Introduction to Tokamak Operations

- Damian King & JET contributors
- Special Thanks to E. Belonohy, J. Mailloux, F. Rimini, D. Ciric and R. Olney for the material

UK Atomic Energy Authority

Background

Background in Tokamak Operations

2007- : NBI operations on JET & MAST

2012- : Heating & current drive physics, plasma and tokamak operations, plasma scenario development

2014- : Session leader (physics pilot) on JET with gradually increasing plasma current license

2016- : Scientific Co-Ordinator on multiple JET experiments related to beam-plasma relations, isotope physics and plasma scenarios

2016- : Operations Manager of JET NBI

2022- : Operations Manager of JET

Current role:

Operational Physics Team Leader, UKAEA

To Note

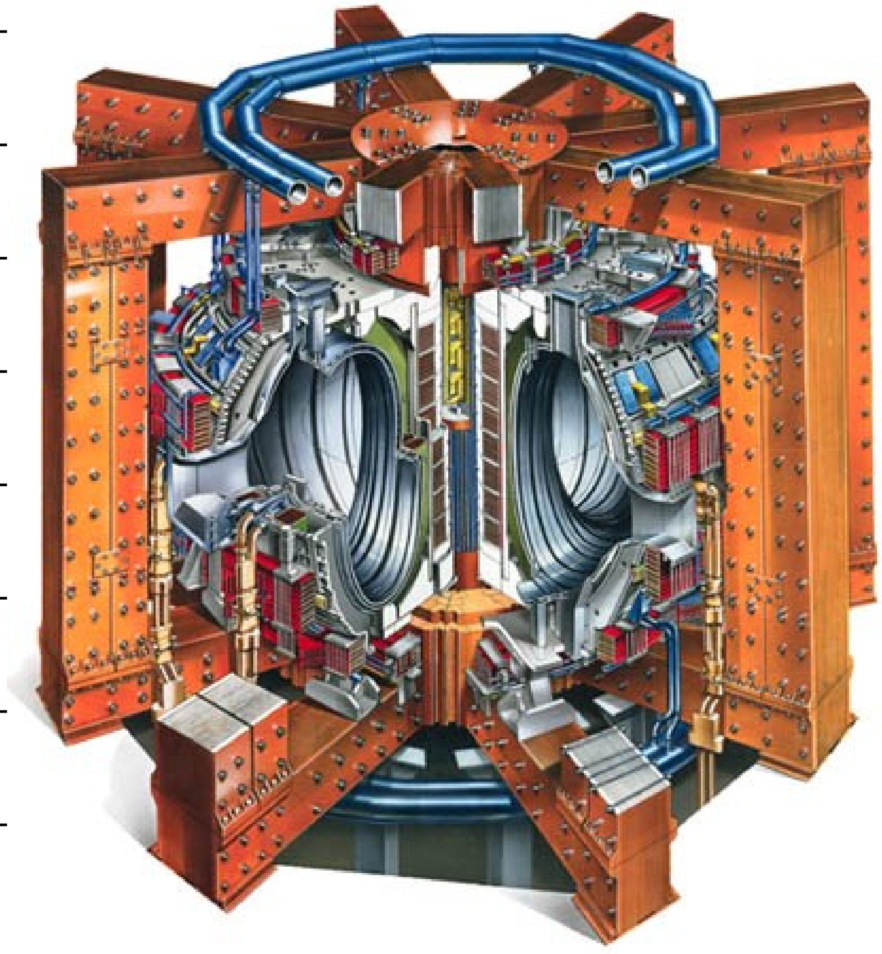
The material here is based on material already presented elsewhere.
If anyone wishes to use the material further, then please make a request to the author.

The material applies to the operation of large tokamaks and while it uses the JET experience as the primary example throughout it is of general application.

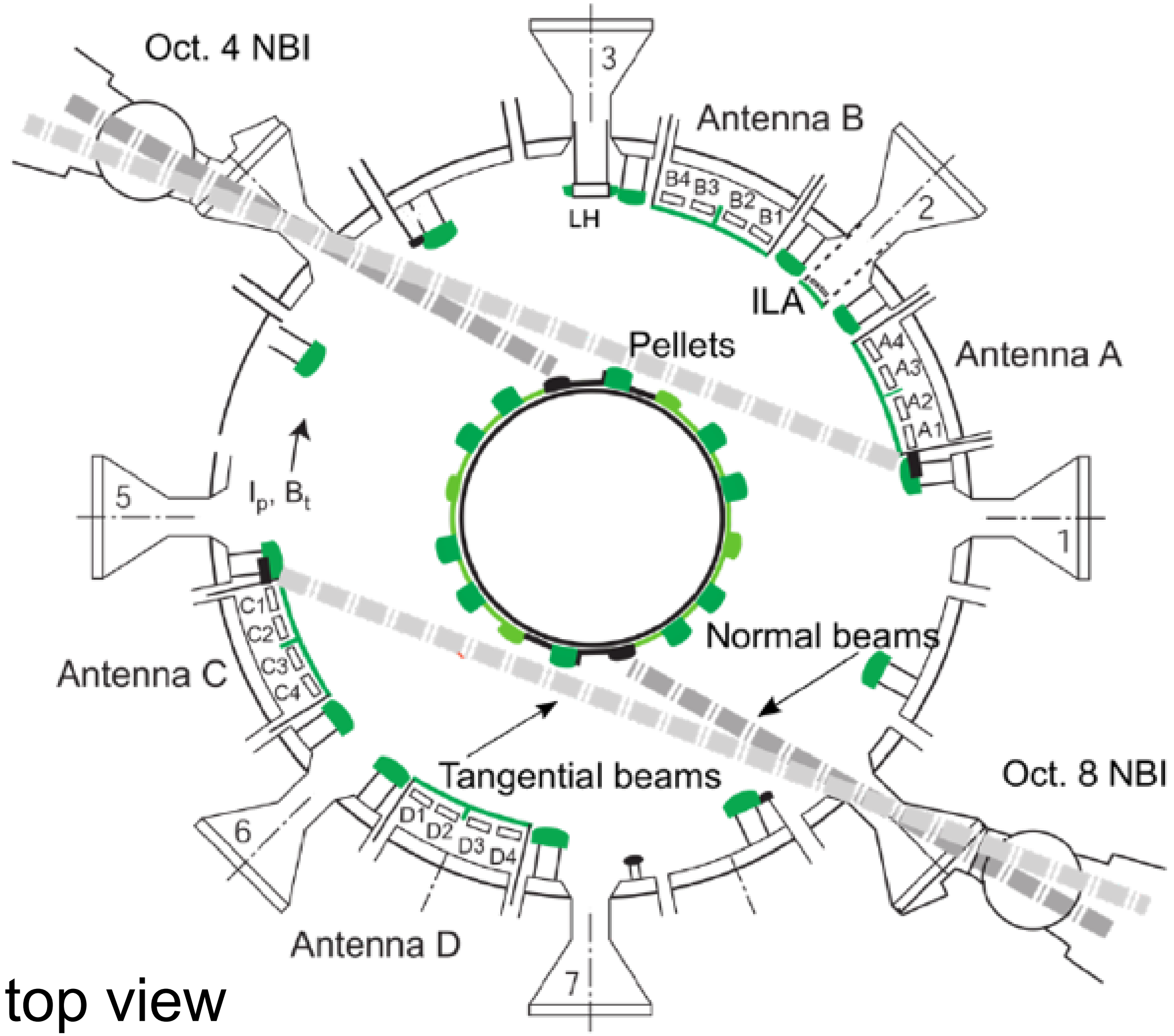
The operation of smaller tokamaks can be much simpler and can be scaled down accordingly to a consideration of the risks to the machines.

Quick reminder : JET Technical specs

Major / minor radius (m)	2.96 / ~0.8-0.9 (large aspect ratio)
Divertor	Single Null – Lower Divertor
Max plasma current (MA)	4.5 (3.5 in DTE2)
Max toroidal field (T)	3.9
Discharge duration (s)	Up to 60s flat top
Main fuel	H / D / T / He
Extrinsic impurities (most common)	Ne, N (not in DT), Ar
Ion Cyclotron Heating	Up to ~ 6-8MW / 25-56 MHz
Neutral Beam Injection	≤ 34 MW (D / T) ≤10 MW (H) and < 15 MW (He)



Additional Heating at JET



top view of JET

Neutral Beam Injection
+
Ion Cyclotron Resonance Heating

note : Lower Hybrid Current Drive system was mothballed

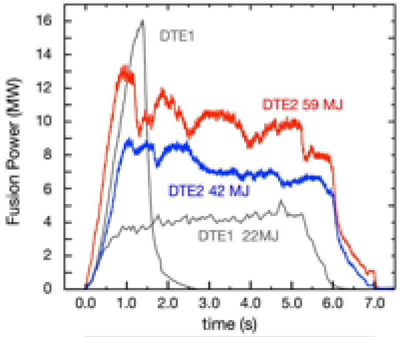
Outline

1. **Fusion Product Lifecyle**
2. Operation of small, medium and large tokamaks
3. Boundary operating conditions and special operations
4. Operator roles and setting up a plasma discharge

What is tokamak operations?

Physics → **Operations** ← **Engineering**

Operation involves all activities following the manufacturing of a plant system, particularly plant commissioning (individual), integrated commissioning (joint), routine operation, maintenance, repair of various plant/hardware and software systems.



M. Maslov et al., accepted for publication in Nuclear Fusion

J. Hobirk et al., accepted for publication in Nuclear Fusion

Objectives:

1. Provide the best conditions and most time for experiments

- High operational reliability and performance (-> JET had 80% availability in sessions)
- Plant performance increase (-> increase heating power, pellet survivor)
- Improve plasma reliability and performance (-> breakdown, scenario development)

2. Do the experiments well – achieve scientific targets, many pulses

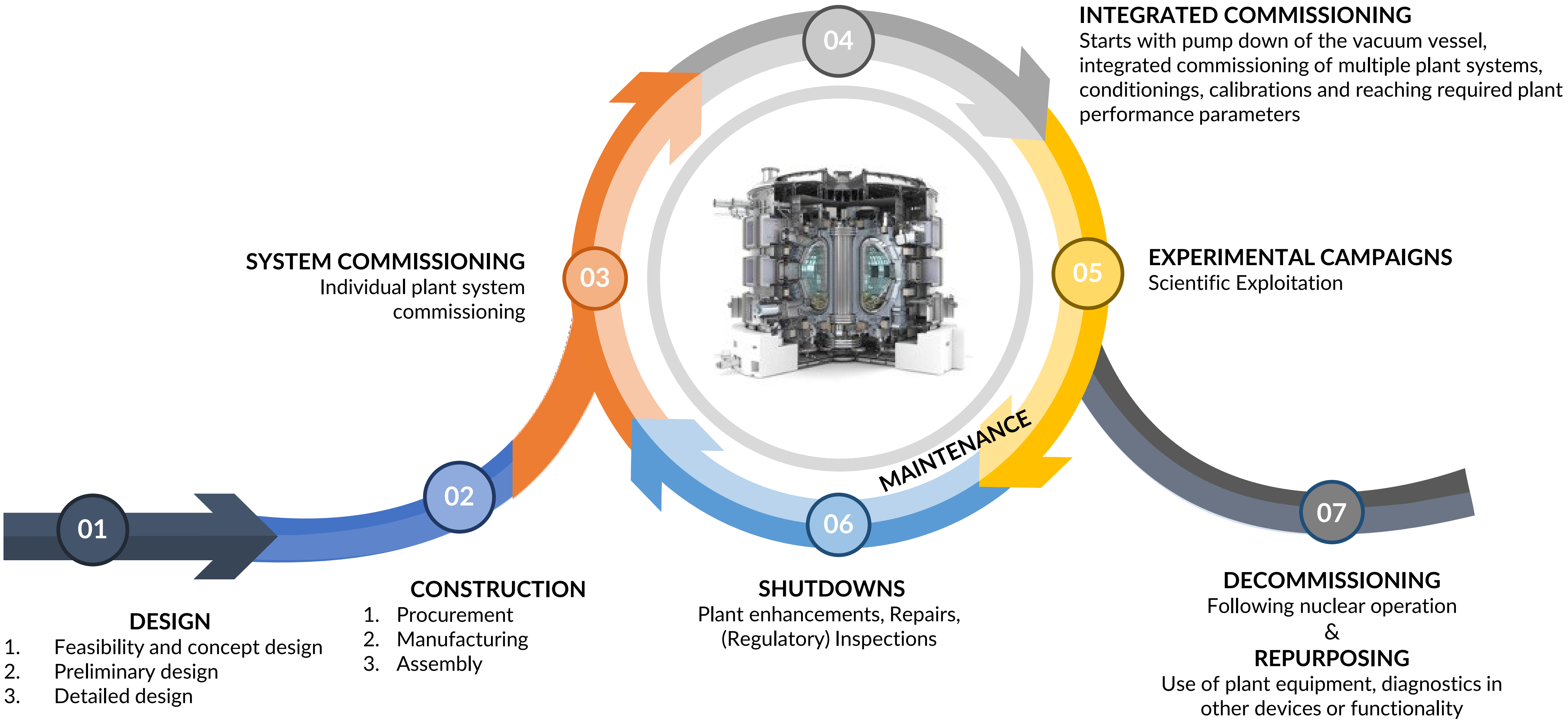
- Achieve the objectives of the scientific experiment with the least number of pulses
- Stay within machine and plasma constraints (operating limits, protection systems)
- Quick, accurate diagnoses of plasma and plant, improve next discharge

3. Do the experiments safely

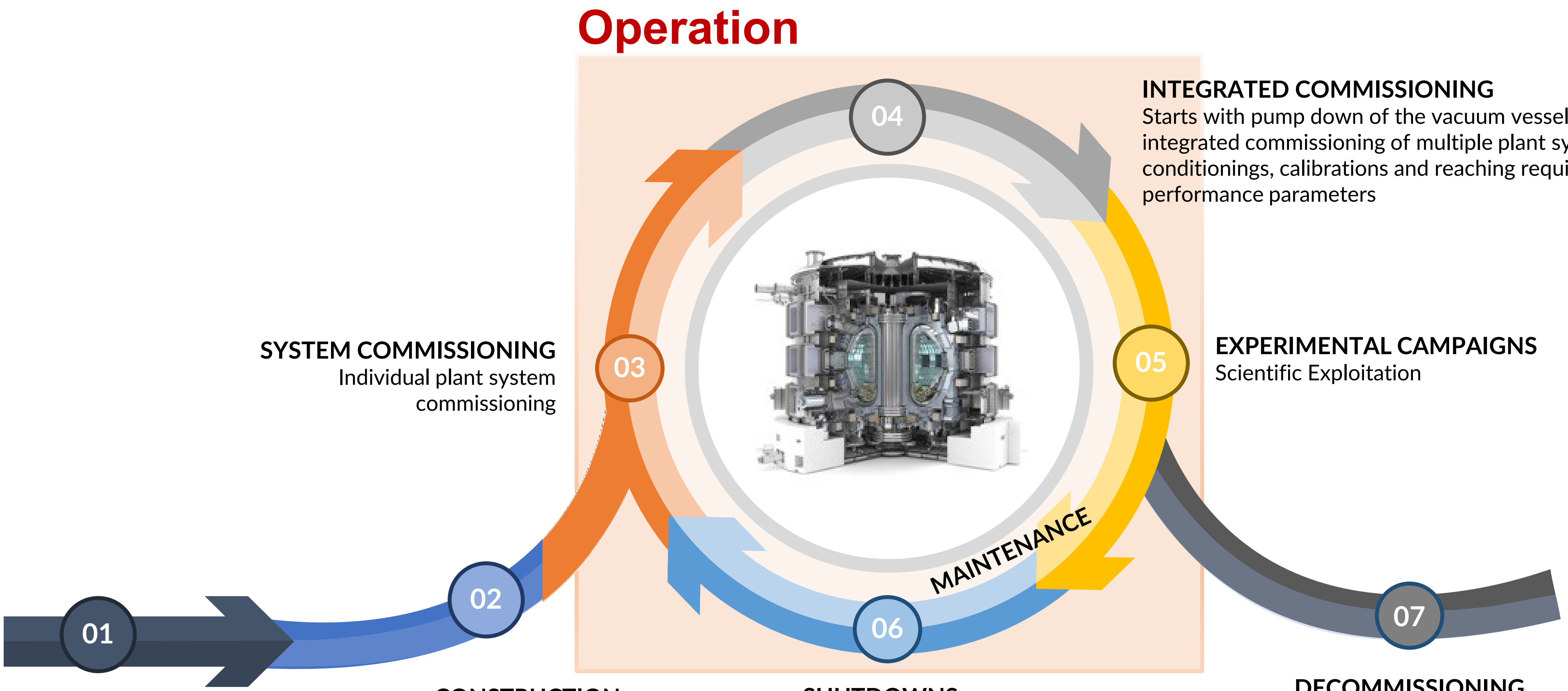
- Protect the machine and the personnel

Product Lifecycle Management (PLM) – Planned phases

EUROfusion



Product Lifecycle Management (PLM) – Planned phases



INTEGRATED COMMISSIONING
Starts with pump down of the vacuum vessel, integrated commissioning of multiple plant systems, conditionings, calibrations and reaching required plant performance parameters

SYSTEM COMMISSIONING
Individual plant system commissioning

EXPERIMENTAL CAMPAIGNS
Scientific Exploitation

DESIGN
1. Feasibility and concept design
2. Preliminary design
3. Detailed design

CONSTRUCTION
1. Procurement
2. Manufacturing
3. Assembly

SHUTDOWNS
Plant enhancements, Repairs, (Regulatory) Inspections

DECOMMISSIONING
Following nuclear operation
&
REPURPOSING
Use of plant equipment, diagnostics in other devices or functionality

Product Lifecycle Management (PLM) – JET

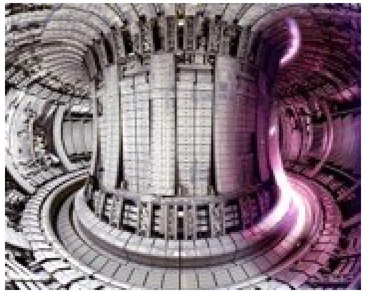
EUROfusion

Joint European Torus (JET)

- Joint European experiment funded by the European Commission
- 40 years of operations
- Originally planned for 10 years
- 100k+ pulses (>10万）

We wish JT-60SA similar or more success!
頑張ってください!

