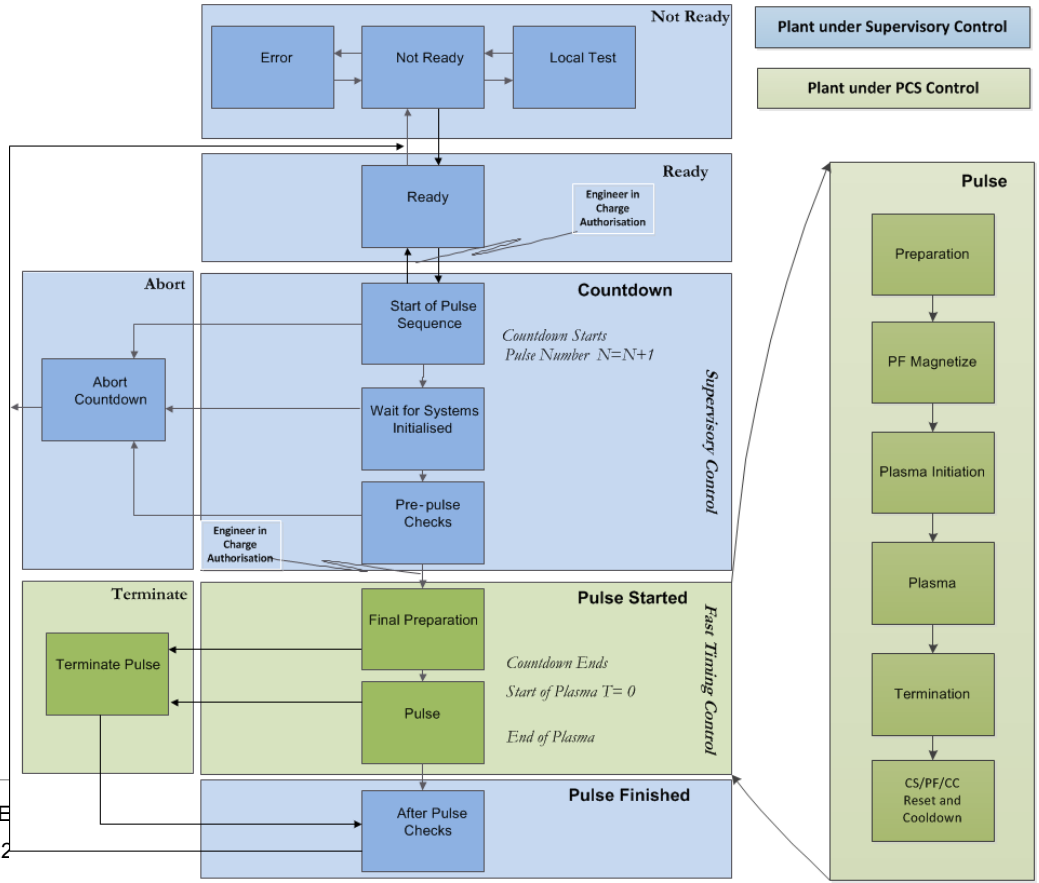
Control System Functions

Sequencing

- Sequence the systems in the right order to execute plasma pulse, cool-down, baking, glow discharge cleaning, etc.

Example pulse execution using plasma operation state:

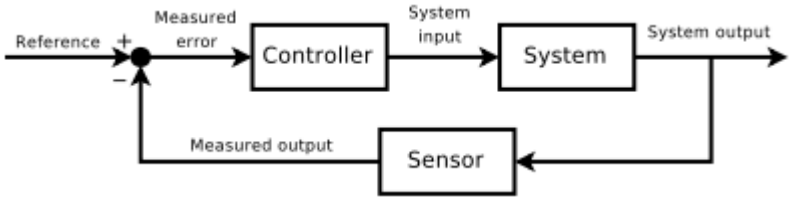
- **Supervisor**
  - Controls operations
  - Performs pre-pulse checks and countdown to pulse
  - Passes control to the PCS
- **Plasma Control System (PCS)**
  - Performs final pre-pulse checks
  - Begins pulse energizing CS/PF
  - Performs plasma initiation, ramp-up, flattop, ramp-down
  - After plasma termination, controls CS/PF currents to zero
  - Returns control to Supervisor

