UK Atomic Energy Authority

Lessons learned from upgrades to the JET RF real-time control system.

Alex Goodyear 2021-07-05

IAEA 13th Technical Meeting on Plasma Control Systems, Data Management and Remote Experiments in Fusion Research

European Commission

Energy

Contract for the Operation of the JET Facilities Co-Funded by Euratom
This work was funded by the RCUK Energy Programme [Grant number EP/T012250/1]

CCFE CULHAM CENTRE FOR FUSION ENERGY

JET Plasma Control System

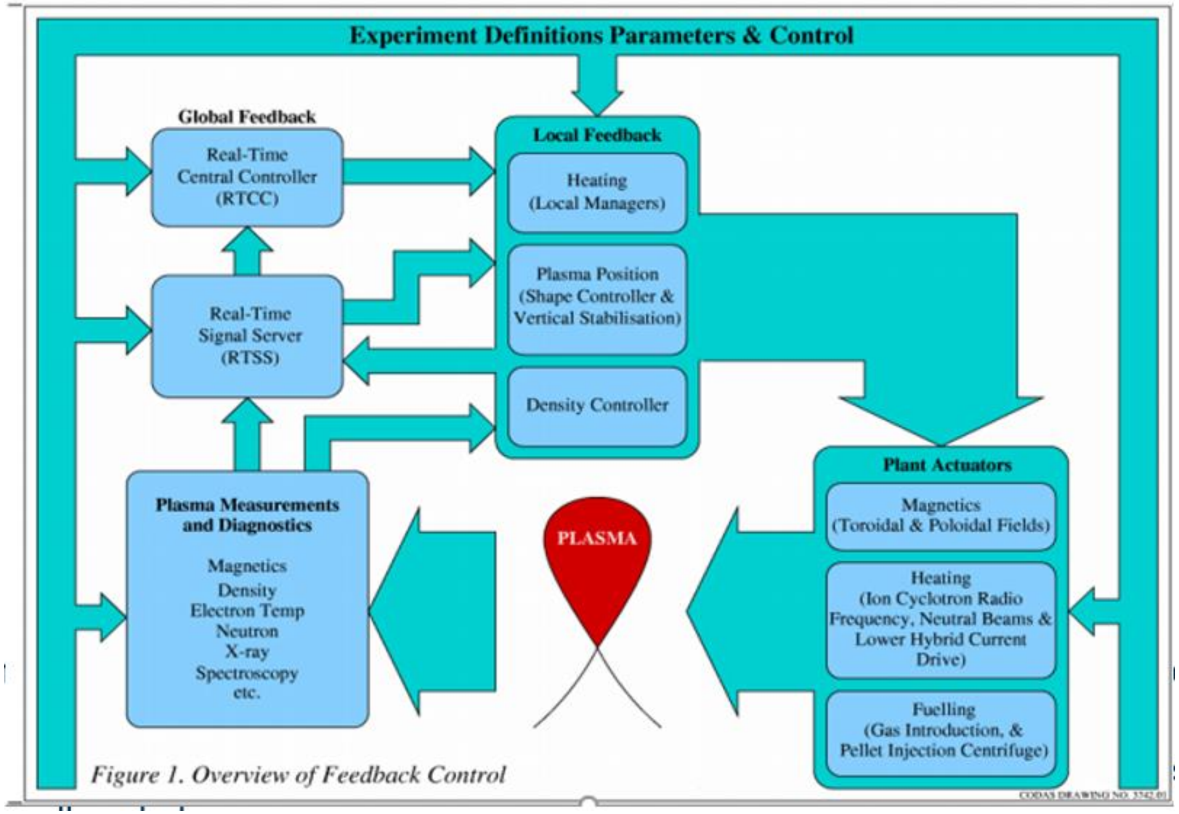


Figure 1. Overview of Feedback Control

JET Plasma Control System

- The PCS is distributed, loosely coupled and heterogeneous.
- **80+ real-time subsystems: diagnostics, support functions, controllers, protection,actuators.**
- Experimental objectives, with limits to protect plant.
- Actuators receive target references and control within local operator specified constraints.
- 500Hz overall cycle time.
- References can be feed-forward or feedback, computed in a number of places.

JET Plasma Control System / ICRH

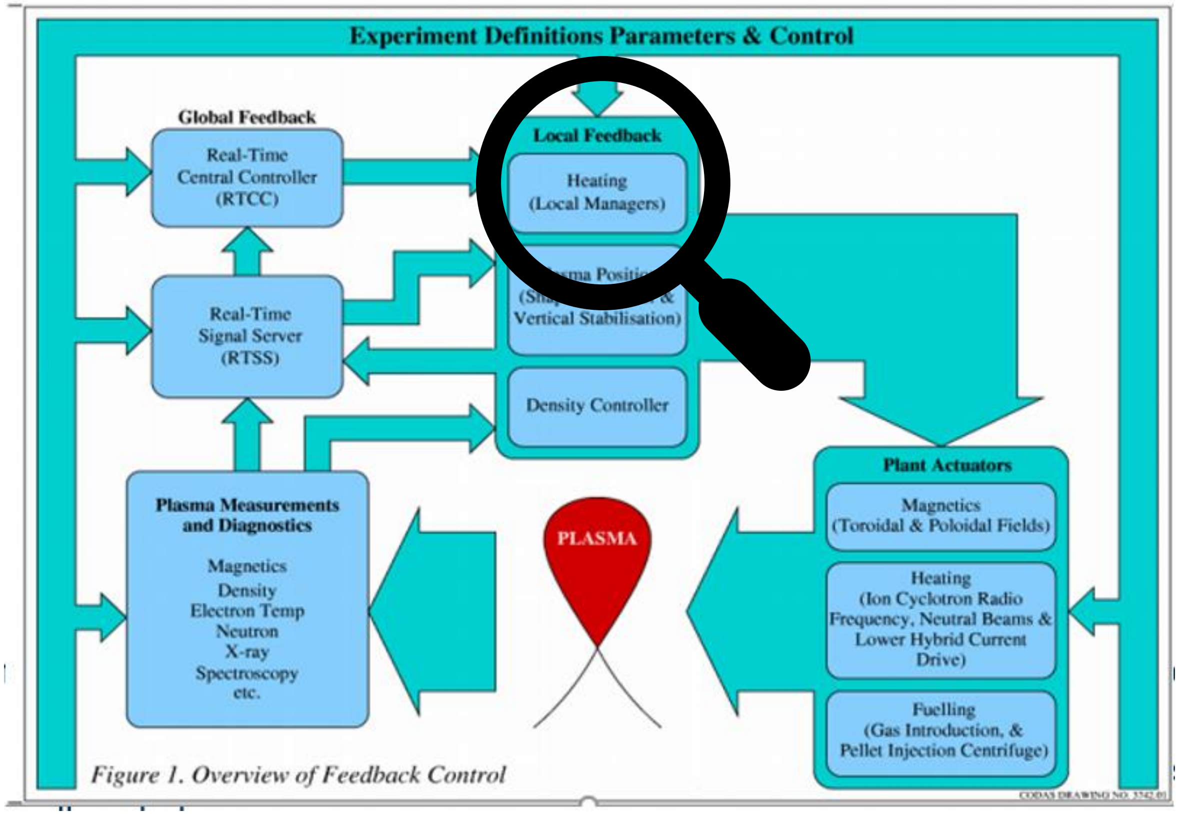


Figure 1. Overview of Feedback Control

JET Plasma Control System

- The PCS is distributed, loosely coupled and heterogeneous.
- **80+ real-time subsystems: diagnostics, support functions, controllers, protection, actuators.**
- Experimental objectives, with limits to protect plant.
- Actuators receive target references and control within local operator specified constraints.
- 500Hz overall cycle time.
- References can be feed-forward or feedback, computed in a number of places.