25/6/1983 – 1st JET plasma



01
1973 -

DESIGN
1. Feasibility and concept design
2. Preliminary design
3. Detailed design

02
1977 -

CONSTRUCTION
1. Procurement
2. Manufacturing
3. Assembly

03

SYSTEM COMMISSIONING
Individual plant system commissioning

04

INTEGRATED COMMISSIONING
Starts with pump down of the vacuum vessel, integrated commissioning of multiple plant systems, conditionings, calibrations and reaching required plant performance parameters

“Restart” – 8-24 weeks

05

EXPERIMENTAL CAMPAIGNS
Scientific Exploitation

1983 – 2023
42 campaigns in 23 years

MAINTENANCE

06

SHUTDOWNS
Plant enhancements, Repairs, (Regulatory) Inspections

Few months – 2 years

07

DECOMMISSIONING
Following nuclear operation
&
REPURPOSING
Use of plant equipment, diagnostics in other devices or functionality

2024 – (2036)
12 years
17 projects

Operational considerations in Design and Construction

Design phase

- Scope, requirements, scenarios
- Component design and <u>interfaces</u>
- Engineering assessments

→ Complete and precise physical description & specification of all the components including the geometry, materials, and tolerances of all the parts through the provision of detail (assembly) drawings.

⇩⇧

- Accessibility and maintainability of components,
- RAMI analysis, maintenance requirements (frequency, regulatory requirements like pressure vessel inspections), potential fault recovery routes
- Engineering and Operating limits
- Components required by safety and protection considerations.

Construction and Assembly Phase

- Visual inspections
- pressure/flow/leak tests
- Electrical testing, connections, insulation
- Mechanical connections, welding

⇩

- Quality of the components and assembly
- Issues can cause faults and damage during future commissioning and campaign operations.

Commissioning – JET

- Preparation for the JET restart usually starts one year before the actual restart with the appointment of the Restart Management Team (Ops manager, Chief Engineer, Planner, …)
- Duration examples:
  - 8 weeks (minor intervention on the machine)
  - 24 weeks (major shutdown which includes major modification of the machine).

Commissioning plan - establish activities, order, dependencies and the duration of various restart tasks, as well as the critical path. Plasma activity plan is separate.

- Takes a few months to prepare. Approved by senior management including representative unit of the European Commission.
- Live document. Updated daily during Restart at 1.30pm meeting
  incl. (senior) managers to make decisions, sign forms, (re)allocate resources.

Commissioning procedures: ~ 250 separate procedures

- Categories:
  1. related to Key Safety Related Equipment (KSRE),
  2. related to machine Integrated Operational Protection Systems (IOPS)
  3. related to other systems

Commissioning – JET Key Machine Elements

- The commissioning/restart on JET has many elements
- Developing a commissioning plan for a large, complex fusion facility is a unique and difficult process
- Many people focus on the first plasma activities but before that can begin many more required
- JET restart timeline often driven by water, cryo, heating systems, particularly those with sequential dependencies

- Plasma and Heating Systems require water, vacuum, cryogenic, diagnostic, CODAC, safety subsystems

- Rough sequence:
  - Basic building services (power, compressed air…)
  - Safety systems and interlocks (~weeks of work)
  - Machine cooling, water systems can take weeks and interact with safety commissioning
  - Coil commissioning (offline) – requires all the above
  - Cryogenic systems need the water cooling to function
  - First plasma, heating systems and diagnostics can begin when above complete
  - Integrated commissioning of the above as available but with strong interaction

Upcoming paper by H. Sun will show this process

Commissioning – JET/MAST-U

EUROfusion

Commissioning procedures

- Clarify requirements
- Ensure all interfaces have been consulted/confirmed
- Confirming required processes were followed (forms, risk assessment)
- Step by step process
- Record experience and any non-corformity
- Signed completion. ”Ready for operations”

UK Atomic Energy Authority

CCFE

MAST-U FACILITY COMMISSIONING PROCEDURE

On completion of the tasks listed in this document the Readiness for Operation (Section F) form must be completed.

Procedure status: Existing ☐ Modified[1] ☐ New ☒	**System Category**
Procedure ID: MAST-U-SYS-SUB-nn-yyyy.v.docx	Safety ☐
Procedure title: Commissioning of the ...	Protection ☐
Estimated duration (days): Hold Point:	Other ☐

Work control

Is a Risk Assesment applicable to this work? Yes ☐ No ☐
Risk Assesment No:
Is a Work Authorisation Form required? Yes ☐ No ☐
WAF No:

Prerequisites[2]

Required services		MAST-U status	List of commissioned subsystems
Mains power ☐	Pulsed power ☐	BH sole access ☐	
PASS ☐	Cooling water ☐	BH locked ☐	
Compressed air ☐	Machine control ☐	Vacuum ☐	
DATAC ☐	Networks ☐	Plasma ☐	
Other (specify):			

Areas to be accessed during commissioning

Control Room ☐	Server Room ☐	North Annex Upper ☐	MAST-U PS Area ☐	NBI SW PS Area ☐
Block House ☐	TARDIS Room ☐	North Annex Lower ☐	ELM PS Area ☐	
Pit ☐	South Annex ☐	North Annex CO_2 ☐	NBI SS PS Area ☐	

Additional key resources required during commissioning[3]

Special requirements[4]

[1] Describe modifications in the Revision history table.
[2] Specify services (cooling, compressed air, etc.), MAST-U machine status and list subsystems that must be commissioned prior to this one. Details to be specified in sections B2 and D1 of this document.
[3] Specify names of the additional staff from other groups required to perform commissioning tasks.
[4] Specify any special requirements (e.g. access to Block House during machine operation, sole access, etc.).

The undersigned declare that this is an adequate procedure for the subsystem commissioning and that all interfaces' comments have been considered.

Author:	Reviewer[5]	Approved by[6]:
Name:	Name:	Name:
Signed:	Signed:	Signed:
Date:	Date:	Date:

[5] Reviewer is appointed by the MAST-U Coordination Meeting
[6] Relevant ATO Holder for safety related systems and MAST-U Programme Manager or nominee for all other systems.

Page 1 of 14 Issue: 2

Procedure Title: Commissioning of the ... Procedure ID: MAST-U-SYS-SUB-nn-yyyy.v.docx dd-mmm-yyyy

Revision history			
Issue	**Date**	**Author's name or e-mail**	**Comment**
1			New procedure

System[7]	Interface's name	Comments included	Signature
Machine Services		☐	
Vacuum Systems		☐	
Power Supplies		☐	
NBI		☐	
Machine Control		☐	
PASS		☐	
Machine Protection		☐	
Plasma Control		☐	
Diagnostics		☐	
DATAC and Networks		☐	
ATO Holder[8]		☐	
Chief Engineer[9]		☐	

[7] Adapt the list to suit the system being commissioned, i.e. delete if not required and add new item if not already in the list.
[8] Relevant ATO Holder is mandatory interface for safety systems
[9] MAST-U Chief Engineer is mandatory interface for machine protection systems

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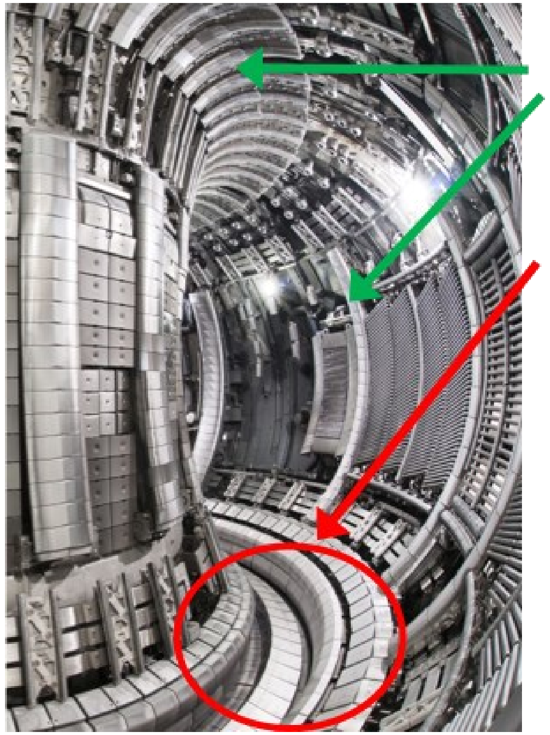
Maintenance and Shutdown

Maintenance

- Weekly, monthly, annual maintenance of equipment and building including regulatory inspections (pressure vessel, electricity grid, radiation monitoring).
- Conducted by the operational team, dedicated maintenance teams and/or can involve external parties.
- In some cases, timing can be adjusted to fit the operational schedule, in rare cases timing is non-negotiable.

Enhancements during Shutdowns

- Usually take 6-12 months and focus on installation of new equipment, diagnostics, plant systems or upgrade of existing infrastructure or repair of known faults.
- Examples of enhancements:
    - Diagnostic installation/upgrade
    - Heating systems and power supply upgrades
    - Installation of a (W) divertor, (Be) inner wall
- Shutdown Management team is often separate from the Commissioning Management team.
- Can endure long delays (50%+).



Beryllium in main chamber

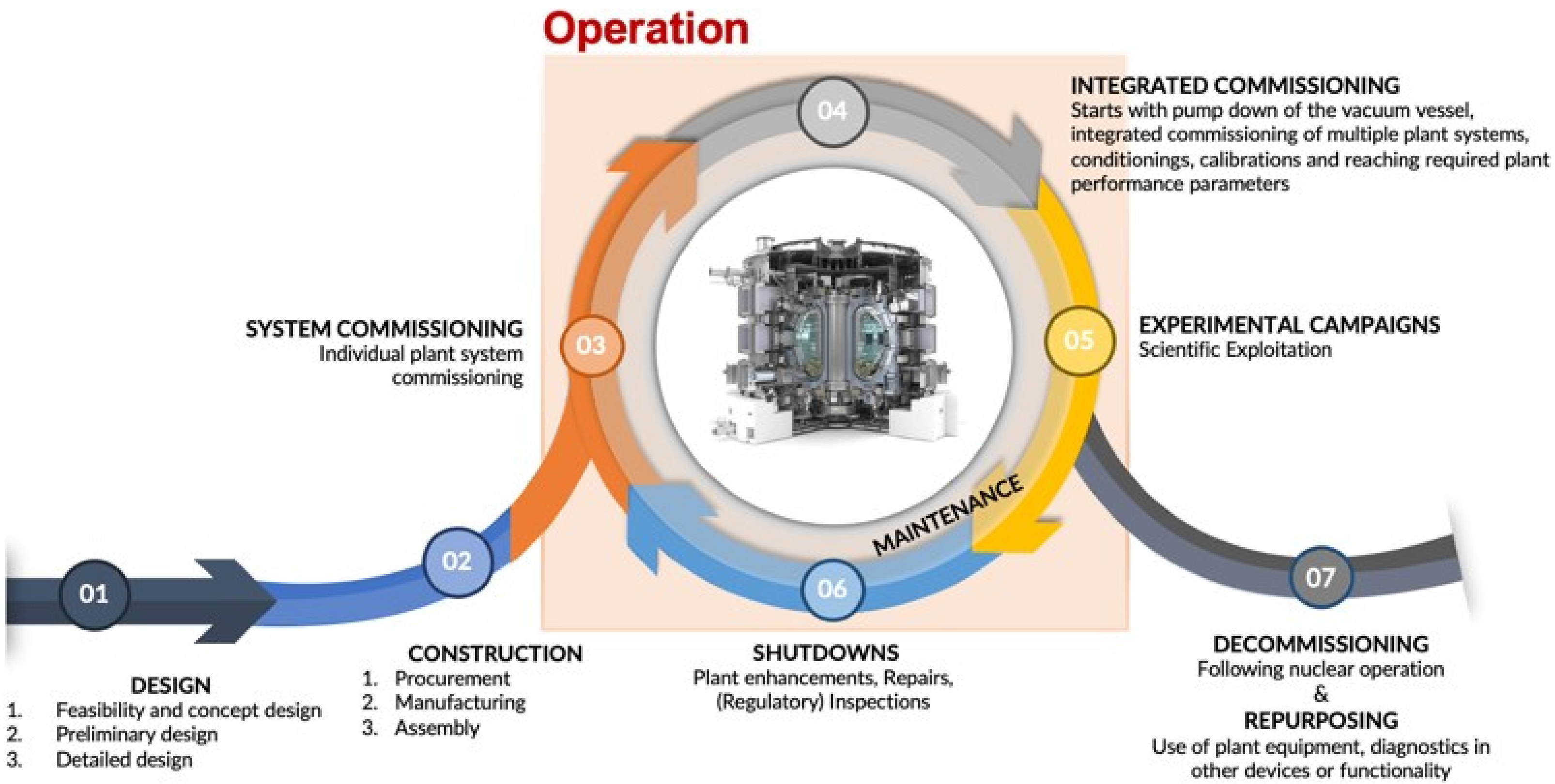
Tungsten (bulk and coatings) in lower divertor and some high flux Inner wall areas

wall NOT actively cooled

JET lifecycle (2000-2018)

Q. What do you think, how much time is spent on shutdown and restart activities?

- Restart (phase 3 & 4 system and integrated commissioning)
- Campaigns
- Shutdow



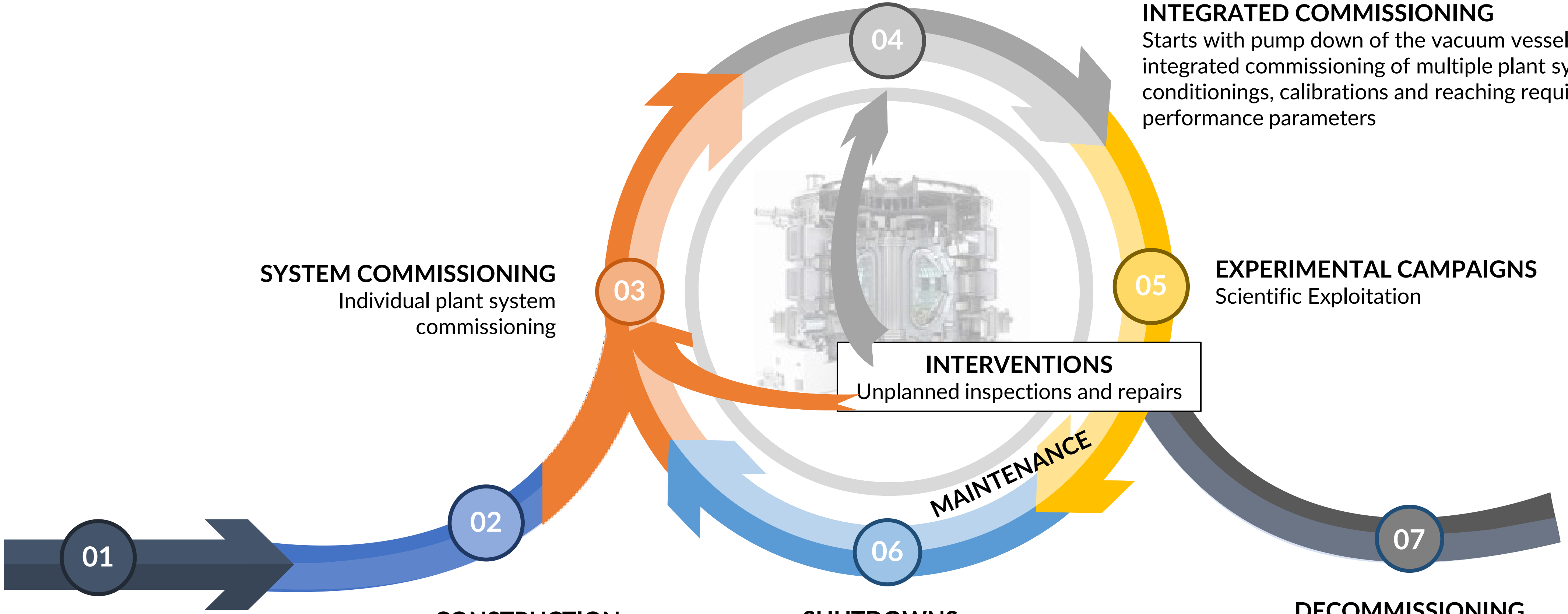
JET lifecycle (2000-2018)