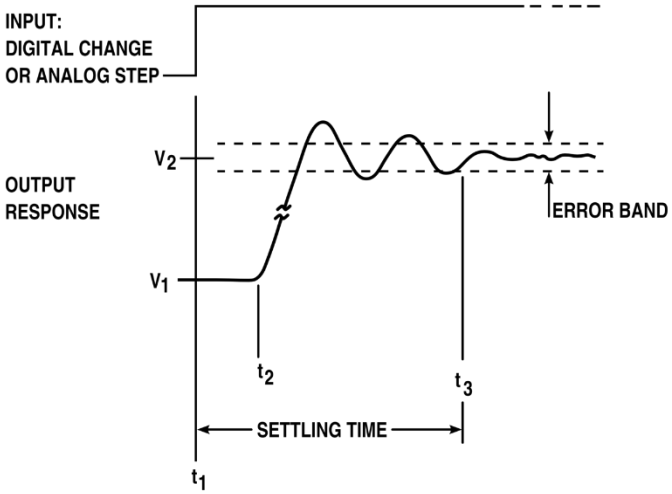


Control System Functions

Feedback control

- Feedback control is everywhere, locally and globally
  - Open/close a valve
  - Start/run a pump
  - Drive a current
  - Drive a flow
  - Plasma control
  - …
- Control System needs sensors, actuators and control laws
- Control System needs sampling rates ~10 times larger than the control bandwidth