RFLM : Radio Frequency Local Manager (controller) Match scientific demand to engineering

UK Atomic Energy Authority

Technical Systems

Ion Cyclotron Resonant Heating Group

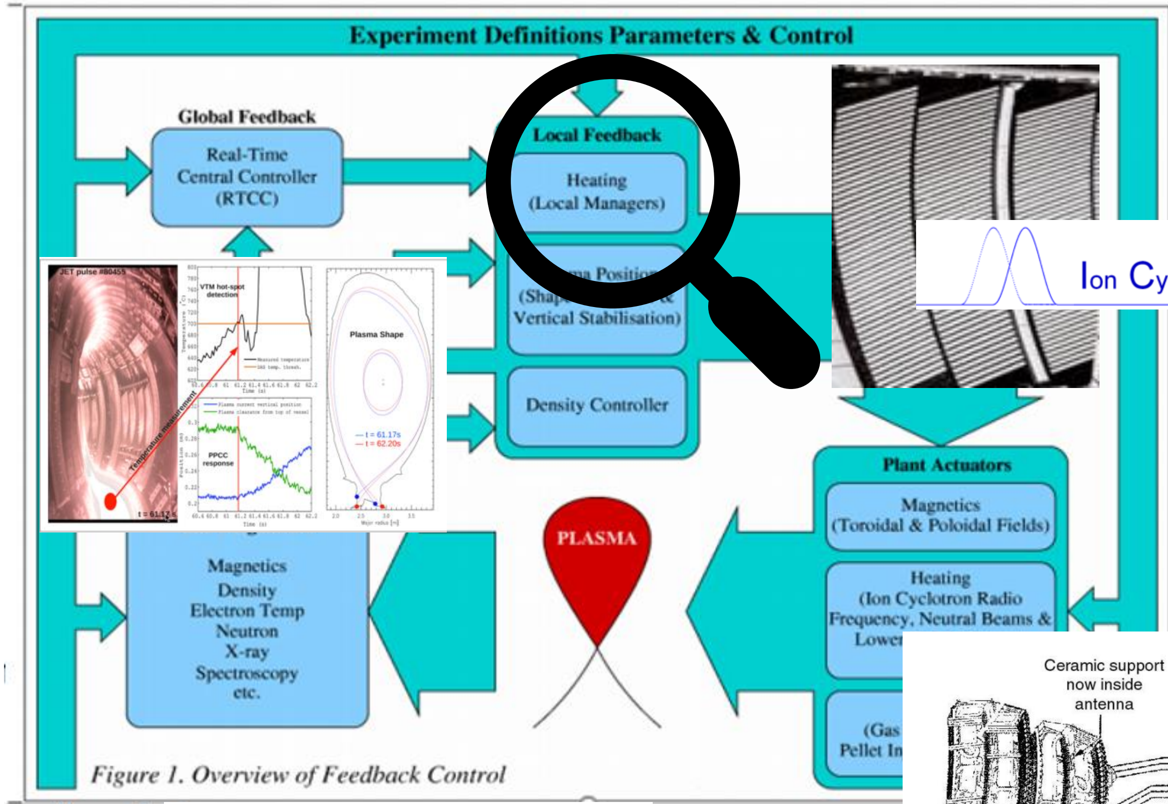
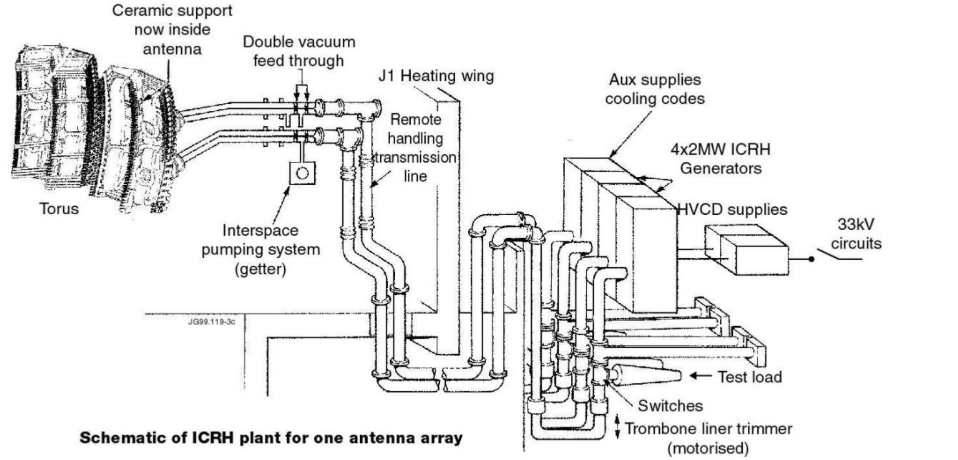


Figure 1. Overview of Feedback Control

EUROfusion — JET Control Room Physics Summary

Task Force: C
Scientific Coordinator: Unknown
Session Leader: Damian King / Unknown
Diagnostic Coordinator: Ashwin Patel
Engineer in Charge: Adrian Whitehead
Session Aims: Continuation of NBI conditioning/power demonstration
Date: Friday 18/06/21
Shift: Early
Week: n/a

Pulse	Time	Bt	Ip	Budget pulse/total (bar-L)	n_e dl ($x10^{19}$)	T_e (keV)	P_{NBI4} (MW)	P_{NBI8} (MW)	%T fraction (KT5P)		Pre & Post Pulse Comments
99106	14:15	2.5	2.2	3.59/19.24	10	3.5	6.5	9.5	37		*Repeat, higher NBI power* OK
99105	13:48	2.5	2.2	1.33/15.66	9.5	2.4	5.5	1.6	35		*Repeat* OK
99104	13:18	2.5	2.2	1.41/14.34	9	2.7	5	1.6	34		*Repeat* OK



Schematic of ICRH plant for one antenna array

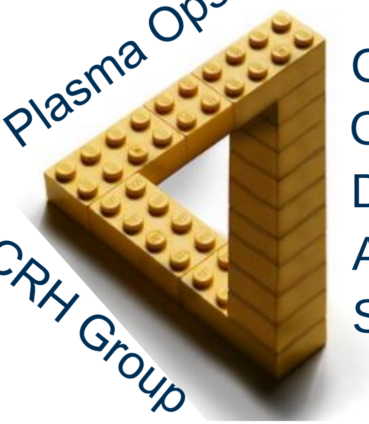
Roles and Responsibilities

UK Atomic Energy Authority

Goal Oriented Performance Requirement

Science Program -> Experiment

Plant & RF Engineering



Plasma Ops

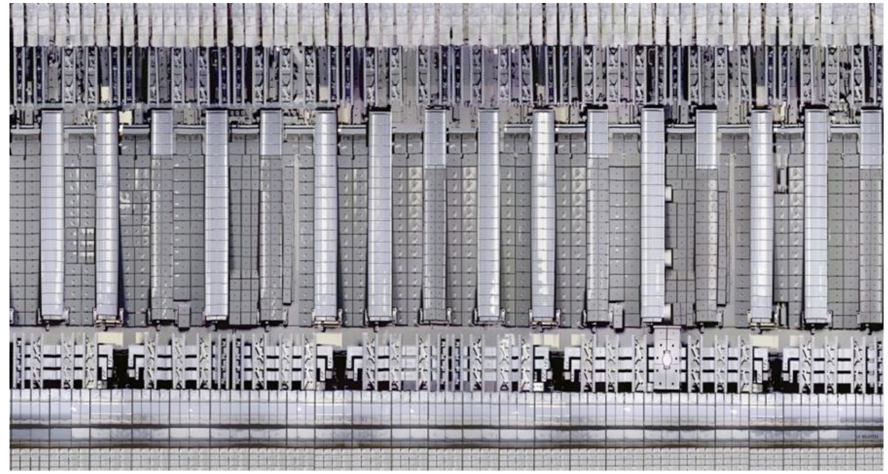
ICRH Group

CODAS

Integrated Control Embedded/Real-Time

Performance Constraints
Resilience/Lifetime
Optimise Effective Delivery

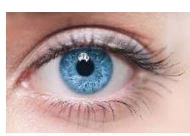
RFLM Upgrades: Requirements/Constraints



- Upgrades are to
  - To support new RF plant equipment i.e integration of the ITER-like antenna (ILA)
  - To improve plasma control schemes i.e modification to protect the ITER-like wall (ILW).
- Challenges
  - Trade off between improving performance and minimising risk
  - Retrofit behaviour into existing code
  - ITER “actuator sharing”
  - No option of redesigning the system from scratch because of
    - Cost in time and money
    - Risk to the program given the existing maturity
    - Level of confidence based on experience
- => Growth in complexity is inevitable <=

RFLM Evolution : 1996

<table>
<tr><td>Global</td><td colspan="16"></td></tr>
<tr><td>Group</td><td colspan="4">G1</td><td colspan="4">G2</td><td colspan="4">G3</td><td colspan="4">G4</td></tr>
<tr><td>Module</td><td colspan="4">A</td><td colspan="4">B</td><td colspan="4">C</td><td colspan="4">D</td></tr>
<tr><td>Generator</td><td colspan="2">A12</td><td colspan="2">A34</td><td colspan="2">B12</td><td colspan="2">B12</td><td colspan="2">C12</td><td colspan="2">C34</td><td colspan="2">D12</td><td colspan="2">D34</td></tr>
<tr><td>Amplifier</td><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>B1</td><td>B2</td><td>B3</td><td>B4</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>D1</td><td>D2</td><td>D3</td><td>D4</td></tr>
</table>