Q. What do you think, how much time is spent on shutdown and restart activities?

- Restart (phase 3 & 4 system and integrated commissioning)
- Campaigns
- Shutdown

[G. Sips et al. (2018)]

Product Lifecycle Management (PLM) – "Unplanned" phases



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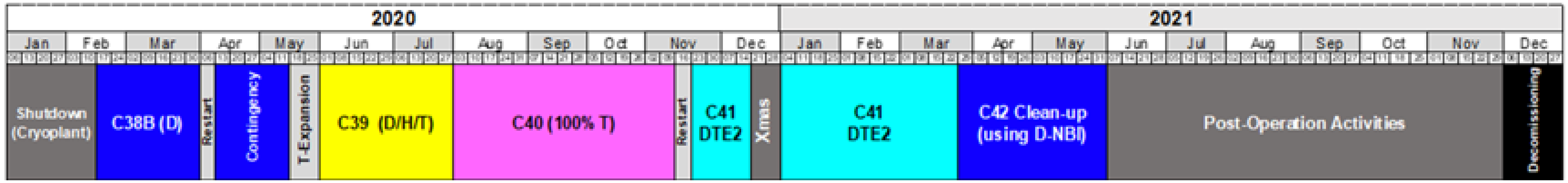
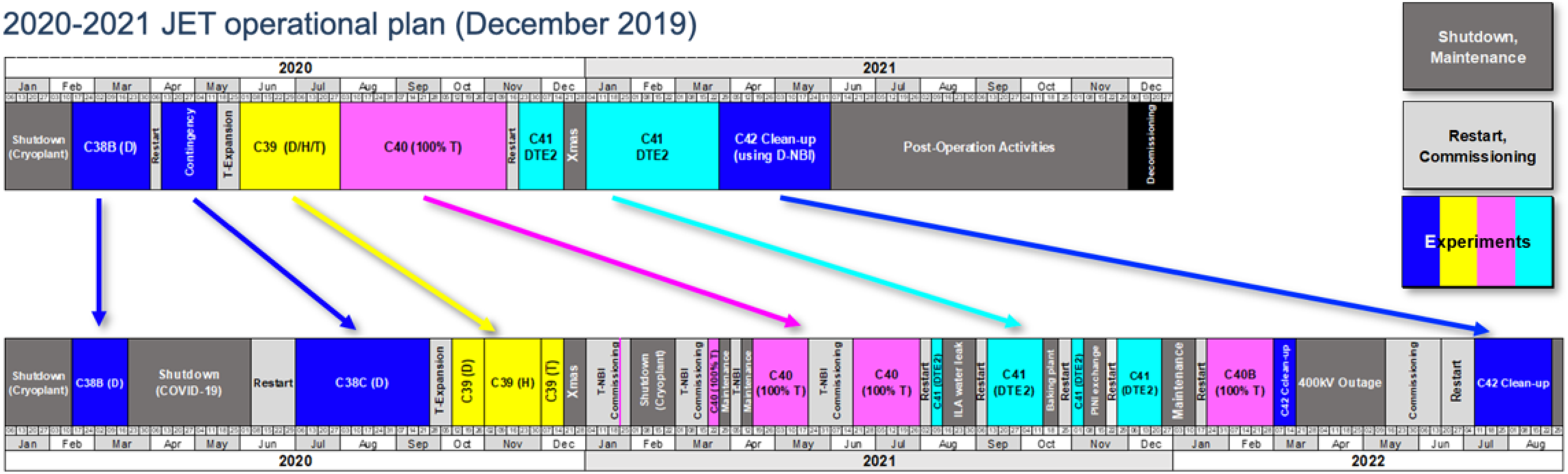
Product Lifecycle Management – Plan vs. Reality

2020-2021 JET operational plan (December 2019)



Product Lifecycle Management – Plan vs. Reality

EUROfusion



Delay of the start of T-NBI commissioning (~2 months)

T-NBI commissioning (~4 months)

Major delays:

ILA water leak (4 weeks)

Baking plant water leak (2 weeks)

PINI exchange (3 weeks)

JET

D Ćirić | SOFE 2023, Oxford, UK | 13 July 2023 | Page 21

Interventions – Major faults

Go to video 1

Q. Can you guess what happened here?

Interventions – Major faults

Major faults/incidents are often well remembered.

- Water leaks
- Oxygen leak during GDC
- Falling tiles (or reciprocating probe)

They often require stopping operation for several weeks as well as repeating the vacuum conditioning of the vessel (depends if the torus was exposed to air).

JET reciprocating probe falling into JET and getting stuck between divertor tiles

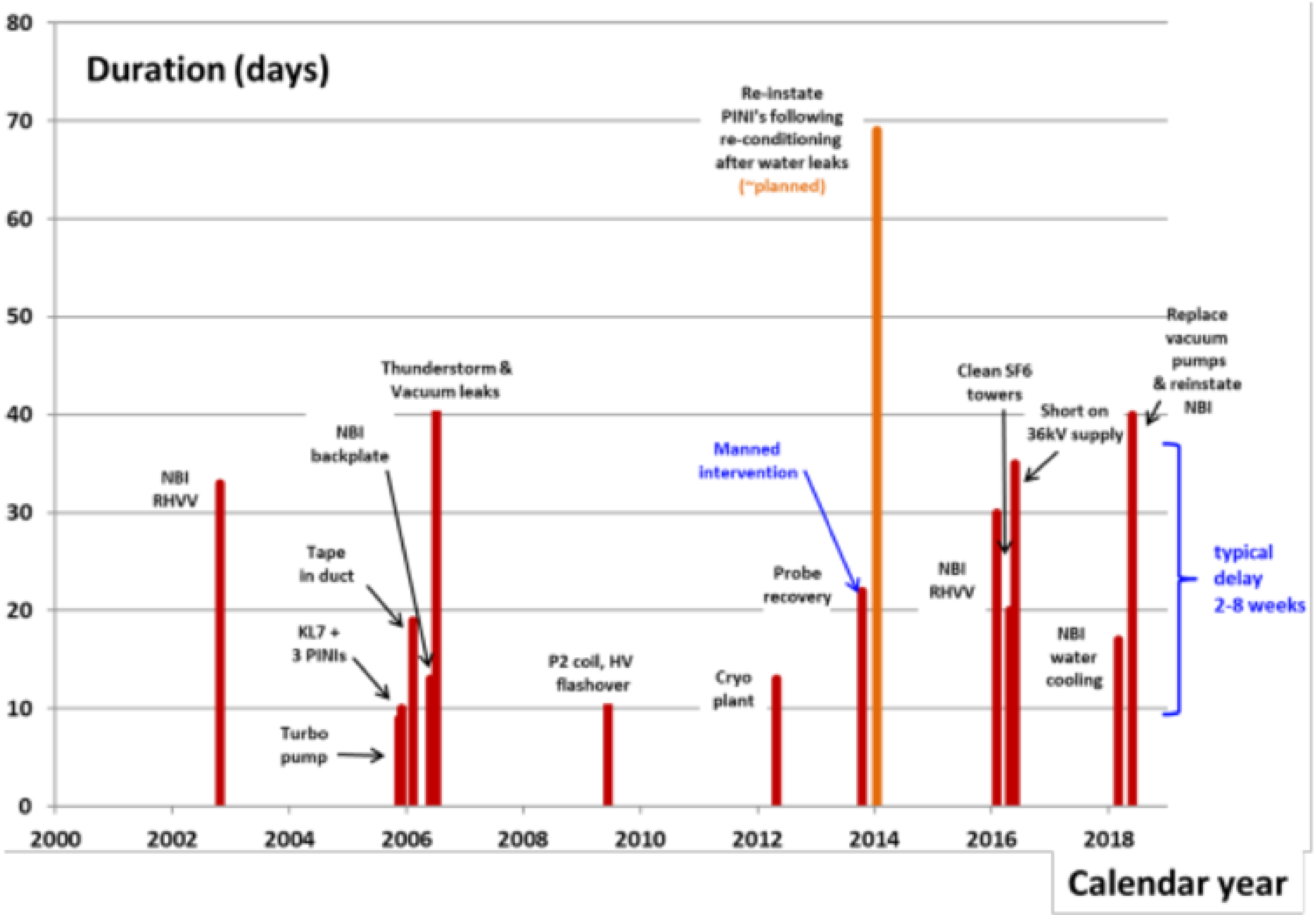
- Process and safety discussions: 6 weeks
- Actual work: access to torus hall + few minutes entry

-> Anticipate failure modes if possible, discuss safety considerations, have a plan "ready"

Go to video 1a

Q. Why is he wearing protective suit during torus entry?

Interventions – Major faults

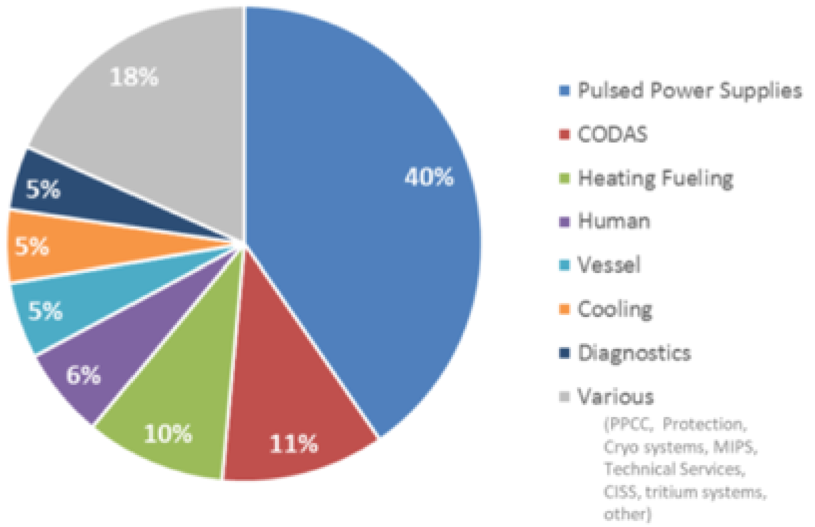


[G. Sips et al. (2018)]

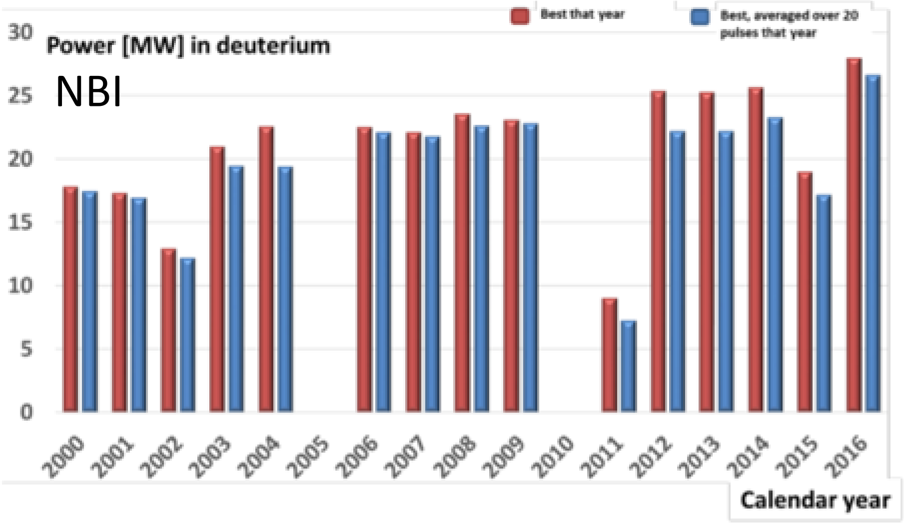
Minor faults

JET Engineer-in-Charge records any delay during experimental shifts ov
5-10 minutes
-> Reviewed at weekly Operations Coordination Meeting ensuring that faults/issues are followed up

Review of the 2000-2018 delay logs identified systems to improve not considered previously (e.g. gas change)
-> Can gain significant operational time resolving regular short delays



Friday 21/10/2016 late shift		**8 pulses, 6 TS+CS, 1 NSB, 3 disrupted, 6 Good Physics**
Fault 3529042	**Investigation of failed CAMAC crate in ASN**	Delay 00:01:30 CODAS – PF
Repeat of the problems of late shift yesterday		
Delay 3529045	**Programme not compatible with state of shutters for cameras**	Delay 00:00:35 Human – Thinking
JOI s require that for a limiter pulse the shutters for KS5, KS9, KL1 and KL7 are closed, and yet that the ops cameras for KL1 are available. After trying out the available permutations it was agreed that this should be given more thought and the programme was changed.		
Fault 3529060	**SS CAMAC crate fault**	Delay 00:00:50 CODAS – SS
CAMAC fault in XSS/ECU1/2		



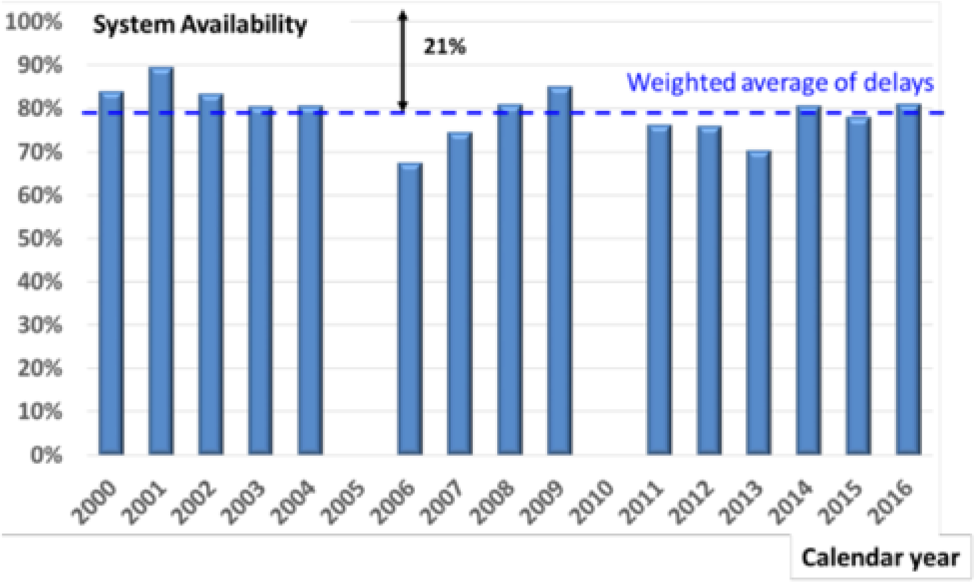
[G. Sips et al. (2018)]

JET Planning

JET had extensive logging, performance and reliability monitoring
Including annual reporting to the European Commission.

JET operated based on assigned experimental sessions

- 80% operational availability during shifts => campaign planning included 20-25% contingency shifts for lost time.
- Campaign could also be shifted or extended in case of lost operational days.



Background:

JET was a European tokamak funded by the European Commission hosted by UKAEA in Culham, UK.