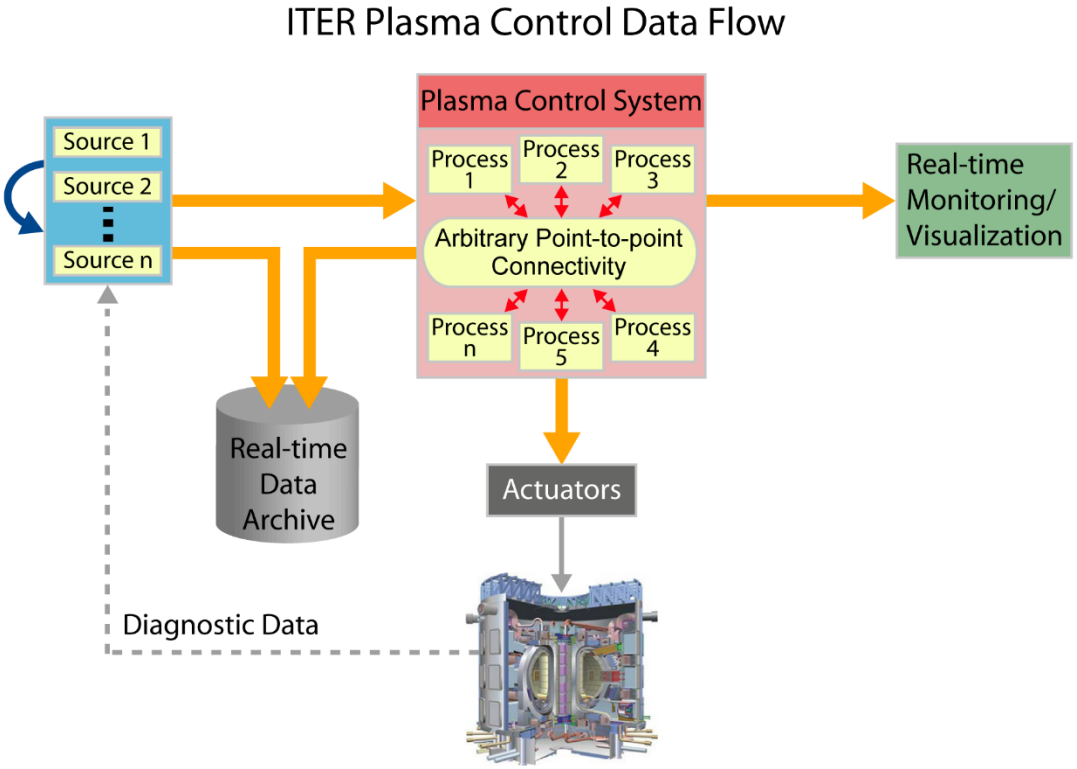




Control System Functions

Plasma control

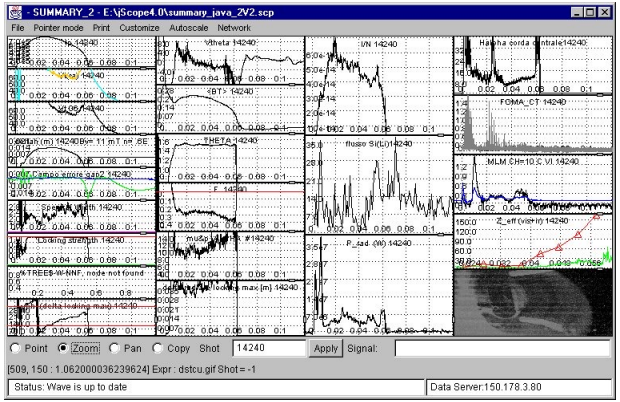
- Control the plasma
  - Current
  - Shape
  - Density
  - Disturbances
  - Disruption avoidance
  - …
- **Sensors:**
  - Diagnostics
- **Actuators:**
  - Coil Power Supplies
  - Fuelling
  - Heating

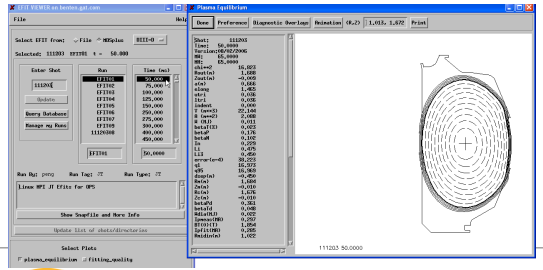


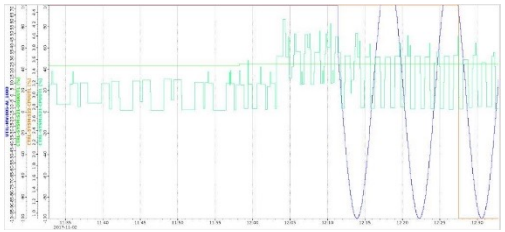
Control System Functions

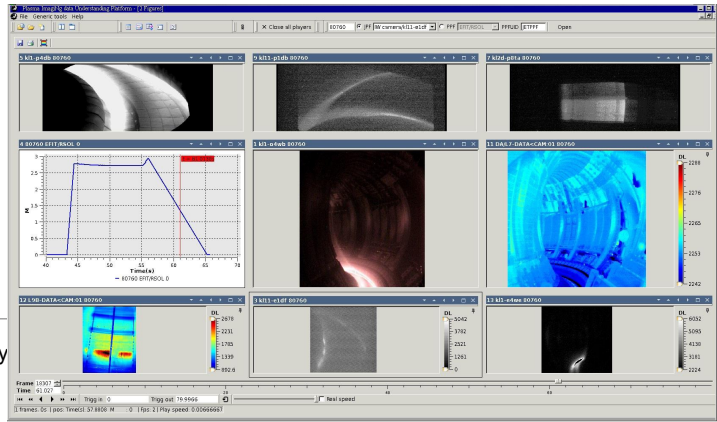
Data Handling

- **Data, not energy, is the deliverable of ITER**
- Collect, archive and give access to all data produced.
- **All archived data are stored in HDF5**
- Control system needs to ensure all data are acquired and safely archived and provide access to this data for understanding what is happening and to scientifically explore ITER