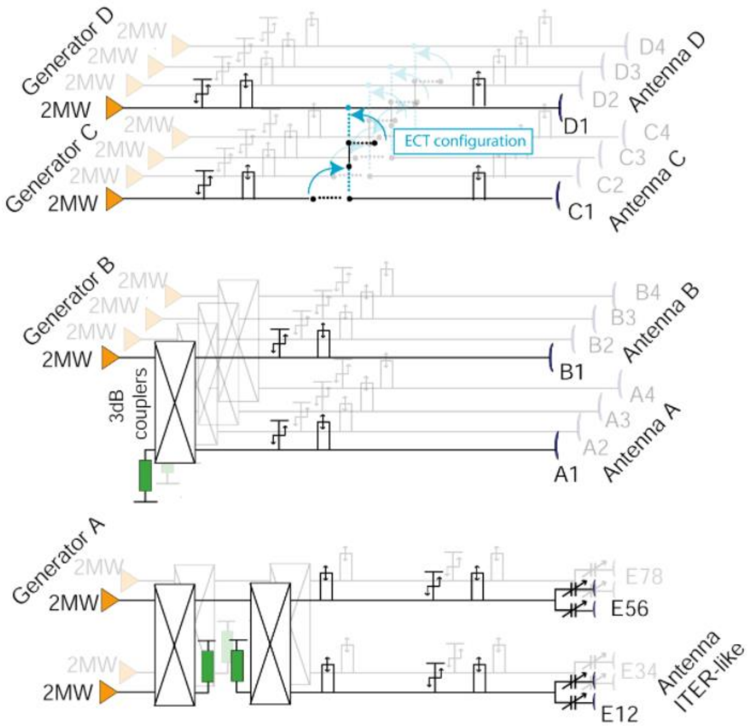


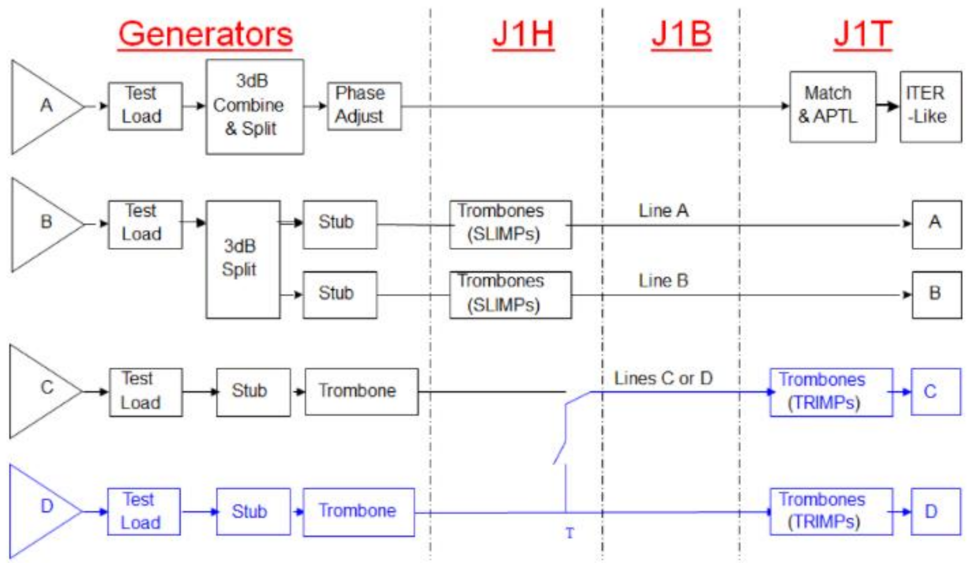
Designers leverage symmetries

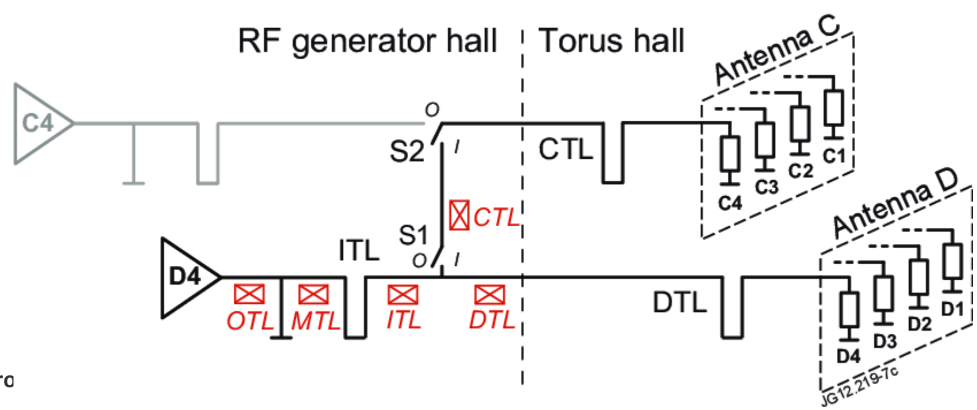
- Elegant
- Comprehensible
- Efficient

RFLM Evolution I : Symmetry breaking

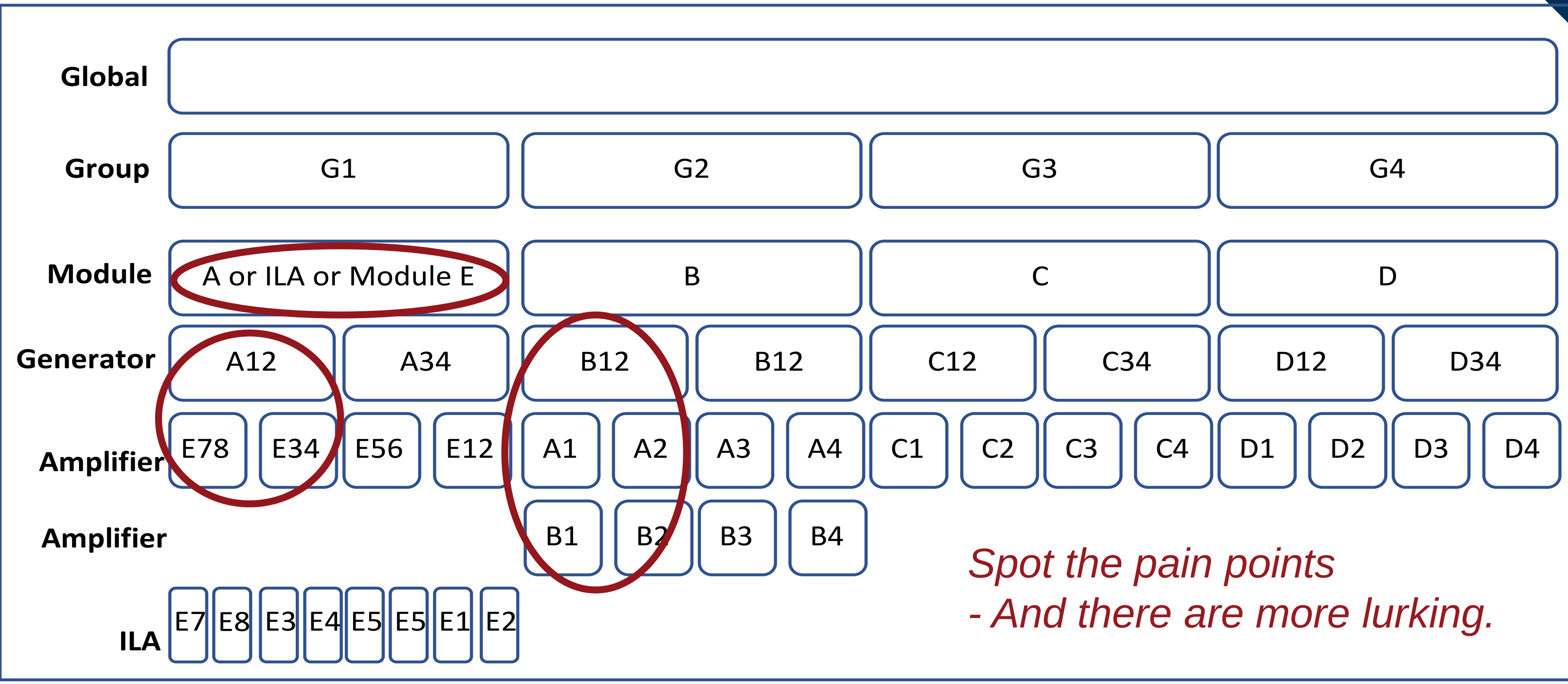
UK Atomic Energy Authority







RFLM Evolution I : Symmetry breaking

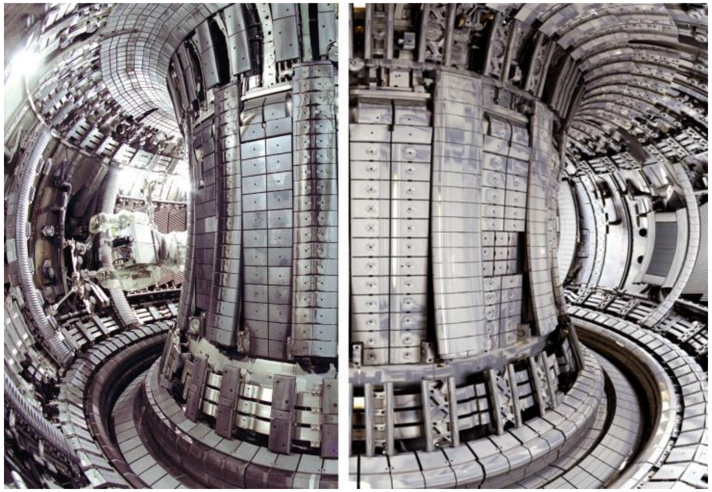


Project Requirements.
***"Just"** adapt the existing software – mostly the functionality is the same.*