- European Commission representatives: all key operational decisions, machine safety, limits, …
- UKAEA: Personnel safety, regulations, host
- EUROfusion: Scientific exploitation

Campaign target	*Goal*	*Achieved 2000-2016*
Campaign days	*90 %*	*82 %*
System availability	*80 %*	*79 %*
Good physics pulses/shift	*7*	*6 to 7*

The JET session leader rates each pulse with a star rating (0,*,**,***) – good pulse: **, ***

1. Fusion Product Lifecyle

2. **Operation of small, medium and large tokamaks**

3. Boundary operating conditions and special operations

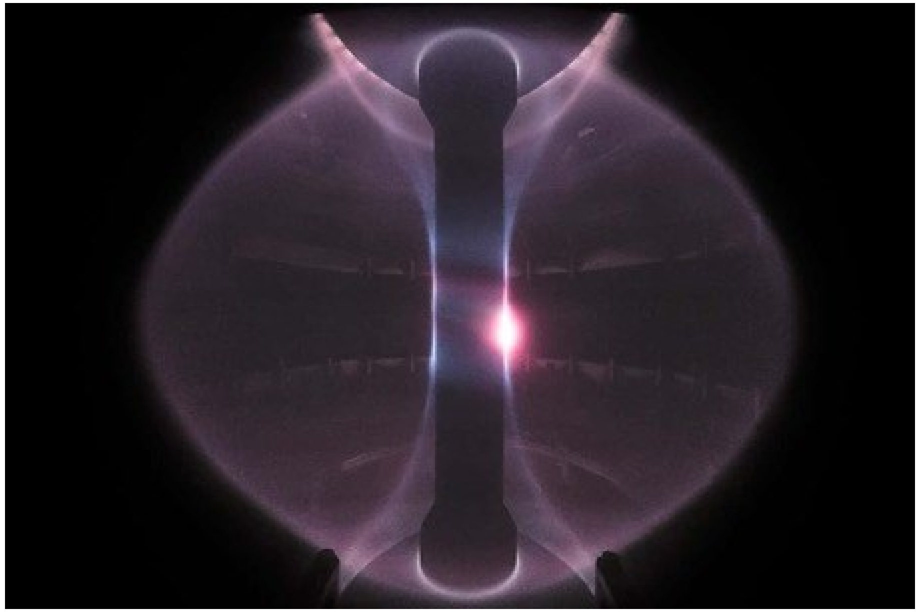
4. Operator roles and setting up a plasma discharge

Do all tokamaks operate the same?

Mega Ampere Spherical Tokamak (MAST) – the physicist view

Major radius (m)	R=0.85m	Plasma current (MA)	Ip = 1.3MA	Total NBI power (MW)	P_{NBI}~ 4MW
Minor radius (m)	a= 0.65m	Magnetic field at R=0.85m (T)	Bt = 0.52T	Plasma volume (m^3)	$V_p = 8m^3$

The MAST Spherical Tokamak



Spherical plasma at MAST

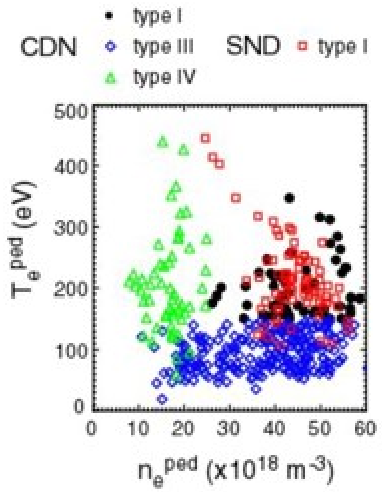


Figure 4 Pedestal operating space achieved on MAST as a function of ELM type.

Source: MAST Upgrade Research Plan

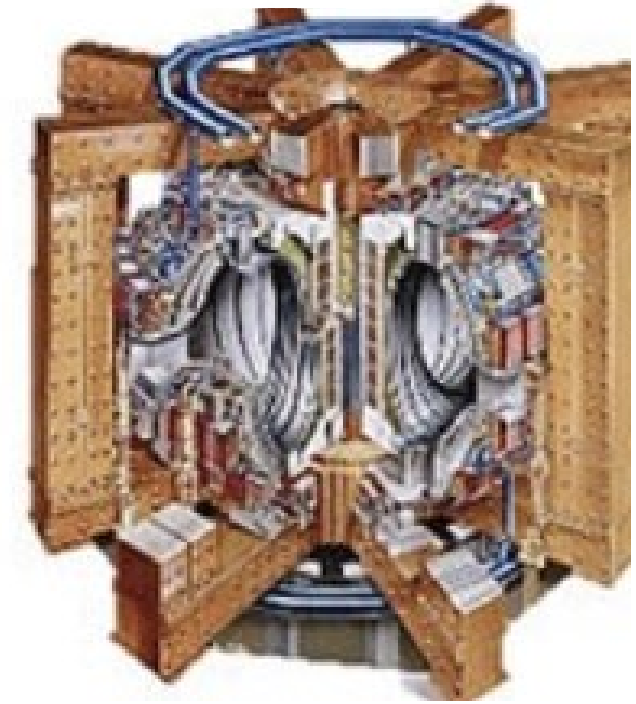
Do all tokamaks operate the same?

ASDEX Upgrade – operator impression (medium)

- Still ~1MA plasmas for <10s, but high heating power (NBI, ECRH, ICRH), W-wall
- Only programme the flattop phase using a table-based discharge editor.
- Ramp-up, ramp-down, terminations and protections are pre-set or from a predefined list.
- 2 experiment leaders, pulses were often prepared during the session.
- Worked on a number of “good pulses” instead of sessions.
- Operation in German. 2 sessions per day, 2-3 days a week.
- Faults are quick to repair and recondition the device.

Joint European Torus (JET) – operator impression (large)

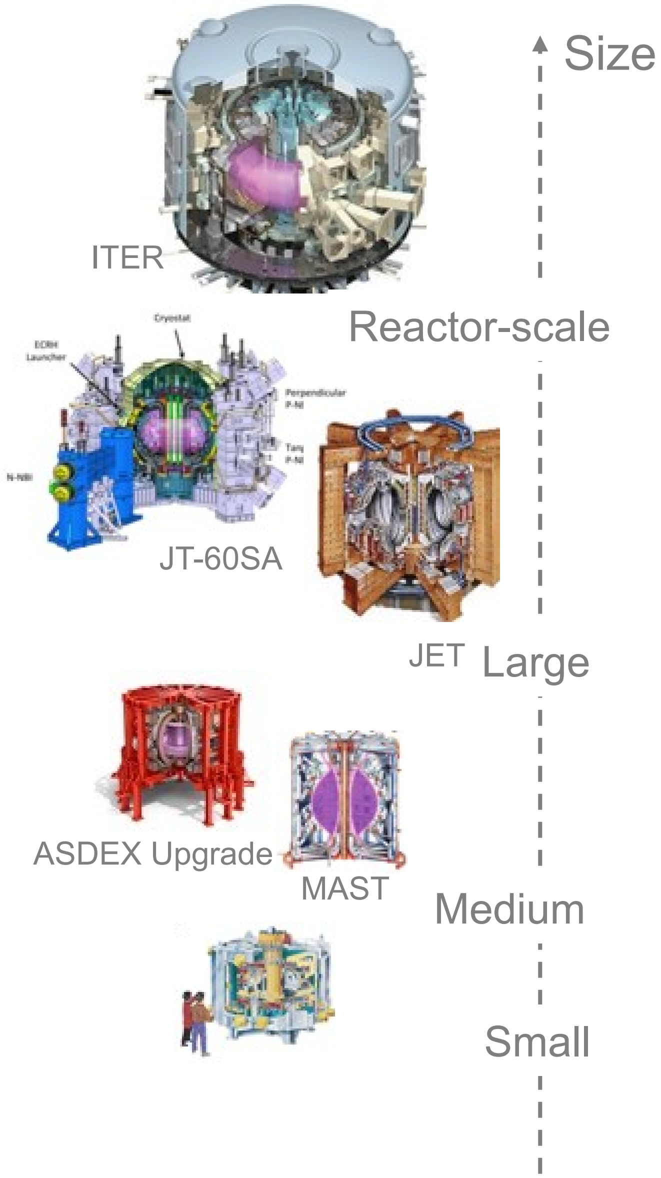
- High current (up to 4MA) -> defined operating instructions, limits, checks.
  - Disruption mitigation valve required in protection mode >2MA, disruption checks.
  - Conditioning following disruptions are not often required (Beryllium first wall)
- Scarce resource (gas, high Bt, neutron …) approval and request for dedicated operators
- Session preparation weeks in advance -> pulse preparation few hours days before.
- Session Leader programmes all discharge phases including 3-5 pages of protection system responses and up to 7 different termination scenarios.
- 2-shift operation 5(-6) days a week (Shift 1: 6.30-14.30, Shift 2: 14.00 – 22.00)
- All time scales are slower – isolations, fault recovery, commissioning, time between pulses



Increase of operational complexity with size of the tokamak

	Small	Medium	Large		Test reactor
Device	**MAST**	**ASDEX-Upgrade**	**JET**	**JT-60SA**	**ITER**
(volume)	$8m^3$	$13m^3$	$80m^3$	$135m^3$	$800m^3$
Pulse length	<0.5s	~s	~10s	~100s	<400s
Plasma current		~1MA	4MA*	5.5MA	<15MA
Integrated commissioning (pump down to campaign)		~week	~2 months	6 months (1st)	1 year (1st)
Session Leader training	~weeks	~months	**4 years**		
Technical roles (experts)	9 (37+)	31 (111)	35 (166)		
Scientific roles (experts)	5 (60+)	11	11 (155)		
Supporting roles (experts)		4	4 (16)		

*Q. Can you guess what is the largest plasma current ever achieved on JET?



Increased plasma current, disruption and vessel forces

Size of the vacuum vessel, performance of plant systems (e.g. explosive gas limit)

Increased number of operators & settings, but AUG and JET number of operator roles are similar

=> Required safety and protection systems

=> Commissioning and preparation time, approval processes

=> Increased time for access, repair, conditioning for recovery

Do all tokamaks operate the same?

- Different tokamaks have different capabilities and risks
- Operators often use “recipes” (e.g. 100-hour GDC at JET) that can be different device to device.
- Operations is often in the local language vs. scientific exploitation can be in English.

BUT the basics of tokamak operation is same/similar (coils, heating, fuelling, protection and safety…)

- **Many transferrable skills**
  - Exposure to type of physics, engineering, operational issues
  - Session management (interaction with scientific coordinator and other scientific and engineering operators)

  -> reduced training time, increased problem-solving capability

Operational culture:

Physics and Engineering

EUROfusion

the research on JET has always relied on a strong interconnection between physics & engineering

e.g. when preparing experiments

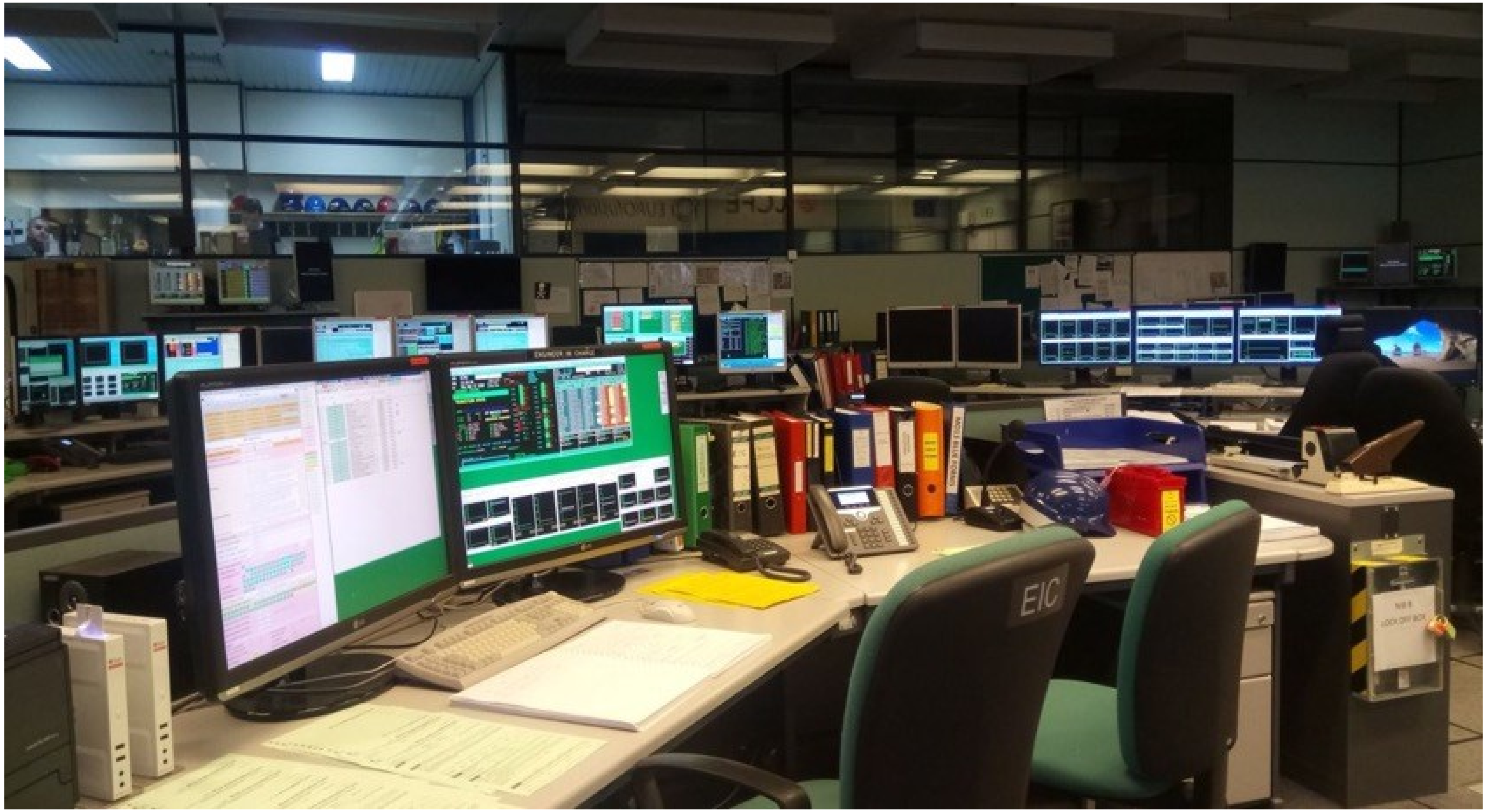
physicists have the original idea & discuss in Team

discussion with tokamak ops experts– translate ideas into machine parameters

Engineering staff gives input
(e.g. machine protection)

1. Fusion Product Lifecyle
2. Operation of small, medium and large tokamaks
3. **Boundary operating conditions and special operations**
4. Operator roles and setting up a plasma discharge

Control room layout



JET Engineer-in-Charge Desk:

- Workstation with 2 large screens
- Printer
- Internal telephone
- External telephone
- Key documentation inc. JOI's, forms and records
- Real paper log book
- Open forms
- PA microphone
- Temporary key exchange lock-off boxes
- Plasma stop button
- Quadraphonic torus hall audio (in ceiling)

Why do we need protection

And what we are protecting against

Known engineering limits or weaknesses :

- e.g. potential for damage due to high forces in disruptions => need to limit max. value of plasma current

Anticipating possible problems :

- e.g. regular monitoring of coils resistivity => early detection of incoming failures

Real-time monitoring and fault detection during pulses

- e.g. disruption prediction => mitigate effects

Machine protection

How are these main risks assessed ?

The boundaries for “safe” operation of the tokamak and its sub-systems have been studies, agreed and consolidated, over the years, in a set of JET Operating Instructions (JOI).