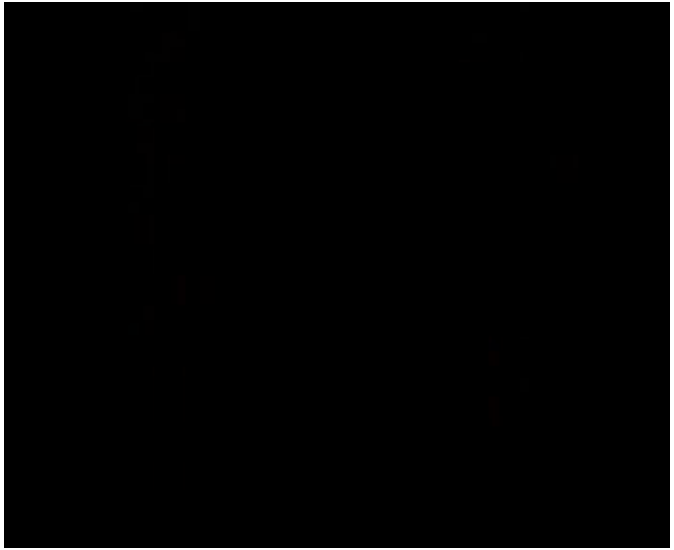


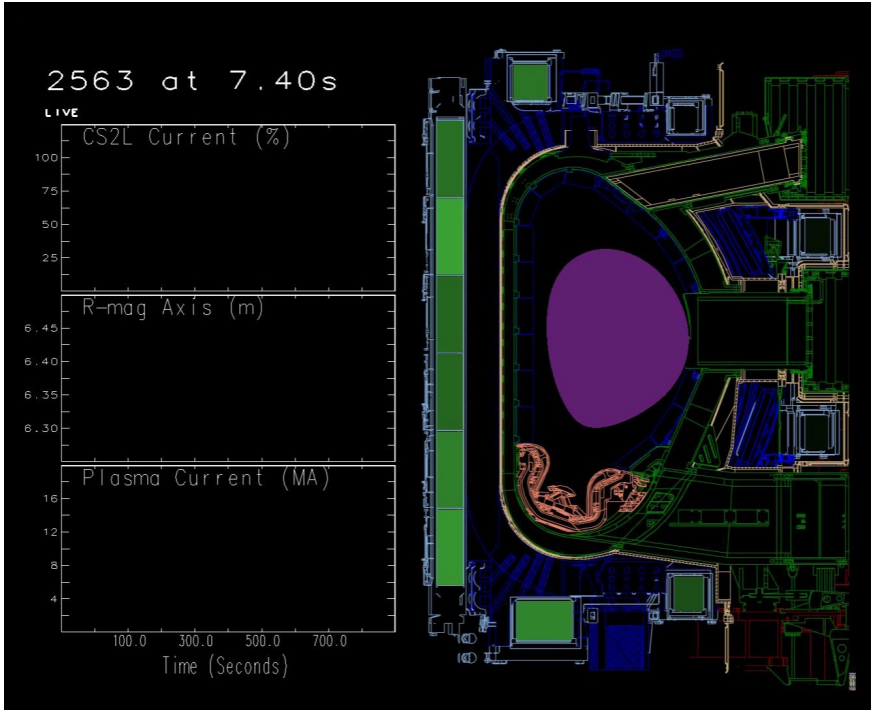




Control System Functions

Real-time visualization

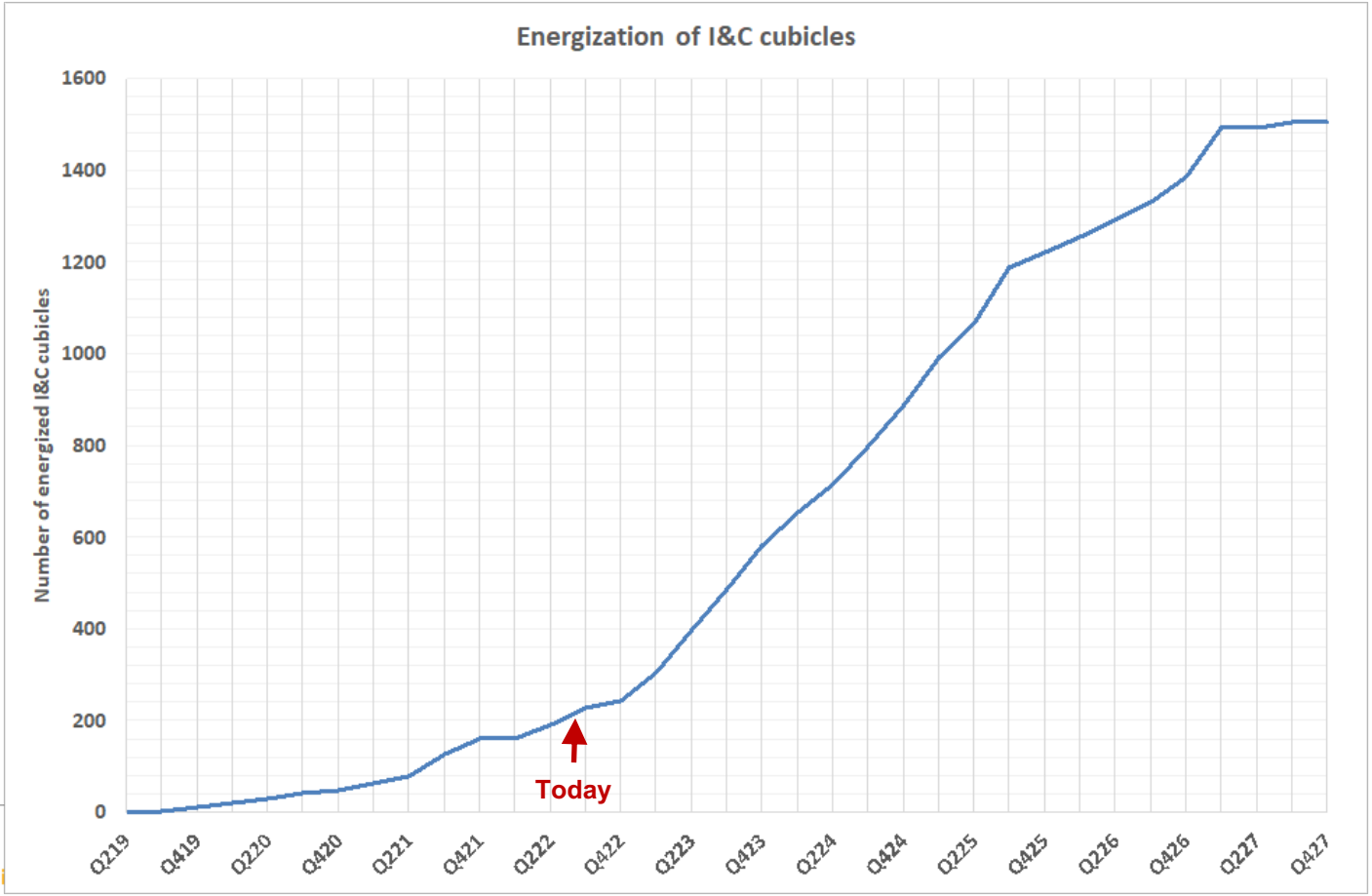




Some Control System Key Parameters

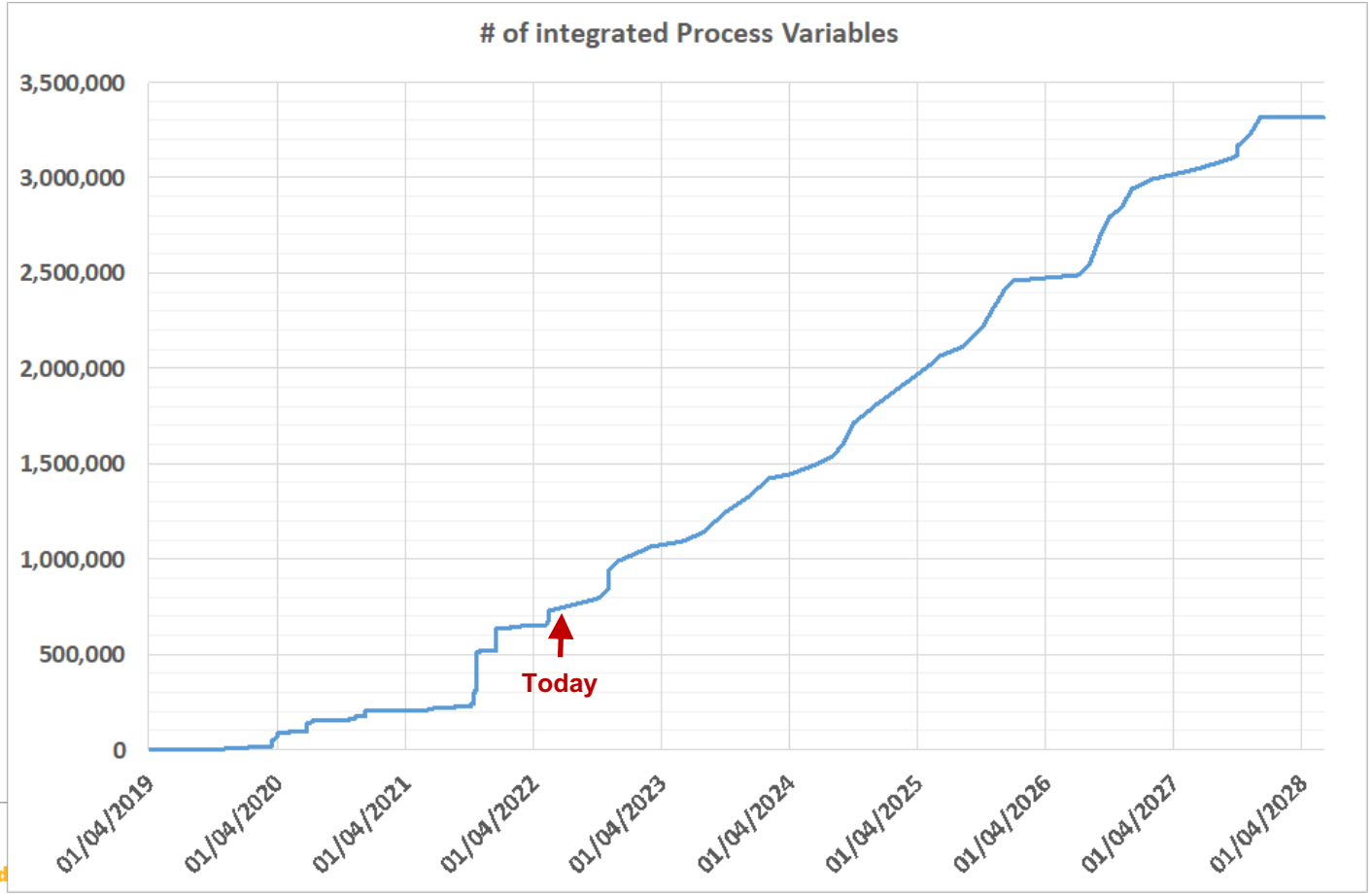
Parameter	Value
Total number of I&C cubicles/racks	~3.000
Total number of plant I&C signals (wires)	>300.000
Total number of process variables (PV)	>5.000.000
Total number of active operator stations	>100
Number of central-plant I&C interfaces	330
I&C cables (sensors/actuators to controllers)	6000 km
Multi-core single mode fiber optic network cables	300 km
Multi-pair copper network cables	170 km
Number of identified machine protection I&C functions	150
Number of identified nuclear safety I&C functions	252
Maximum sustained data flow on plant operation network	50 MB/s
Total archive capacity	90-2200 TB/day
Accuracy of time synchronization	<50 ns RMS
Maximum communication latency sensor to actuator node (real-time network)	50 µs