The JET PCS evolution

UK Atomic Energy Authority

RTGS
- RTSS Signals
- PDV+RTCC Algorithms
- Control for normal + off-normal



	Protection	Experiments
	RTGS-P	RTGS-E
Signal server	RTSP	RTSS
Algorithms	PDV	RTCC
Protection	RTPP	RTEP

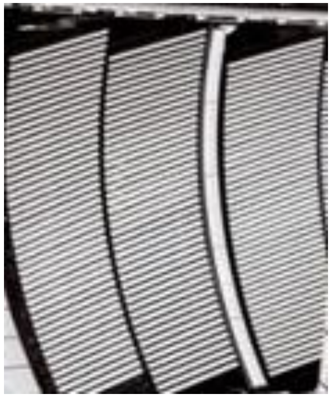
1996 Early RT Control + DT1

200x Eth/ATM

2010 ITER-like Wall

2020 DTE2

- Re-engineered in 2009 to protect ITER like wall (ILW).
- Infra-red camera systems were installed to detect hotspots.
- Real-time protection sequencer (RTPS) was introduced.
- Actuators modified to accept RTPS override instructions.
- *Maintain control – both for experiment goal AND machine protection.*



RFLM Evolution II : Functional changes

Basic protection: pulse termination PTN

PCS computes references [Why] → RF Actuator allocates power [What] → Power units PWM [How]

PLASMA PROTECTION SYSTEM

KY3-FAIL	0.000
SC-SOFT	76.902
SC-FAST	0.000
HIGH-FAIL	0.000

FAST>RF	0.000
SLOW>RF	0.000
STOP>PEL	0.000
SLOW>LH	0.000
TRIG>DM2	0.000
STOP>DM2	65.001

RFLM Evolution II : Functional changes

UK Atomic Energy Authority

Basic protection: pulse termination PTN

Time window / Power window : PEWS

PCS computes references [Why] → RF Actuator allocates power [What] → Power units PWM [How]

PEWS	RTSP	DMV	Plant Enable Window System (PEWS)

Algorithm	Parameter	Value		Out
Radio Frequency:	Min |Ip|	500.00 k	A	Ena
Radio Frequency:	Notch Min |Ip|	500.00 k	A	Ena
Radio Frequency:	Notch Tstart	40	s	Ena

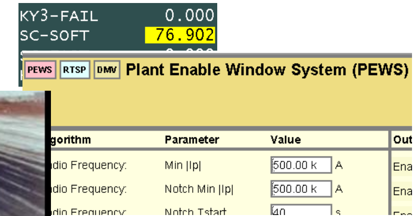
RFLM Evolution II : Functional changes

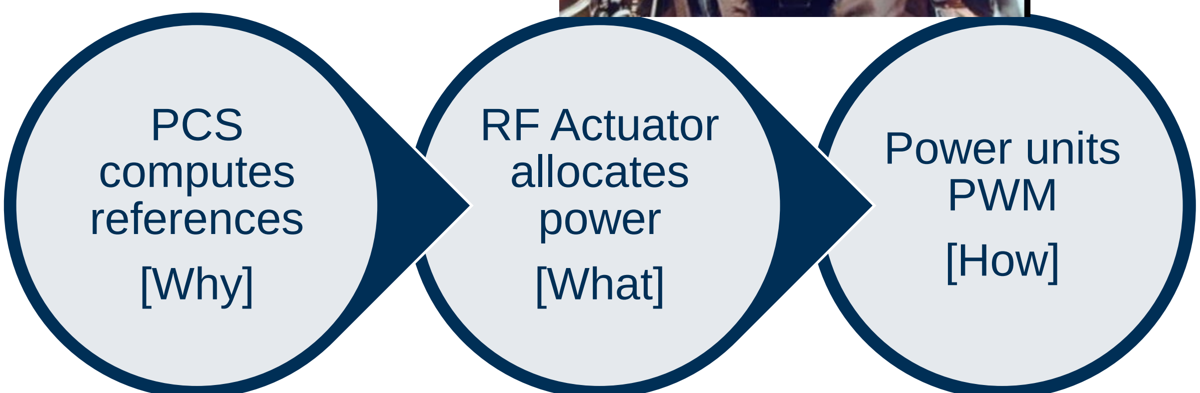
UK Atomic Energy Authority

Basic protection: pulse termination PTN

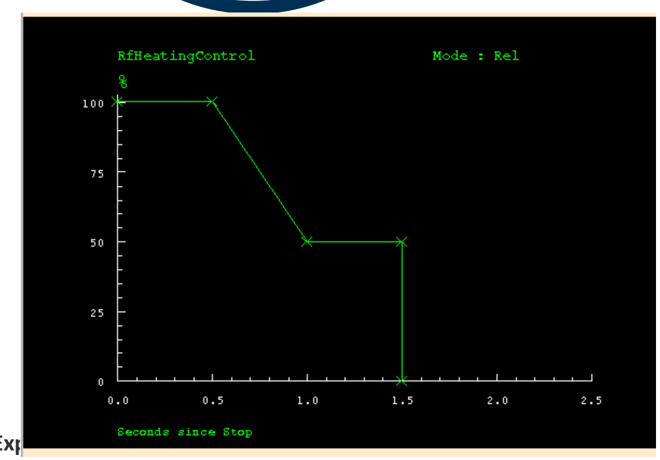
Time window / Power window : PEWS

Scenario Dependent Variation : RTPS



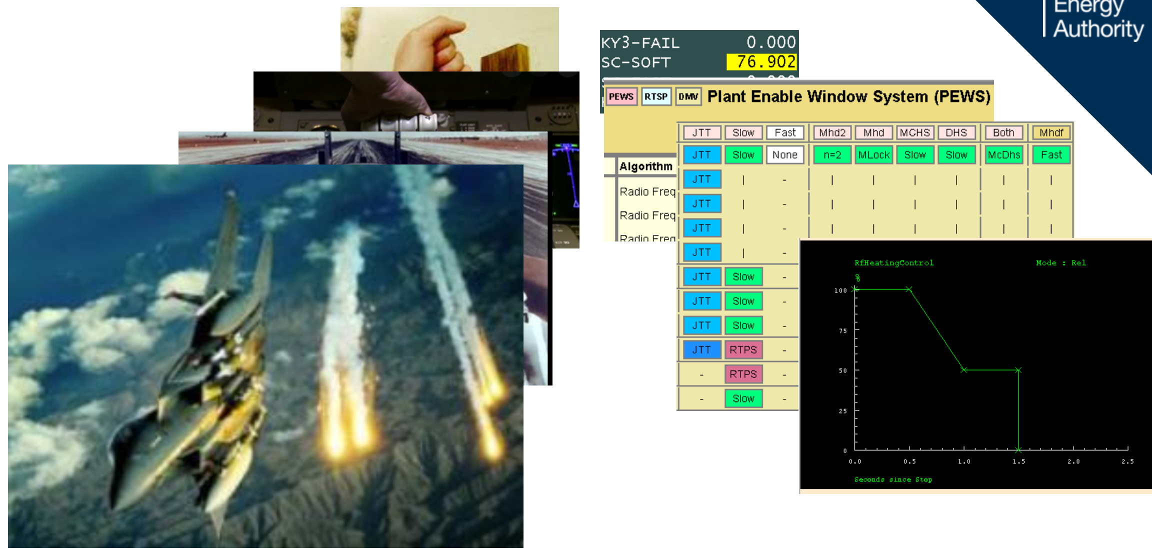


JTT	Slow	Fast	Mhd2	Mhd	MCHS	DHS	Both	Mhdf
JTT	Slow	None	n=2	MLock	Slow	Slow	McDhs	Fast
JTT	|	-	|	|	|	|	|	|
JTT	|	-	|	|	|	|	|	|
JTT	|	-	|	|	|	|	|	|
JTT	|	-	|	|	|	|	|	|
JTT	Slow	-	n=2	MLock	Slow	Slow	McDhs	Fast
JTT	Slow	-	n=2	MLock	Slow	Slow	McDhs	Fast
JTT	Slow	-	n=2	MLock	Slow	Slow	McDhs	Fast
JTT	RTPS	-	RTPS*	RTPS*	RTPS	RTPS*	RTPS*	RTPS*
-	RTPS	-	RTPS*	RTPS*	RTPS	RTPS*	RTPS*	RTPS*
-	Slow	-	n=2	MLock	Slow	Slow	McDhs	Fast