For example : max. plasma current, max. toroidal field, max. Wall temperature

These were

- implemented in the pre-pulse validation of the programmed plasma parameters
- checked in real-time during the pulse
- and after the pulse

JET Operating Instructions

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JET FACILITY OPERATION INSTRUCTIONS INDEX	ISSUED JANUARY 2020	VALIDITY From **25/01/2020** until further notice

List all JOI Annexes

Upload JOI Annexe

			Issue	Date
1.	JOI Annexes	**Disruptions**		
	1.1	Plasma Current	15/11	22/09/15
	1.2	F Number and Vessel Forces	15/16	22/09/15
	1.3	Limit on Number of Disruptions	16/11	20/10/16
	1.4	Vessel Displacements	19/12	23/04/19
	1.5	Limits for Protection of the KS7 Diagnostic Port Extension	19/8	13/05/19
	1.6	Number of Disruptions at High Toroidal Field	16/8	24/11/16
	1.7	Transverse Forces on the TF Coils in Disruptions	16/7	20/10/16
	1.8	Rotary High Vacuum Valves	17/8	27/03/17
	1.9	Vacuum Vessel Operating Temperatures	19/10	21/10/19
	1.10	**Cancelled**		
	1.11	Identification and Avoidance of Melting by Off-Normal Events	19/2	24/06/19
	1.12	Use of Disruption Mitigation Valves for ITER-Like Wall Protection	19/2	26/07/19

Over the years, the *risks* have been catalogued and systems have been developed to protect the machine:

- administrative tools, the JET Operating Instructions (JOIs)
- and real-time implementation of limits

The JET Operating Instructions were *living* documents, reviewed regularly to ensure they are always matched to the actual machine conditions

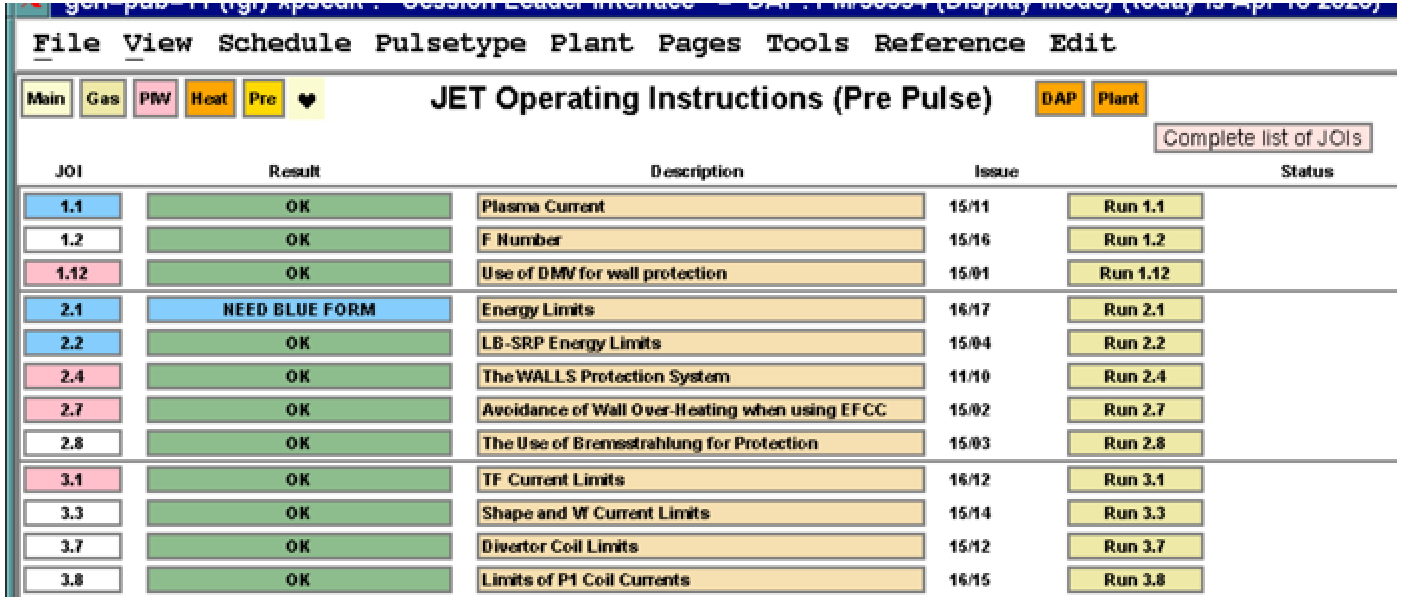
For example, the installation of the metal Wall required :

- a major review of the wall temperature and energy limits
- compulsory active mitigation of disruptions to avoid beryllium melting risk

Operating Instructions implementation

there were several methods for managing compliance of JET tokamak pulses with Operating Instructions

pre-pulse validation of *Pulse Schedule* by Session Leader and Engineer in Charge



File View Schedule Pulsetype Plant Pages Tools Reference Edit

Main Gas PIW Heat Pre DAP Plant

JET Operating Instructions (Pre Pulse)

Complete list of JOIs

JOI	Result	Description	Issue	Status
1.1	OK	Plasma Current	15/11	Run 1.1
1.2	OK	F Number	15/16	Run 1.2
1.12	OK	Use of DMV for wall protection	15/01	Run 1.12
2.1	NEED BLUE FORM	Energy Limits	16/17	Run 2.1
2.2	OK	LB-SRP Energy Limits	15/04	Run 2.2
2.4	OK	The WALLS Protection System	11/10	Run 2.4
2.7	OK	Avoidance of Wall Over-Heating when using EFCC	15/02	Run 2.7
2.8	OK	The Use of Bremsstrahlung for Protection	15/03	Run 2.8
3.1	OK	TF Current Limits	16/12	Run 3.1
3.3	OK	Shape and Vf Current Limits	15/14	Run 3.3
3.7	OK	Divertor Coil Limits	15/12	Run 3.7
3.8	OK	Limits of P1 Coil Currents	16/15	Run 3.8

real-time protection, e.g. Coil Protection System, Infrared measurements of ILW temperatures

post-pulse checks with actual data, e.g. divertor thermocouples for energy to divertor / first wall

Exceptions to Operating Instructions

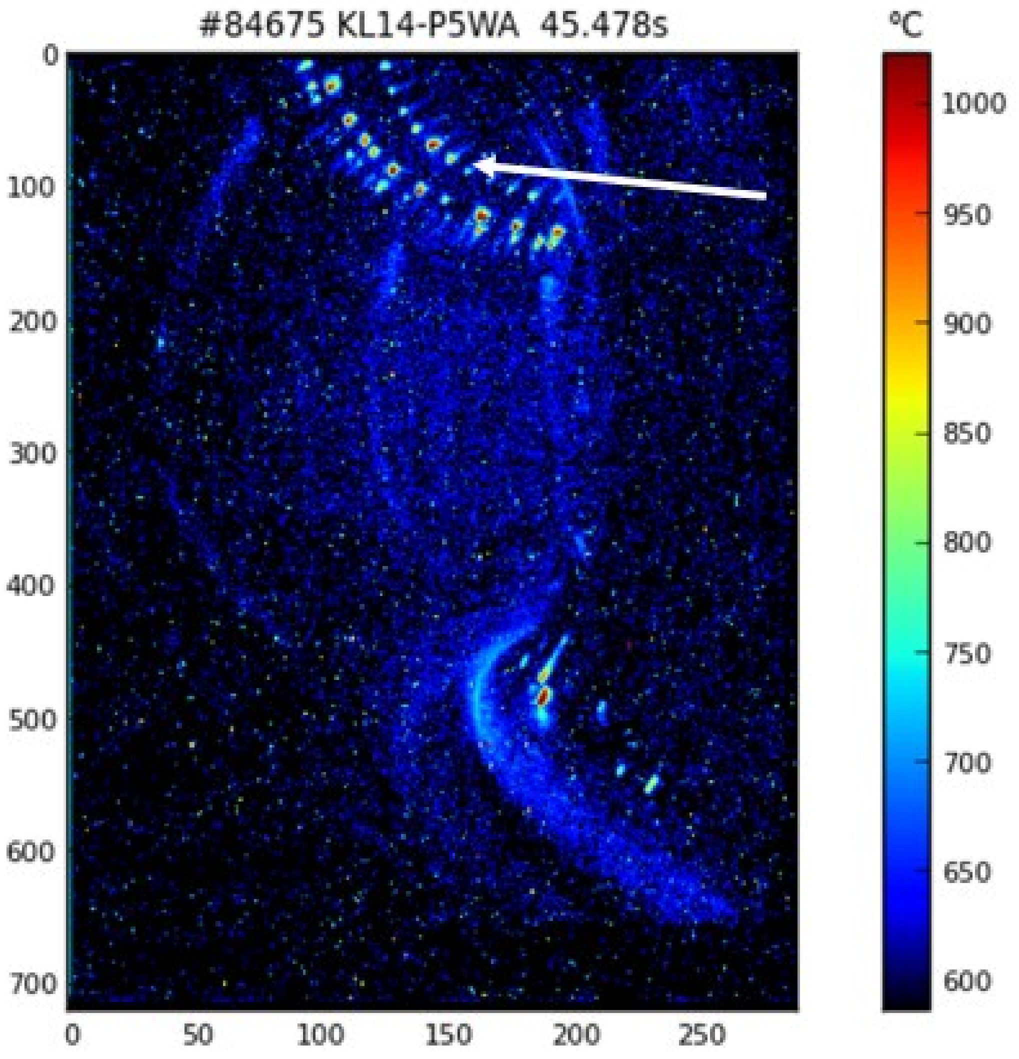
Experiments were allowed to ask for exceptions to the limits set in JOIs.

Typically, these exceptions fall in two categories :

- Exploit the safety margins built in the JOIs and demonstrate that the experiment, even if it goes beyond the administrative limit, is safe, and that additional protections are in place (and ensure experiment would stop in case of problems). For example changes to plasma density-NBI shinethrough limits by using more detailed calculations.
- Accept the increased risk of damage against a very high scientific value of an experiment. For example, Disruptions and Runaway Electron studies in support of ITER.

A demand for exception would be reviewed by a panel of experts, including the JET Chief Engineer. If agreed, the conditions on how to carry out the experiment, and when to stop, would be clearly defined and signed by the top management.

JOI examples : beryllium components protection



Beryllium melts at 1287 °C => the main chamber in in the metal wall configuration, since 2011, is at higher risk of melting

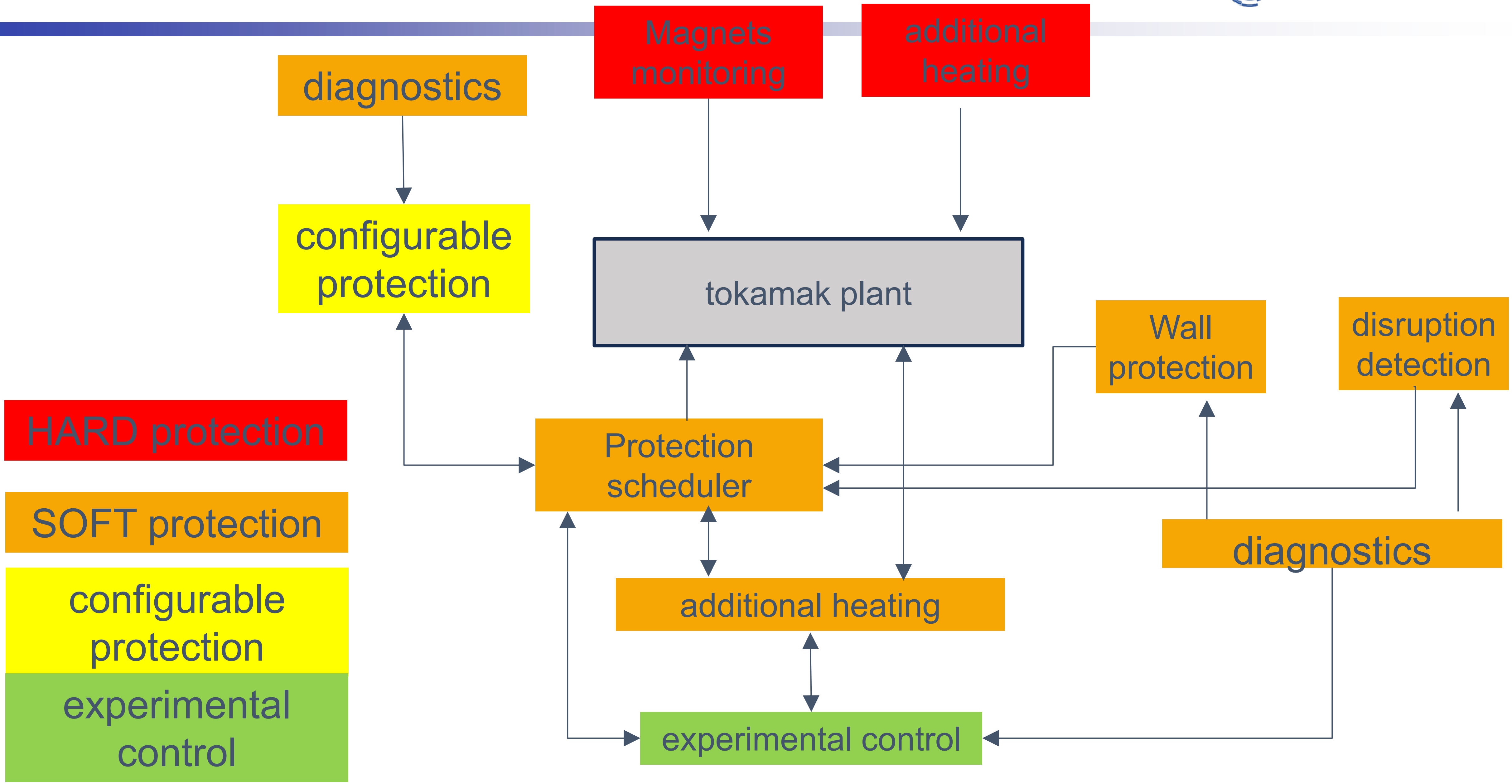
Steady state and transient (disruptions) heat-loads are a MAJOR concern

➔ JOIs impose :

- limit of 900 C for max. (steady-state) wall temperature
- use of Massive Gas Injection above 2MA to mitigate impact of disruption.

Exceptions, allowing for potential melting, for Runaway Electrons studies !!

Real-Time protection during pulses

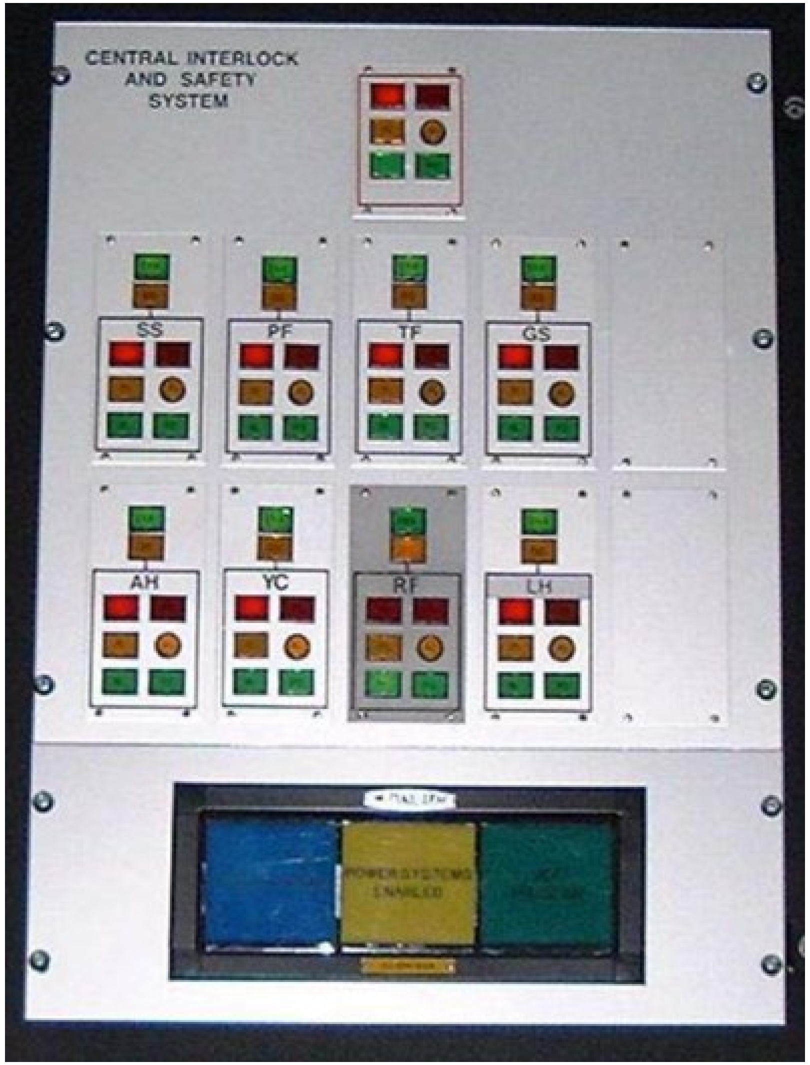

Magnets monitoring
additional heating
diagnostics
configurable protection
tokamak plant
Wall protection
disruption detection
HARD protection
Protection scheduler
SOFT protection
diagnostics
additional heating
configurable protection
experimental control
experimental control

Event Detection systems

Event Detection is distributed amonst a variety of systems :

- low level, simple, robust interlocks
- real-time software tools - using diagnostics and sub-systems data - for example WALLS real-time calculation of Last Closed Flux Surface proximity to first wall and heat loads to divertor
- software algorithms configurable for each experiment.