Metrics (hardware)



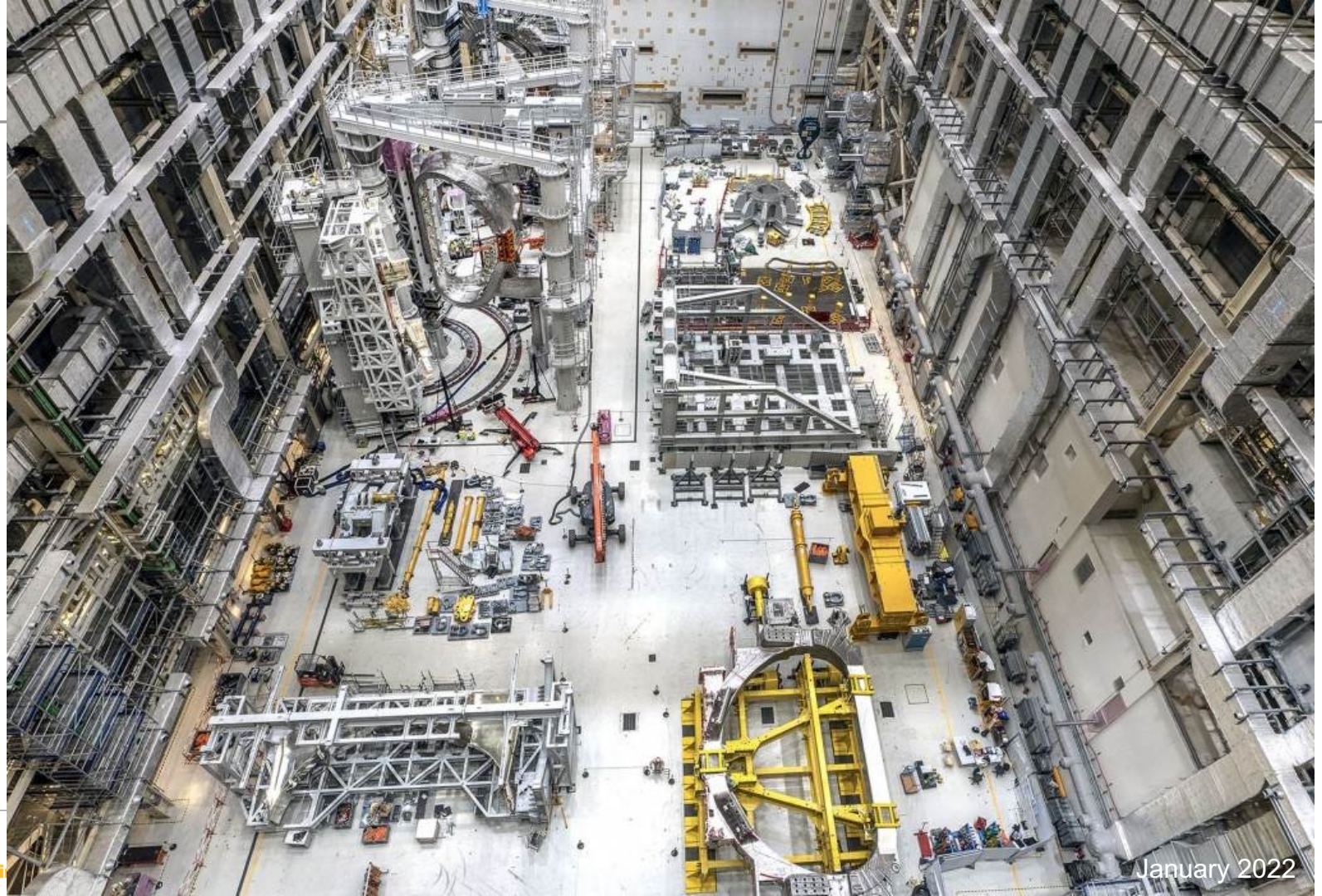
12% of first plasma scope complete

Metrics (software)