RFLM Evolution II : Functional changes

Basic protection: pulse termination PTN
Time window / Power window : PEWS
Scenario Dependent Variation : RTPS
Avoid Thermal Limits : VTM



PCS computes references [Why] → RF Actuator allocates power [What] → Power units PWM [How]

Vessel Thermal Map (VTM)

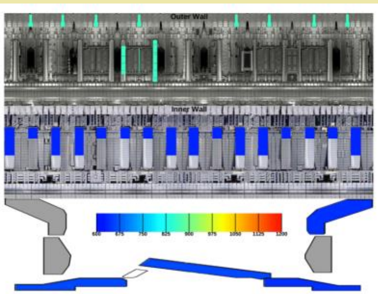
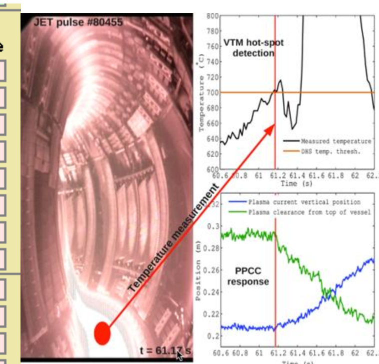


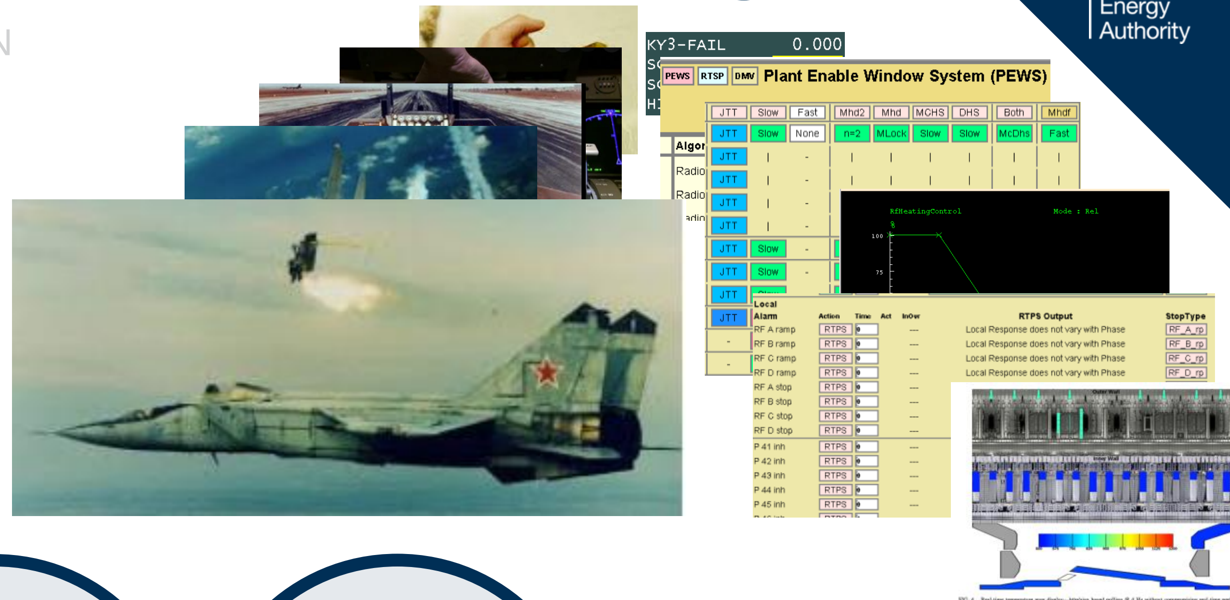
FIG. 4. Real-time temperature map display—http/ajax based polling @ 4 Hz without compromising real-time performance.

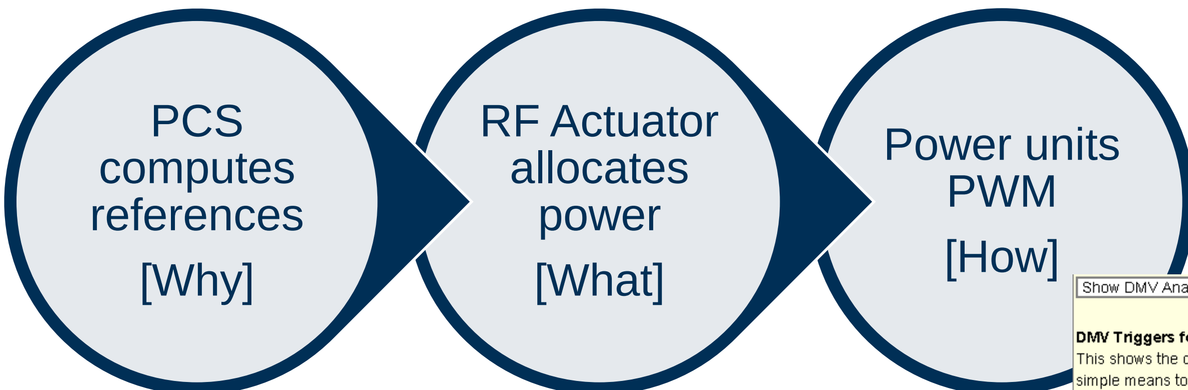
Local Alarm	Action	Time	Act	InOvr	RTPS Output	StopType
RF A ramp	RTPS	0		---	Local Response does not vary with Phase	RF_A_rp
RF B ramp	RTPS	0		---	Local Response does not vary with Phase	RF_B_rp
RF C ramp	RTPS	0		---	Local Response does not vary with Phase	RF_C_rp
RF D ramp	RTPS	0		---	Local Response does not vary with Phase	RF_D_rp
RF A stop	RTPS	0		---	Local Response does not vary with Phase	RF_A_st
RF B stop	RTPS	0		---	Local Response does not vary with Phase	RF_B_st
RF C stop	RTPS	0		---	Local Response does not vary with Phase	RF_C_st
RF D stop	RTPS	0		---	Local Response does not vary with Phase	RF_D_st
P 41 inh	RTPS	0		---	Local Response does not vary with Phase	P41_inh
P 42 inh	RTPS	0		---	Local Response does not vary with Phase	P42_inh
P 43 inh	RTPS	0		---	Local Response does not vary with Phase	P43_inh
P 44 inh	RTPS	0		---	Local Response does not vary with Phase	P44_inh
P 45 inh	RTPS	0		---	Local Response does not vary with Phase	P45_inh

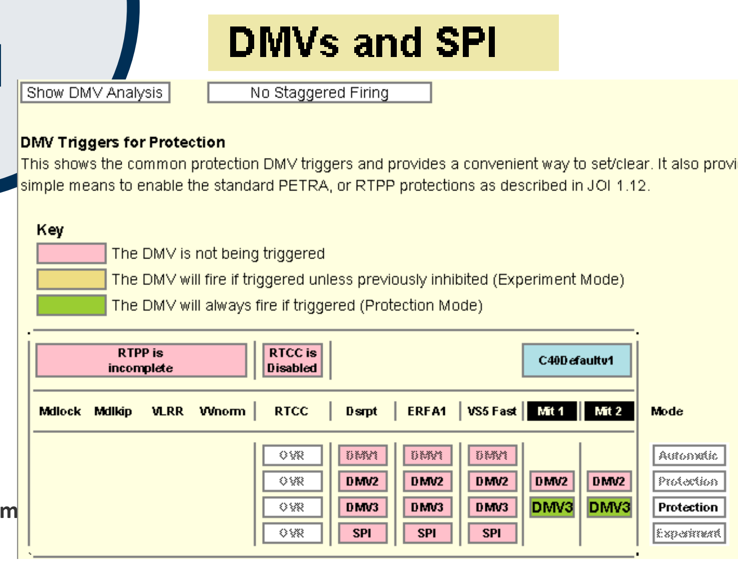


RFLM Evolution II : Functional changes

Basic protection: pulse termination PTN
Time window / Power window : PEWS
Scenario Dependent Variation : RTPS
Avoid Thermal Limits : VTM
Mitigate Disruption : DMV