Real-Time Event Detection is tied to the limits specified in the JET Operating Instructions



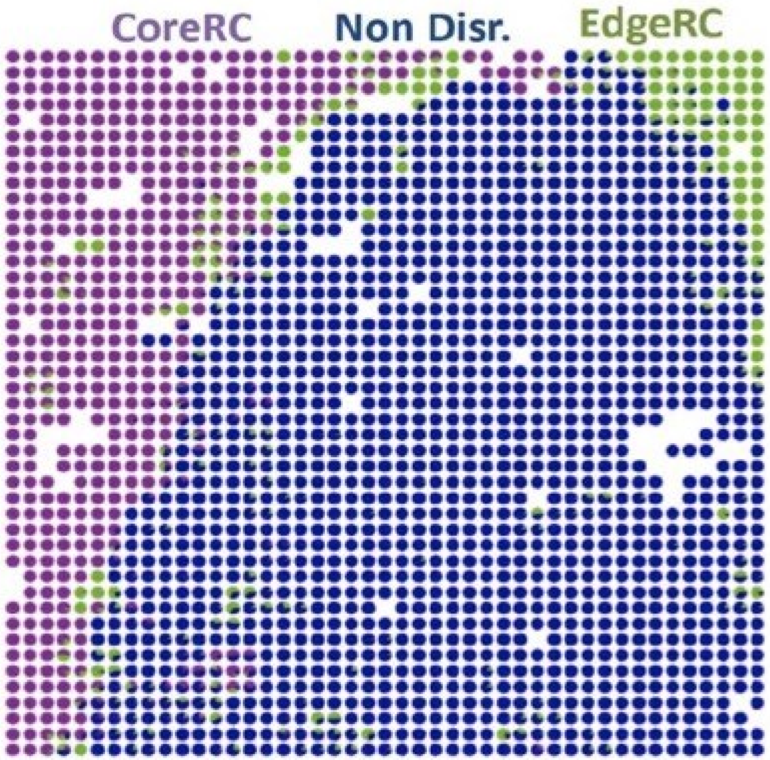
(software) Real-Time event detection

Complex (software) real-time tools combine information from several diagnostics and produce

- estimate of heat loads to the various wall components
- real-time temperature of the first wall (IR)
- detection of imminent disruption, e.g. high value of locked mode amplitude, or loss of vertical stabilization

but also even more complex “advanced” algorithms - tests of faster-than-real-time control & Machine Learning based disruption detection

note : rigorous Verification & Validation of protection & control software tools !!!



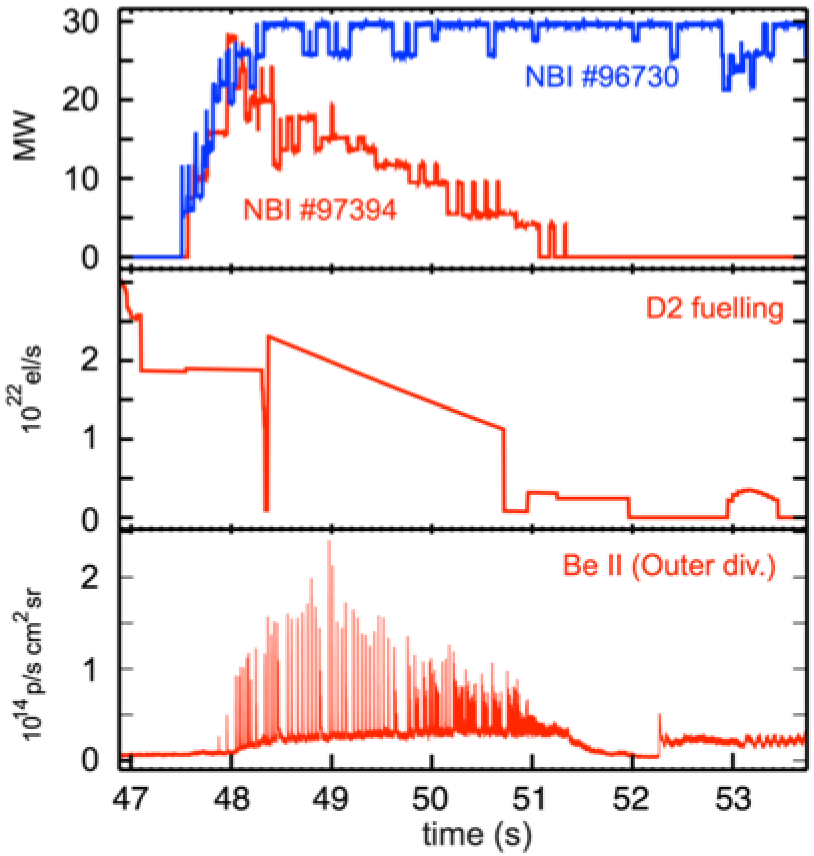
A. Pau et al., IEEE Transactions on Plasma Science, July 2018

Generative Topographic Mapping for disruption prediction

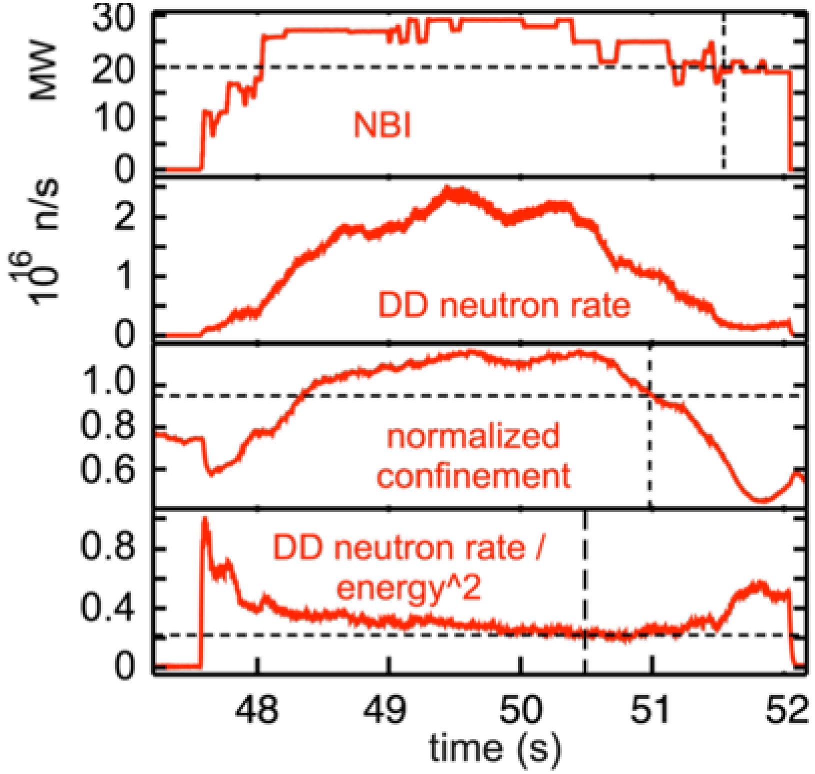
Configurable Event detection

Algorithms can be implemented to ***optimize*** the way we exploit the machine for example stop a pulse early (and save on neutron budget) if not good enough

NBI power too low



performance insufficient for DT (*dud* detection)



Real-Time alarm & exception handling

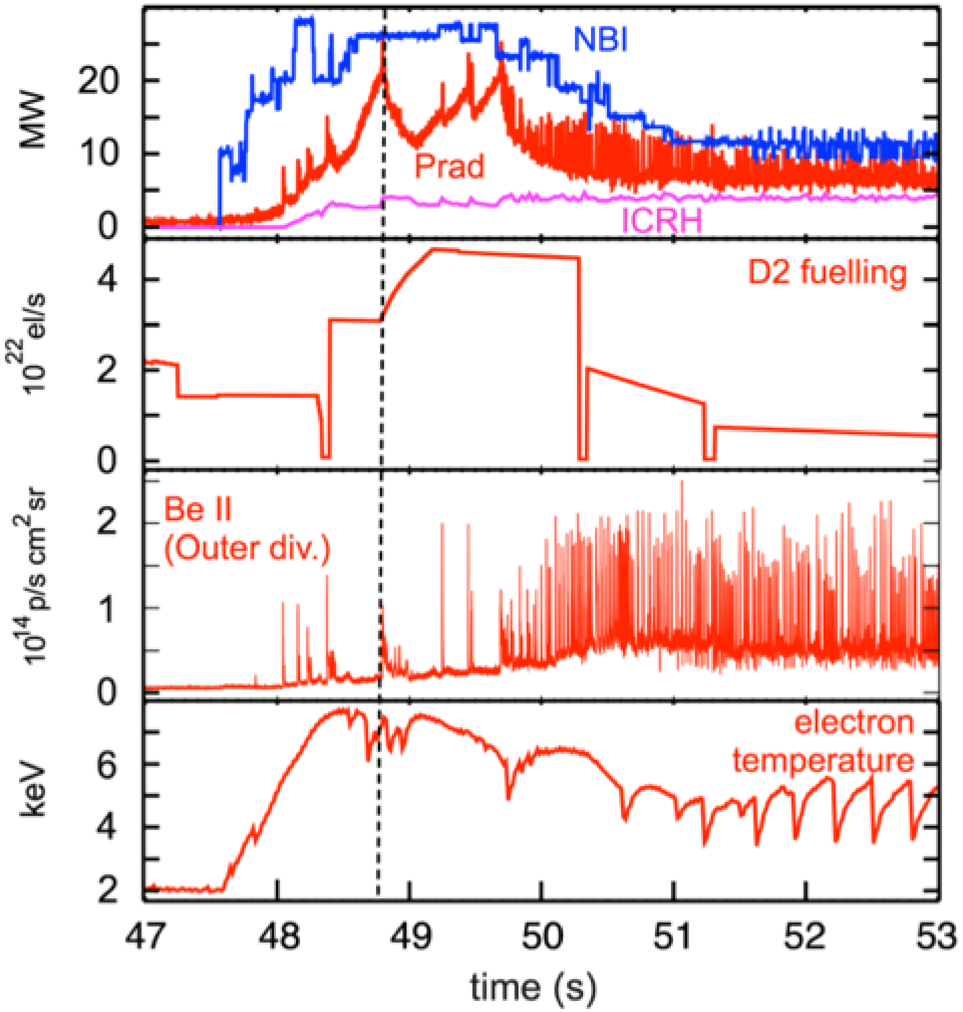
Like the event detection system, the alarm handling has been built over the years and, more recently, upgraded to support the safe exploitation of the metal wall

Alarms from the various detection systems are managed by

- a Central Interlock hardware system - for example high voltage power supply faults during pulse
- an older software / hardware Pulse Termination Network, with only a minimum of response configurability
- a new Real-Time Protection Sequencer with a very high level of alarm-to-response configurability – for example capability to control plasma current & shape, heating and fuelling depending on the type of alarm

Disruption management

rapid increase of radiated power



Over the years, JET (Operations & Science contributors) has developed algorithms to

- **predict** if plasma is evolving towards a potentially disruptive event - e.g. loss of power
- **detect** off-normal plasma behaviours which could lead to a disruption - e.g increasing radiated power, MHD modes growing
- send an alarm with enough warning to **avoid** a disruption - e.g. suitable H-mode termination strategy
- and **mitigate** effects if disruption unavoidable – e.g. trigger Massive Gas Injection

JET Operating Instructions (JOIs) – again!

EUROfusion

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JET FACILITY OPERATION INSTRUCTION	No. 5.3 Issue 20/11 Page 1 of 1	ISSUED NOVEMBER 2020	VALIDITY From **04.11.2020** until further notice

NECESSARY PLASMA DIAGNOSTICS

The following plasma diagnostics are mandatory to ensure compliance with various Operation Instructions according to the nature of the pulses to be run. The EiC must ensure that they have been flagged "Essential".

The requirement for KH1 to be essential may be overridden where the session leader has agreed that the plasma configurations have a low likelihood of generating runaway electrons and when approved via MO13. In this case the EiC should ensure that the KH1 RO is informed.

Plasma Configuration	Diagnostic	Computer
1. Dry Run	Magnetics: KC1D	DA
2. Plasmas without any additional heating (NBI, ICRH, LHCD) or pellets	Magnetics: KC1D Neutrons: KN1 Note 1 Runaways: KH1 Density: KG1 or KS3. Expert session leaders can run these plasmas without validated density. A wide angle, visible view must be available in real time to the SL and EiC.	DA DD DD DF(DD) DA
3. Plasmas with additional heating other than lower hybrid	Magnetics: KC1D Neutrons: KN1 Note 1 Runaways: KH1 Density: KG1 and KS3 Divertor thermocouples: KD1D A wide angle, visible view must be available in real time to the SL and EiC. IR systems and pyrometers as required by OI 2.6.	DA DD DD DF(DD) DB DA
4. Plasmas with additional heating including lower hybrid (see O.I 4.12 for KT2 and KB5V)	Magnetics: KC1D Neutrons: KN1 Note 1 Runaways: KH1 Density: KG1 and KS3 Divertor thermocouples: KD1D Bolometers: KB5V VUV spectroscopy: KT2 A wide angle, visible view must be available in real time to the SL and EiC. The KL10-P4LA camera view must be available in real time to the LH operators. IR systems and pyrometers as required by OI 2.6.	DA DD DD DF(DD) DB DB DF DA

Note 1: When a 14 MeV neutron budget is set in the Machine Configuration Overview, KM7D neutron diagnostic (on computer DD) must also be set essential.

Responsible Officer: K-D Zastrow	Torus ATO Holder: R Marshall	Chief Engineer: M Porton	Senior Manager: J Milnes	JET Exploitation Manager: C Ibbott

Let's look at limitations related to gas as an example…

Q. What gas limits can you think of?

JET Operating Instruction 5.3 –
Essential diagnostics for JET operations

JET Operating Instructions – Maximum Gas Limit

Explosive Gas Limit: limit of hydrogen isotope gas in the torus and NBI systems that can potentially explode during a loss of vacuum incident (incursion of oxygen).

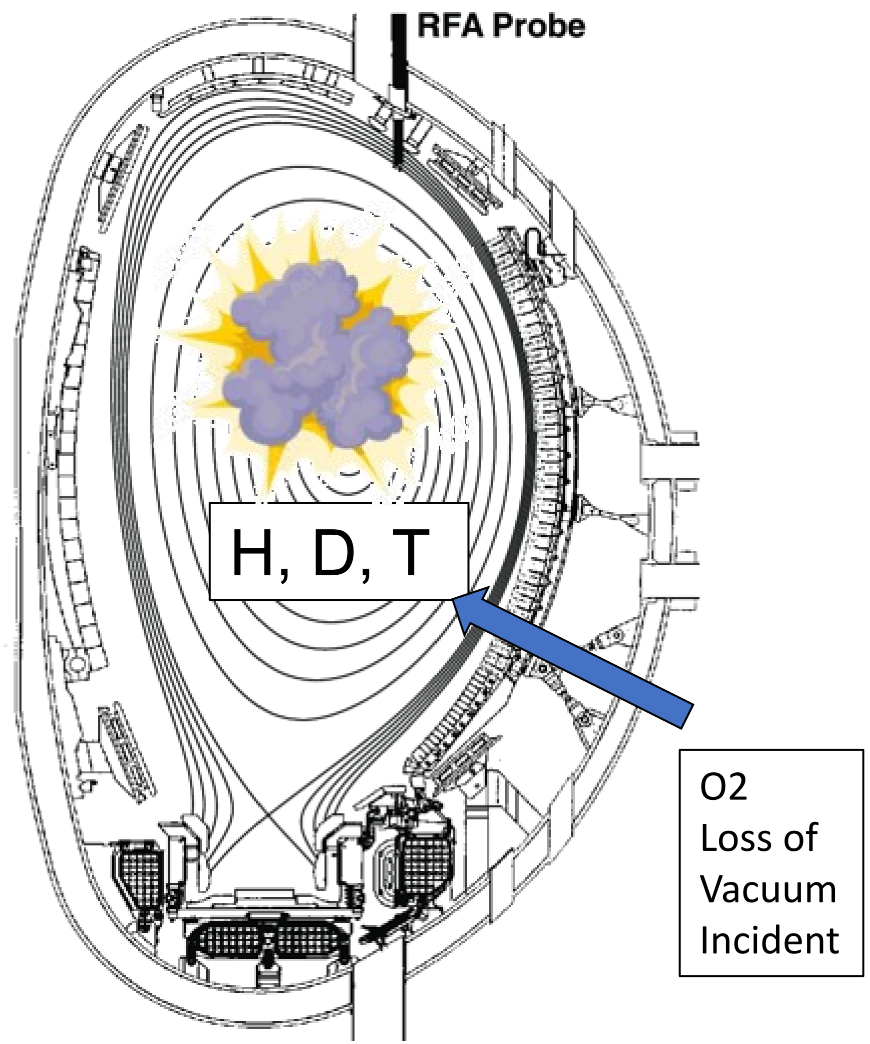
- Limits how much can be injected before the cryo pumps need to be regenerated (heated up to remove the collected hydrogen gas).