20% of first plasma scope complete

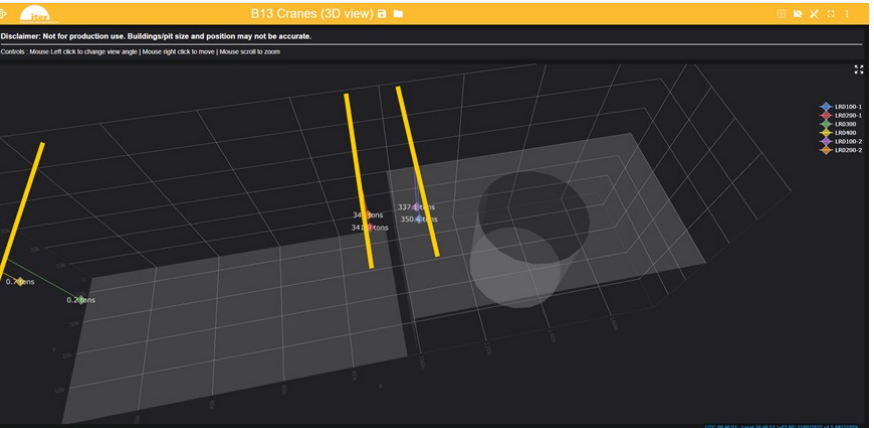
Some pictures from recent assembly activities

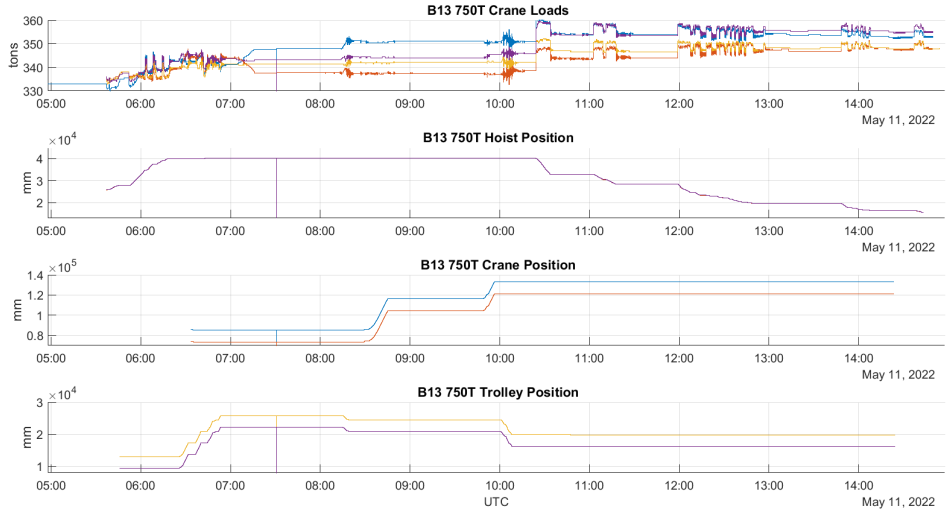



February 2022

The “Big Lift” May 11, 2022

- First out of nine subsectors lifted and installed in the Tokamak Pit
- A subsector consists of one 40^{o} vacuum vessel sector with thermal shield and two toroidal field coils weighting 1200 tonnes






9
8
4
3
2
1

Summary

- ITER can contribute to secure energy supply
- ITER construction towards first plasma 75 % complete
- ITER Control System is in design, construction, commissioning and operation

- ITER is producing (HDF5) data today