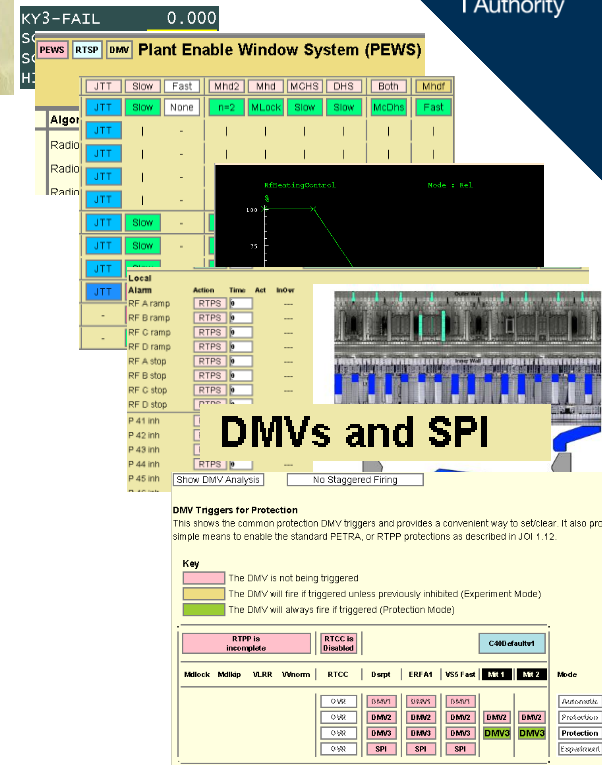


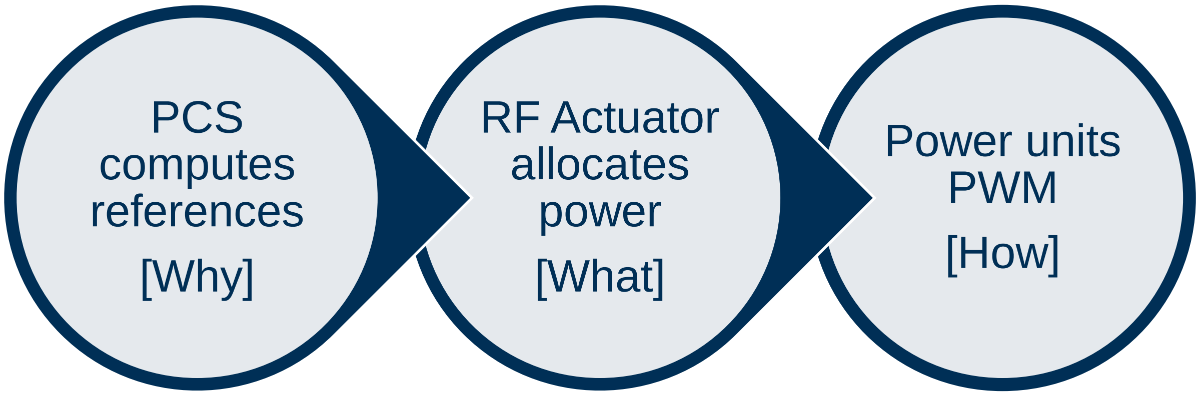
IAEA 13th Technical Meeting on Plasma Control Systems, Data Management and Remote Experim
Fusion Research. Culham, 5-8 July 2021

UK Atomic Energy Authority

RFLM Evolution II : Functional changes

Basic protection: pulse termination PTN
Time window / Power window : PEWS
Scenario Dependent Variation : RTPS
Avoid Thermal Limits : VTM
Mitigate Disruption : DMV
Optimise Performance
Continue Mission with Remaining Resources

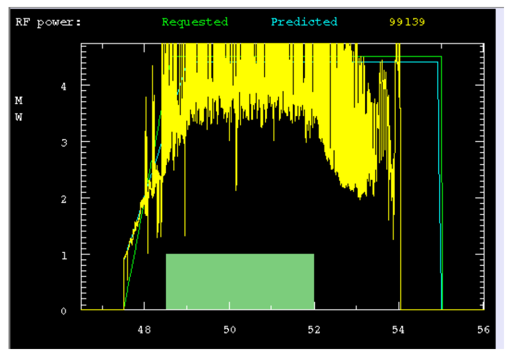


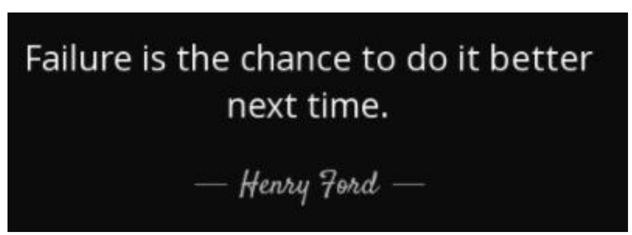


RFLM Evolution II : Debrief

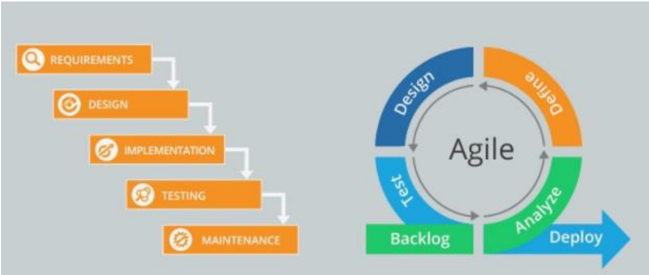
Did all the systems act :
- as expected,
- in all of the modes,
- given all of the observed events?

This turns out to be non-trivial and needs tool support.
Correctly identifying edge cases is difficult but important.





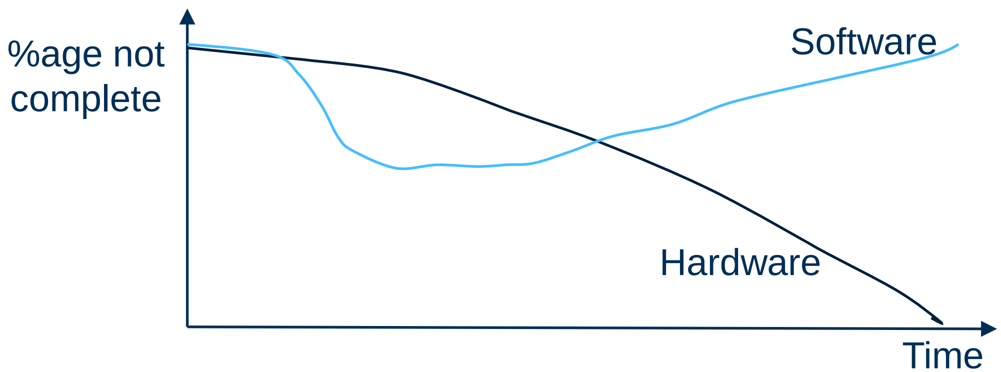
Software Engineering / System Engineering



waterfall is always agile in the long run
requirements are always incomplete
balance short/long term

extreme rigour : every line of code ⇆ requirement

extreme agile : rapid code/run cycles



software costs usually underestimated
software volume(t) generally increasing
feature creep leads to combinatorial growth

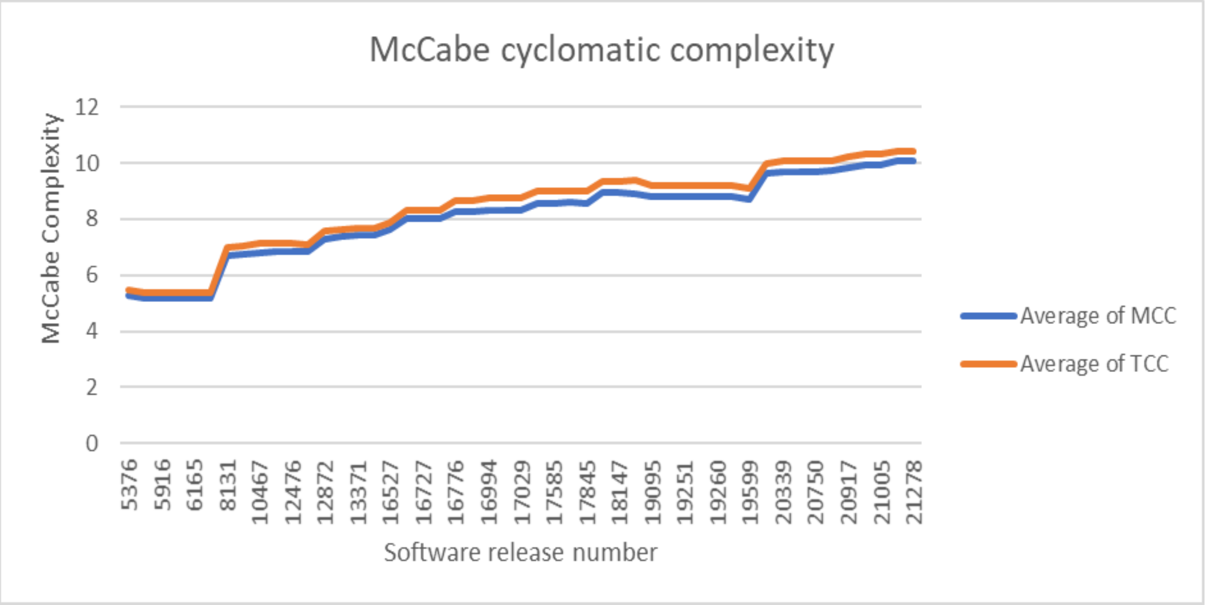
quality software costs are ~ 5x normal

Best modern practice is to measure software quality to manage it better...