  Limit = 3 x 330barl D2 to torus and the 2 NBI systems

Implementation:

- Pre-session gas estimate (default 150barl) -> approval
- Pre-pulse estimate – worst case scenario with maximum opening of feedback gas valves
- Post-pulse gas inventory

ITER: sequential cryo regeneration during pulses for the torus,
but not for the NBI cryos



JET Operating Instructions - Minimum Gas Limits

Minimum gas limits:

- **for ICRH coupling:** minimum hydrogen gas for ICRH coupling to avoid fast particle generation.
  -> Session Leader responsibility

- **For NBI shine through:** minimum density to allow absorption of the NBI power and limit damage to inner wall.
  -> real-time density check of approved list of diagnostics

- **Avoidance of runaway electron generation at the plasma start:** gas requirement at the plasma startup to avoid conditions that can generate runaway electrons that can damage the inner wall.
  -> pre-pulse check

Table 1: Fundamental (N = 1) hydrogen minority heating scheme in D, T, DT or He^4 plasmas

Line integrated density measured by KG1V/LID3 (or equivalent as advised by the KG1 RO)	P = RF coupled power (ICRH/PTOT)	H concentration
$n_eL < 0.5\times10^{20}$ m^{-2}	P < 0.5 MW	No restriction, the natural level of H in the machine is enough
	0.5 MW < P < 4 MW	> 4 %
	P > 4 MW	> 6 %
0.5×10^{20} m^{-2} < $n_eL < 1\times10^{20}$ m^{-2}	P < 0.5 MW	No restriction, the natural level of H in the machine is enough
	0.5 MW< P < 5 MW	> 2 %
	P > 5 MW	> 4 %
$n_eL > 1\times10^{20}$ m^{-2}	P < 6 MW	No restriction, the natural level of H in the machine is enough
	P > 6 MW	> 2 %

Standard Alignment Normal Bank for Deuterium Beams

Maximum Beam Energy (keV)	Notch Min Ne (10^{18}m^{-2})	Pulse Min Ne (10^{18}m^{-2}) for Pulse Length t (s)						
		0<t≤1	1<t≤2	2<t≤5	5<t≤7.5	7.5<t≤10	10<t≤15	15<t≤20
80	18	5	9	15	17	19	21	23
90	20	13	19	25	28	29	32	34
100	24	22	29	36	39	41	43	46
110	39	36	44	52	55	57	60	63
115	44	41	49	58	61	63	66	69
125	53	53	61	70	74	76	79	83

Standard Alignment Tangential Bank for Deuterium Beams

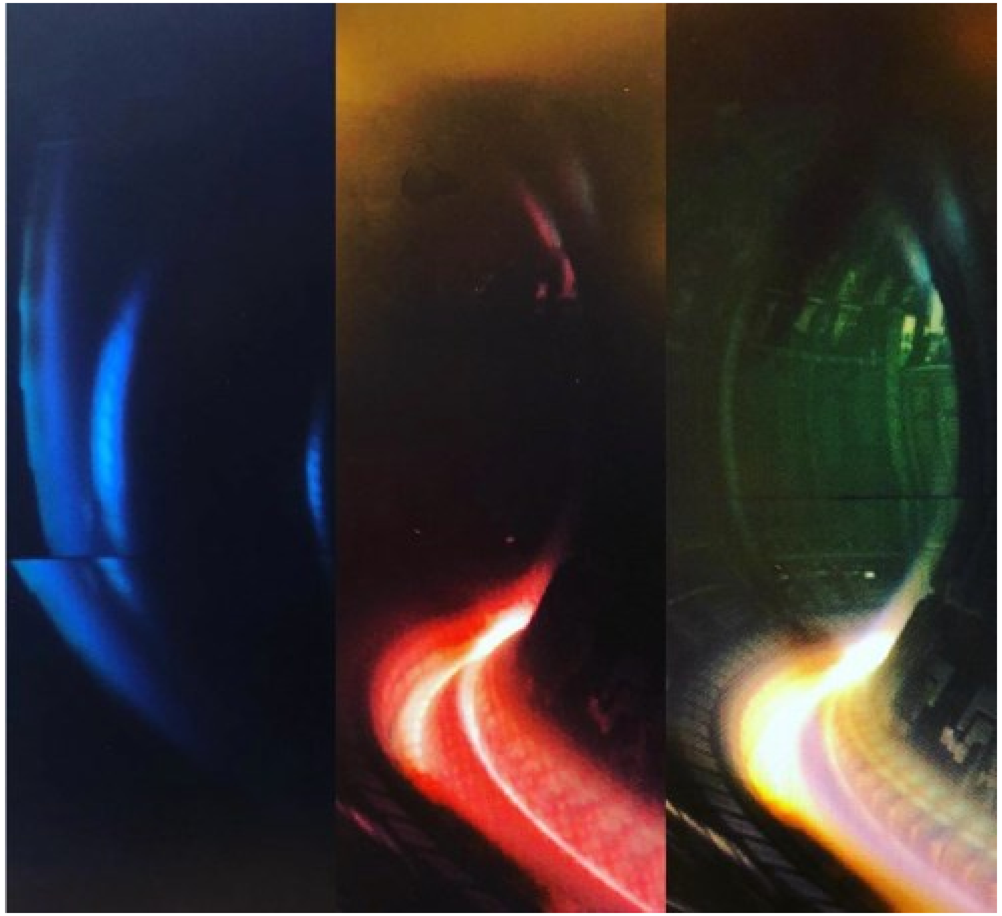
Maximum Beam Energy (keV)	Notch Min Ne (10^{18}m^{-2})	Pulse Min Ne (10^{18}m^{-2}) for Pulse Length t (s)						
		0<t≤1	1<t≤2	2<t≤5	5<t≤7.5	7.5<t≤10	10<t≤15	15<t≤20
80	24	24	30	38	42	45	49	53
90	28	30	38	47	51	54	59	63
100	37	37	46	56	60	64	69	74
110	50	45	55	66	71	75	81	86
115	55	48	59	71	76	80	86	91
125	62	56	67	80	86	90	97	104

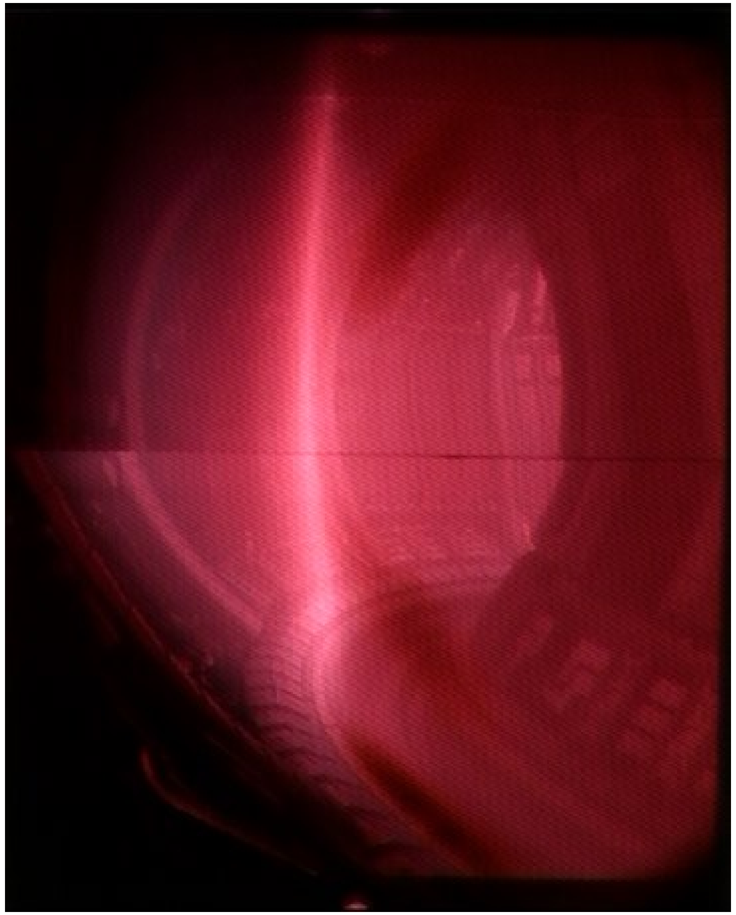
JET Operating Instructions – Tritium Limits?

?

No spoilers here – this is the next lecture!

Special Operations





Q. Can you work out what is in these pictures?

1. Fusion Product Lifecyle

2. Operation of small, medium and large tokamaks

3. **Operator roles and setting up a plasma discharge**

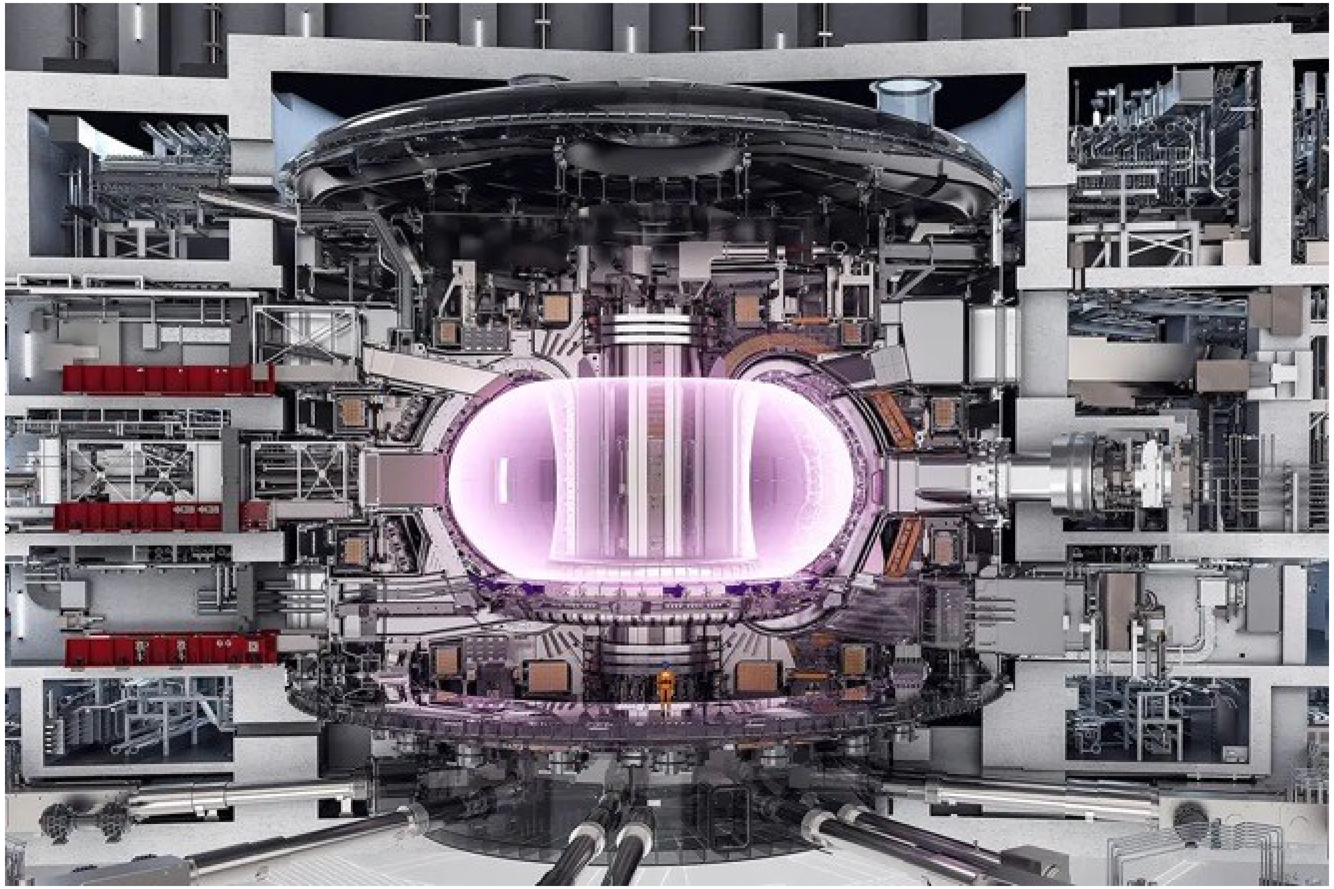
Operation of a tokamak is a team effort

Go to video 2

Myth? – Tokamaks can be operated with a few operators

Operation of large-scale facilities can involve 30-50 roles, areas and ~ 500 people

- Site services (water supply, etc.)
- Power supplies – magnets, heating systems
- Vacuum and gas (vacuum conditioning)
- Cryogenics
- Dedicated plants for beryllium, tritium
- Heating systems – NBI, ECRH, ICRH, LH
- Pellets
- Diagnostics
- **Plasma operations**
- Real-time Control (plant, protection
- systems, scientific real-time networks)
- IT systems (CODAS/CODAC)
- Disruption mitigation (DMV, SPI)
- Maintenance services
- Safety (personnel and machine)
- Health physics, safety case
- Protection systems
- Waste management



Control room

EUROfusion

Scientific roles

Physics pilot: Session Leader
Lead diagnostician
Scientific Coordinator
Cameras
Real-time control
Diagnosticians
Scientists
Experts for MHD, TRANSP, …
Disruption experts

Engineering roles

Lead engineer
Shift Technician (always there, all systems)
Power supplies
Heating systems
Pellets
Vacuum
Cryogenic systems, pumps
Safety
IT systems

Session Leader – Physics Operator

Session Leader (SL): physics pilot of a tokamak responsible for development of a pulse schedule based on discussion with the scientific coordinator. Manages the scientific roles in the control room and is the lead scientific contact to engineering competences.

JET SL Training:

1. 1-2-week(s) course every few years since 1995
2. Practical control room training as SL2 (Optimal: 1 session/week)
3. Licensing based on plasma current & disruption force
4. Continuous training with seminars, forums, email updates (ensure exposure/awareness to current issues and solutions)

Machine/License	Time to license	No. of shifts to obtain license
Small device / Full	Weeks	
Medium device / Full	Months	
JET / license A (Ip<2MA)	1+ year	21 (13-43)
JET / license B (Ip<3MA)	1+ year	15 (8-22)
JET / Full (Ip<4MA)	1+ year	22.5 (21-24)
JET / Expert	10+ years	

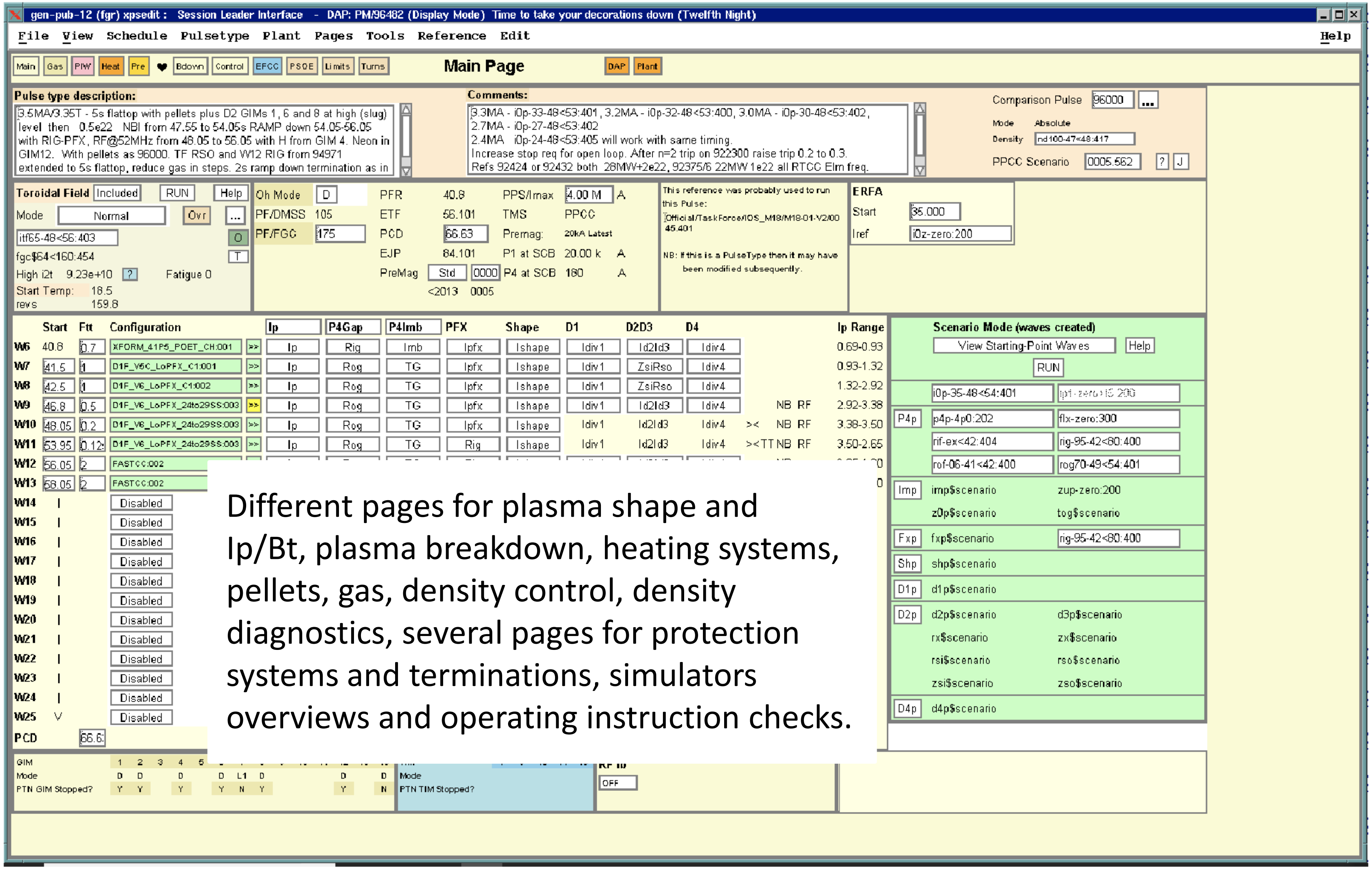
Training material from every JET SL course is available to Eurofusion members.