Growth in Complexity

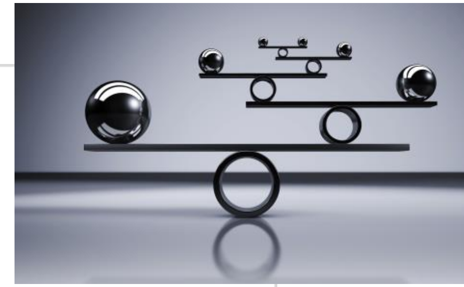
- Considerable increases in the McCabe cyclomatic complexity are due to algorithm enhancements or physical plant changes.
- Software release 8131 included the move from a dual 68K CPU setup to a quintuple 68K system.
- Software release 12872 added 3DB calculations.
- Software release 16527 added control of the new ILA Antenna.
- Software release 16776 added RTPS local protection.

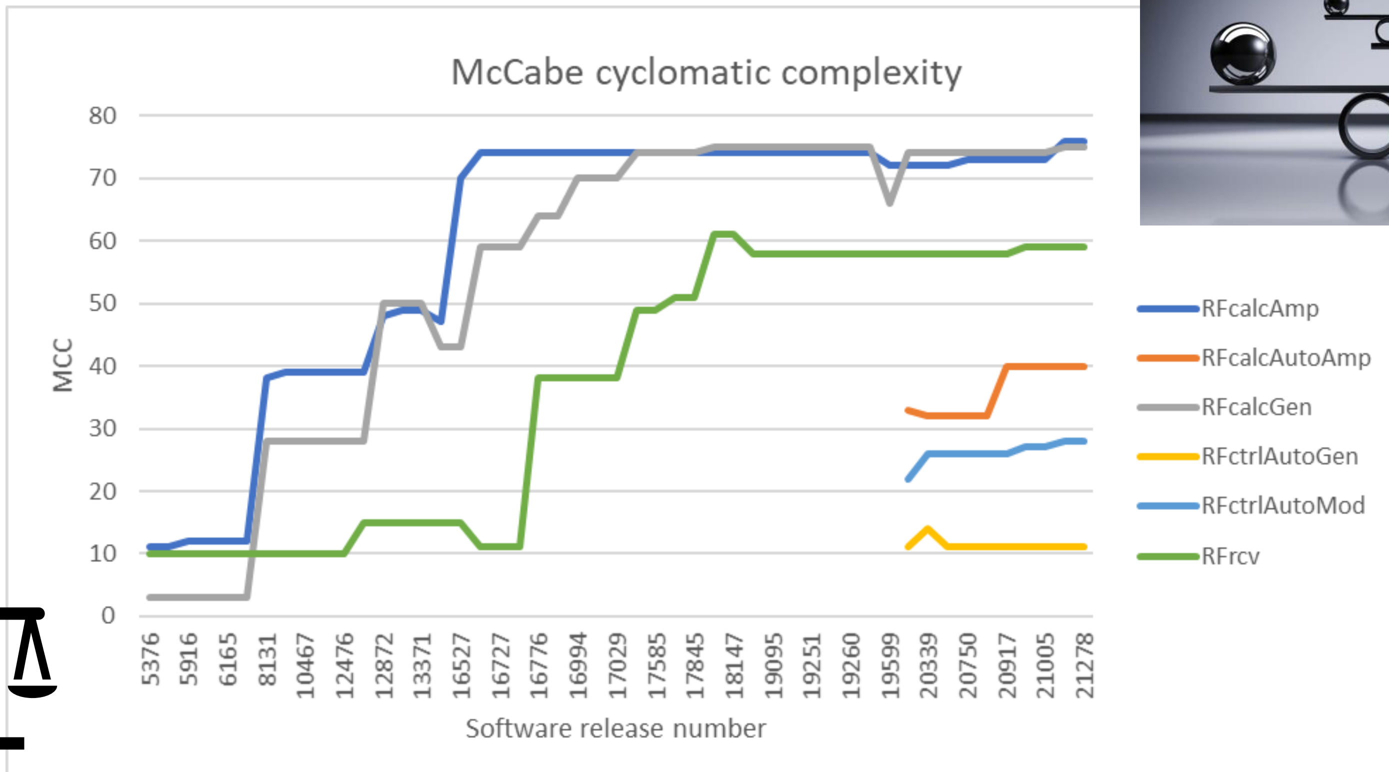
- Software release 19989 added the new Advanced Power Control Algorithm, but kept the ability to select the old control mechanism.



Growth in complexity

- The new Advanced Power Control Algorithm created 3 new functions
- Complexity greater than 20.

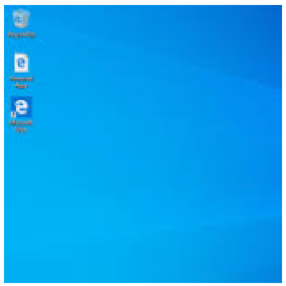




- The drivers of this complexity come mostly from project level decision processes and constraints (backwards compatibility, not all the plant upgraded).

Root causes of complexity.

progressing with leaps of faith is risky
we prefer safe, incremental change



stakeholders don't like to throw things away
they may need them again in future

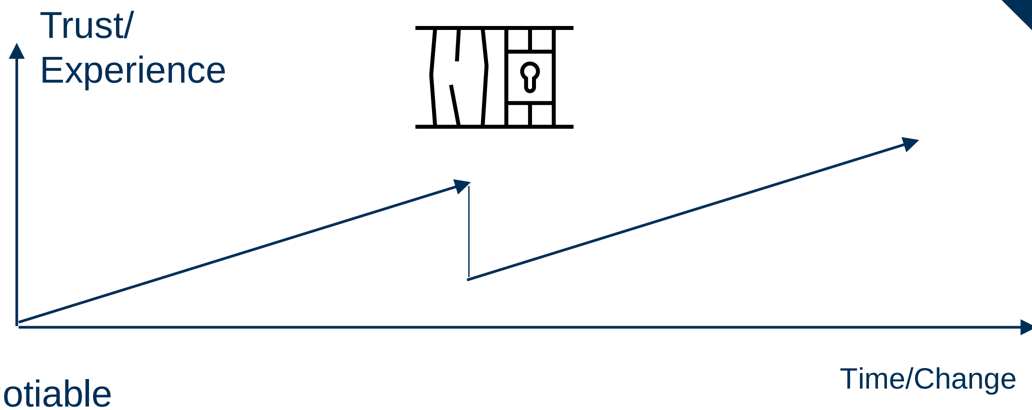
Delete nothing
Break nothing

Change
~~nothing~~
quite a lot

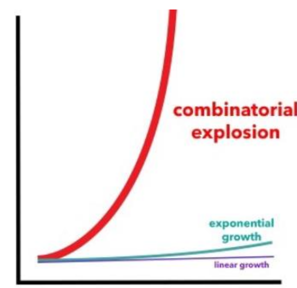
Preserve identical behaviour using copy/paste techniques.

Intentional QA rule breaking. Accept the complexity as the cost of the compromise.

System Testing



- Challenges
  - Highly complex
    - Internal logic / many interfaces
    - Large parameter space
  - Backwards compatibility non-negotiable
    - Number of features always growing
    - Prove the new ; maintain the old
  - Multi-disciplinary
    - Embedded expert must understand enough RF + POG
  - Law of unintended consequences
    - Must re-examine previous design assumptions
    - Just doing the same as before may not be enough



- Methodology and supporting infrastructure
  - Simulations running on workstations
  - Offline test rigs that support hardware in the loop testing
  - Toolkit to simulate external inputs, replaying JET data from archive pulses.

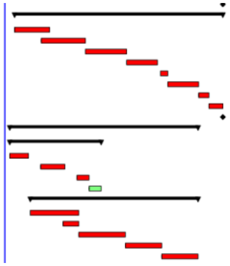
Integrated Commissioning

- Challenges
  - Demonstrate end to end (real world)
  - Minimize machine time required (£$€₽ ¥¥₩)
  - Don’t break anything (high confidence in advance)
  - Avoid test bias with independent test/make teams
- Methodology
  - Use low risk conditions/reduced limits
  - Pulse schedules written by plasma operations team
    - method and pass criteria specified
    - reviewed independently by interface ROs
  - Compress many tests within one pulse
    - Different behaviours in different time windows
    - Can run in the tail of broader commissioning activities
    - Shortens critical path to full science operations
  - Accept risk/time balance
    - Enough variation to cover main behaviours
    - Not feasible to be exhaustive
    - Ultimately ; FOAK ; Experiment


UK Atomic Energy Authority

Procedure	
Commissioning of JET Tokamak Systems	
Author: M Cleverly	Reviewer: D Ciric

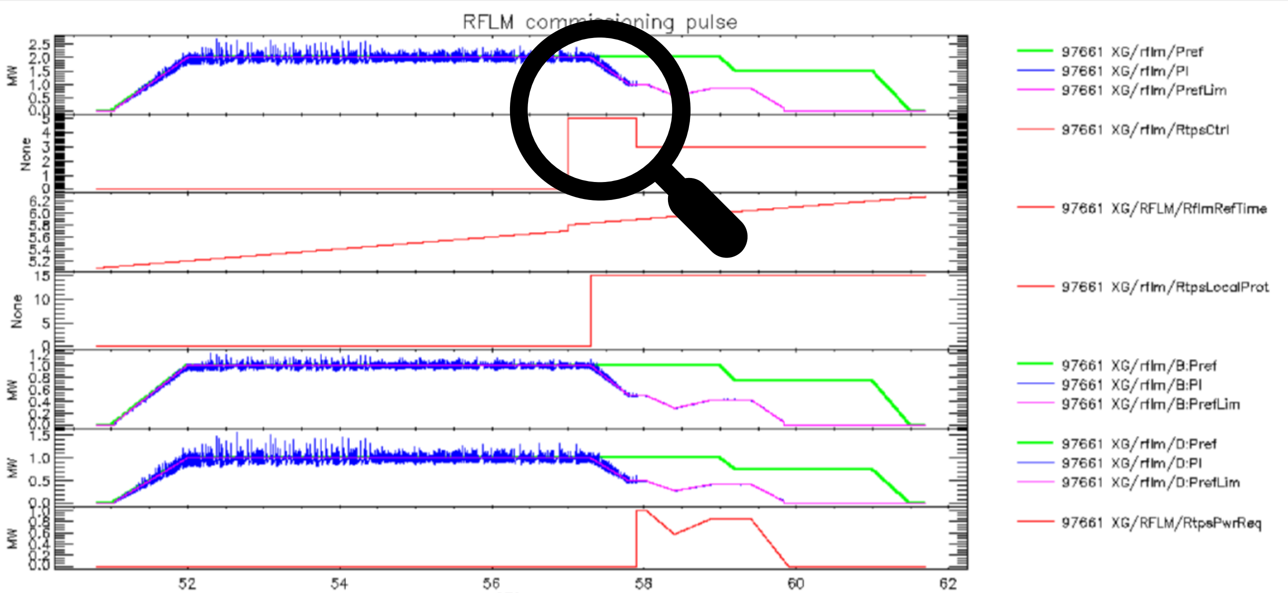
RS1957		End of Restart	0.0h		17-Jun-19 08:00
Plasma Conditioning/Commissioning			208.0h	08-May-19 06:00 A	17-Jun-19 08:00
RS1490	fgr	Diagnostic commissioning with some ICRH power	80.0h	08-May-19 06:00 A	14-May-19 22:00
RS2292	fgr	Diagnostic Commissioning with Some NBI Power No.2	108.0h	13-May-19 08:00*	21-May-19 20:00
RS2296	fgr	Diagnostic Commissioning > 100kV	62.0h	21-May-19 20:00	29-May-19 18:00
RS2508	fgr	He Plasma Diagnostic Commissioning	64.0h	29-May-19 18:00	04-Jun-19 18:00
RS2510	fgr	Experiment M18-46	16.0h	05-Jun-19 08:00	06-Jun-19 16:00
RS1496	fgr	NB High Power Commissioning	64.0h	06-Jun-19 16:00	12-Jun-19 16:00
RS1502	fgr	Diagnostic Commissioning with High NBI Power (3MA)	32.0h	12-Jun-19 16:00	14-Jun-19 16:00
RS1714	fgr	Demonstrate JET Targets	8.0h	14-Jun-19 16:00	17-Jun-19 08:00
RS1514	fgr	Plasma Commissioning Completed	0.0h	17-Jun-19 08:00	
Heating & Fuelling Systems Commissioning			198.0h	07-May-19 06:00 A	12-Jun-19 14:00
NIB 4 Conditioning/Commissioning			224.0h	07-May-19 06:00	24-May-19 22:00
RS2336	dking	NIB 4 Initial SYNC Commissioning-2	64.0h	07-May-19 06:00*	10-May-19 22:00
RS1466	dking	NIB 4 High Power Sync Duct Commissioning	80.0h	13-May-19 06:00	17-May-19 22:00
RS1486	dking	NIB 4 High Power Sync Commissioning at 100kV No.1	40.0h	20-May-19 06:00*	22-May-19 14:00
RS2314	dking	NIB 4 High Power Sync Commissioning at 110kV No.2	40.0h	22-May-19 14:00	24-May-19 22:00
NIB 8 Conditioning/Commissioning			166.0h	11-May-19 06:00 A	12-Jun-19 14:00
RS1456	dking	NIB 8 Initial SYNC Commissioning No.1	120.0h	11-May-19 06:00 A	20-May-19 14:00
RS2384	dking	'J' Plate tests	16.0h	17-May-19 14:00	20-May-19 14:00
RS1476	dking	NIB 8 High Power Sync Duct Commissioning	80.0h	20-May-19 14:00	29-May-19 14:00
RS2324	dking	NIB 8 SYNC Commissioning No.2 > 100kV	80.0h	29-May-19 14:00	05-Jun-19 14:00
RS1492	dking	NIB 8 High Power Sync Commissioning at 110KV No.1	80.0h	05-Jun-19 14:00	12-Jun-19 14:00



Case Study

UK Atomic Energy Authority

- Protection system multi-function combined test within a single pulse
- Units under test:
  - Two "global" stops
    - jump to termination event.
    - total power ramp down (cascades to modules)
  - Four Hotspot warning limits by local module ramp (impacts total power capacity)
    - Ramp down each module (need to check all modules go through path as expected)
    - Local ramp parameters chosen symmetrically : reduce to 50% in 0.5s (each test needs two checks)
  - Four Hotspot alarms by local module stop (impacts total capacity)
- Overall then
  - 10 functional tests, in a short period of the pulse
  - Local ramps run in between the global stops (must still have power to demonstrate)
  - Local ramps staggered at 50ms intervals to enable traces to be identified
  - Local stop sequencing also tuned to be identifiable



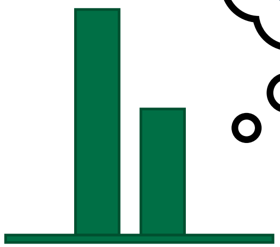
Verification of complex hardware designs with timing and logic is supported by specific tools.

Verification of complex systems in PCS would benefit from an equivalent.

Case Study: Lessons learned in test data.

UK Atomic Energy Authority

Symmetrical values are a bad idea.



to 50%

by 50%

right is not enough
right for the right reason

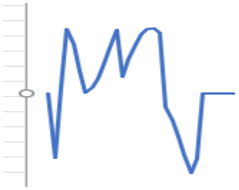
Duplicated values don't detect errors.

Module	A	B	C	D	E	…	AA
Power	50	50	50	50	50	50	50

all the same?

Cutting back eventually costs more than you save.

sine;+pulse; -pulse



sine; pulse
+pulse;

Invest in careful test design.

Allocate sufficient time.

Consider tooling to help check complex traces.

Summary : regarding RFLM

UK Atomic Energy Authority

- RFLM software has adapted over 25 years to cope with a lot.
  - Maximum freedom to achieve a clean design came at the start.

    it was the time of maximum symmetry

    it was the time of least operational knowledge
  - Tested and trusted features became essential tools for operations

    ops team proposed improvements progressively as we learned
  - Each feature change considered alone seems relatively small

    complexity is multiplicative, not additive.
  - Major engineering changes were encountered (ECT, ILA, ILW, …)

    Most physical updates replace predecessors (self contained)

    BUT – the impact on software requirements can be hard to assess.

The integrated increase in measured complexity is significant and would be a concern but for our thorough understanding of the cause.

Conclusions : more broadly.

UK Atomic Energy Authority

Operations software should be expected to change through the life of a tokamak: this gives resilience and ability to optimise.

Supporting the systems, tools, knowledge and people to achieve this effectively needs significant resource and recognition.

Managing software change can be counter-intuitive
- Keeping old features to reduce risk often increases it.
- Changing operations software regularly is much easier than only touching it during major maintenance outages.
- Some best practices and software quality metrics if strictly followed can compete with operational requirements.
- The output of the software team is invisible and the value may be discounted when it is working well. But it is an essential link in running any machine and if invested in adequately, the ROI will be high.

UK Atomic Energy Authority

Thank you.

Acknowledgements.

Adam Stephen, Nicoletta Petrella, Igor Monakhov
United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom.

The views and opinions expressed do not necessarily reflect those of UKAEA and Fusion for Energy which are not liable for any use that may be made of the information contained herein.

This work was funded jointly by the RCUK Energy Programme and by Fusion for Energy. To obtain further information underlying this paper, whose release may be subject to commercial restrictions, please contact PublicationsManager@ccfe.ac.uk*.*

This work has been carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the European Union's Horizon 2020 research and innovation programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.