- Multi-machine or other control room role experience & exposure can reduce training time significantly.
- Complexity & training time increases with plasma current & size
- Basic plasma & plant operation knowledge allows full exploitation of a device including better scientific proposals and communication between scientific and engineering staff. (reference SLs to support scientific coordinators)

A pulse setup

1. Find a **similar plasma discharge** (starting point)
2. Programme toroidal **magnetic field** and **plasma current**
3. Define the **shapes** and shape transitions (programme in coil current or geometrical parameters, select control modes)
4. Check and adjust plasma **breakdown** scenario
5. Select the **gas** species and fuel locations. Programme the fuelling waveforms and select control mode (fueling rate, density control)
6. Consider **pellet** injection (for fuelling or ELM pacing)
7. Select the **diagnostics** used for density control and related protections
8. Select **heating** systems (timing, duration, -> diagnostic requirements)
9. Set up **protection** systems (type, limits, time window)
10. Programme up to 7 **termination** sequence reacting to various stop scenarios.
11. Check against the **operating limits**, ensure approvals are available
12. Prepare information for scientific (e.g. Real-time control settings, pulse information for diagnostics coordinator) and engineering experts (heating and pellet set up)

JET Discharge Editor



Different pages for plasma shape and Ip/Bt, plasma breakdown, heating systems, pellets, gas, density control, density diagnostics, several pages for protection systems and terminations, simulators overviews and operating instruction checks.

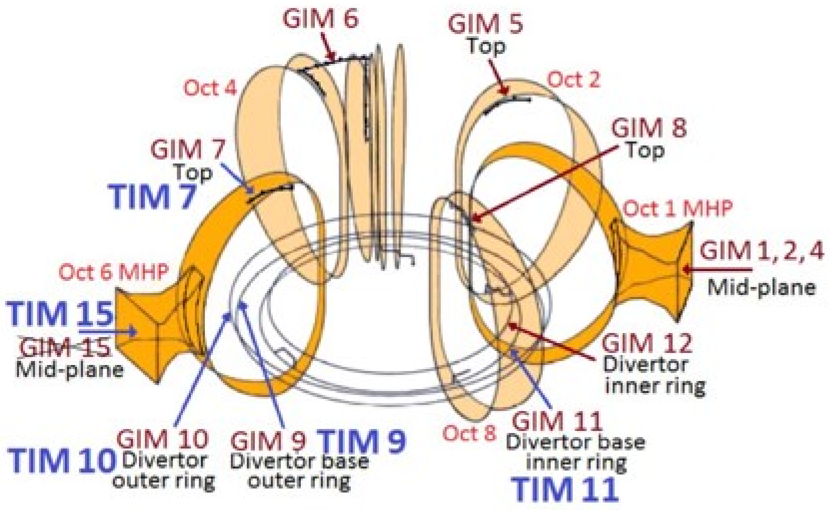
JET gas setup

Species during Campaign	Deuterium	Hydrogen	Tritium
Prefill	D_2	H_2	H_2
Main plasma species	D_2	H_2	T_2
Pellets	D_2	H_2	H_2
Disruption mitigation*	D_2+10% Ar	H_2+10%Ar	H_2+10%Ar
Shattered pellet injector	D_2 with Ar, Ne	H_2 with Ar, Ne	-
RF minority	H_2, ^4He, ^3He	D_2, ^4He, ^3He	H_2, ^4He, ^3He
Seeding	N_2, Ne, Ar	N_2, Ne, Ar	**N_2 not allowed**, Ne, Ar

Consider **function**:

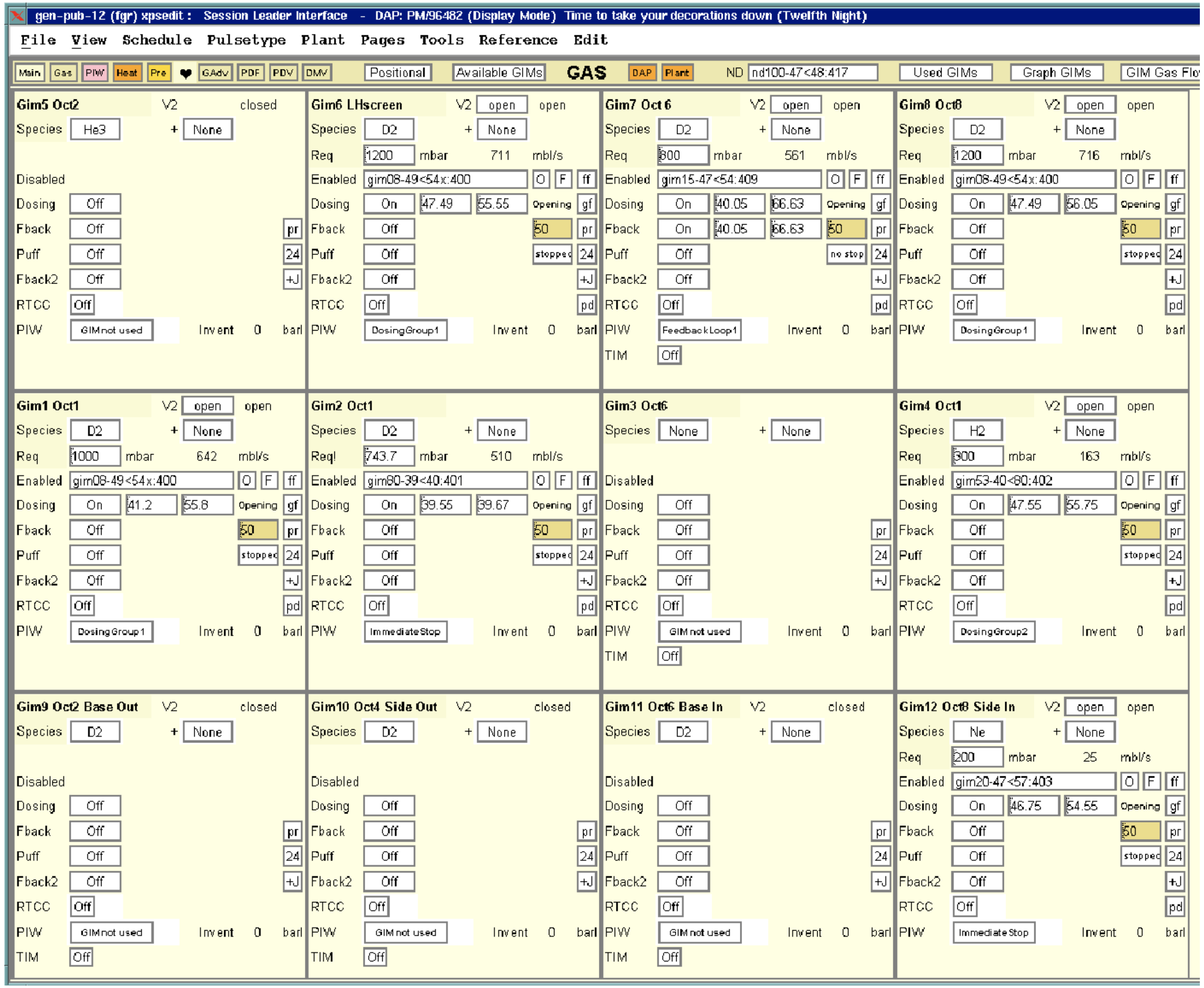
- main species (dosing/feedback/real-time control, pre- and post-heating, optimal gas for ICRH coupling, termination),
- minority species for ICRH,
- special gases for radiation or diagnostics.

Select **location** (top, midplane, divertor)

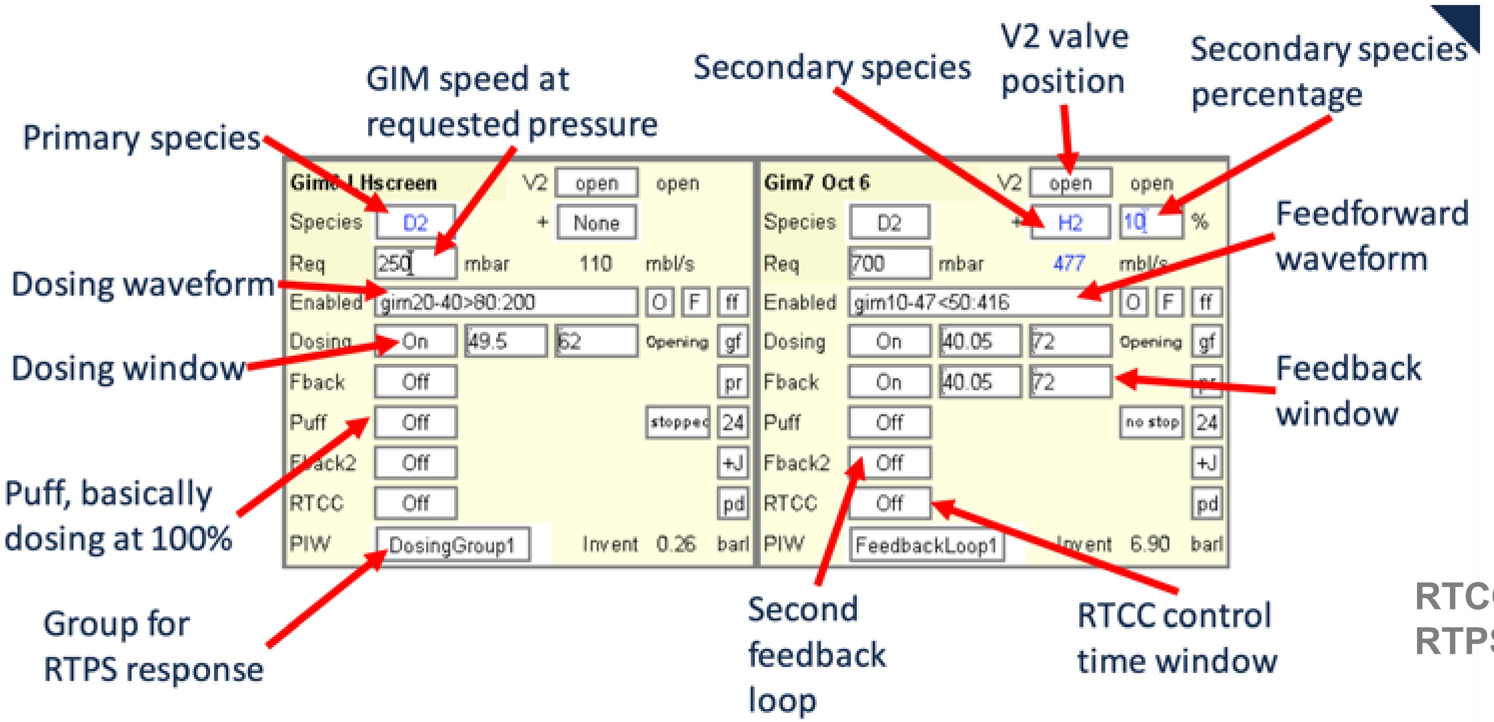


GIM: Gas introduction volume (H, D, special gases)
TIM: Tritium introduction volume (T, D)

JET gas setup page



JET gas setup



RTCC: Scientific real-time protection
RTPS: Real-time Protection system

Select **volume** (standard or V2 large)

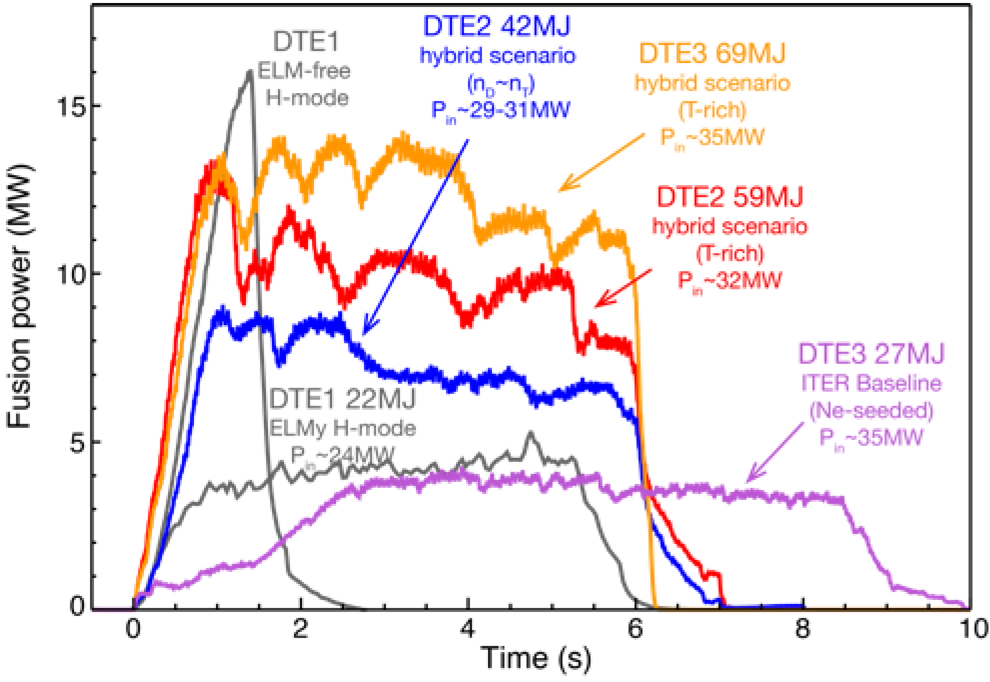
Request and Select **species**, set **pressure** ($p*V = N*k*T$), programme time evolution of the **waveform** (opening of the valve)

Consider pumping speed (species, location), pressure reduction over time, hysteresis of the valve

Set **feed forward, feedback, real-time** control and role in **protection** response

Special Operations – DT world record 21 December 2021

Go to video 3



Pulse 104522

What to take away from operations?

Understanding the plant and plasma limitations, boundary conditions can enable you to

- develop better experimental proposals, support session preparation (exploit plant system to the highest performance)
- work better with the operators (provide relevant information, know your options)
- build connection with diagnosticians and operators to better understand what happened in the pulse, how to avoid it.
- get big picture view of a plasma discharge, quick and efficient analysis of discharge components and interactions

Learn time management, prioritization and work as a team

- Find the right reference pulse -> particularly important for dimensionless scaling experiments
- Use first pulse of the session as reference -> Compare if conditions are the same when pulses spread across multiple experimental days. Standard H-mode as first plasma pulse at ASDEX Upgrade every day.
- Know the next two pulses. -> Plan ahead what your next pulse is going to get more good pulses in the session.
- Change as little from pulse to pulse as you can -> for optimal comparisons -> breakdown, ramp-up often kept the same

Back-up slides - Solutions

1. Highest plasma current reached on JET was 7MA (before the installation of the divertor)
2. ICRH resonance line at given magnetic field in an Ion Cyclotron Wall Conditioning discharge
3. Helium plasma discharge (blue – limiter, green – divertor) vs. Deuterium (salmon pink)