Second Technical Meeting on Long-Pulse Operation of Fusion Devices

Technical and Engineering Challenges for Long Pulses on JET-ILW

D.B. King[1], E. Lerche[2], X. Litaudon, S. Brezinsek, E. Joffrin, F. Auriemma, M. Beldishevski, N. Balshaw, M. Baruzzo, A. Boboc, P. Card, I. Carvalho, P. Carvalho, I. Coffey, P. Mc Cullen, S. Dalley, E. Delabie, P. Dumortier, R. Felton, S. Gerasimov, Z Ghani, A. Goodyear, N. Hawkes, R. Henriques, S. Hotchin, P. Jacquet, I Jepu, D. Keeling, D. Kinna, D. Kos, E Litherland-Smith, R. Lobel, P. Lomas, C. Lowry, J. Mailloux, M. Maslov, D.Matveev, A. Meigs, S. Menmuir, J. Mitchell, I. Monakhov, C. Noble, M. Poradzinski, F. Rimini, S. Silburn, H. Sun, C. Srinivasan, B. Thomas, D. Valcarcel, J. Waterhouse, A. West, I. Young

and JET Contributors* and the EUROfusion Tokamak Exploitation Team**

UKAEA

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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Special thanks to the JET/UKAEA Engineering, Technical, SL, Pilot ,CODAS and Diagnostics teams

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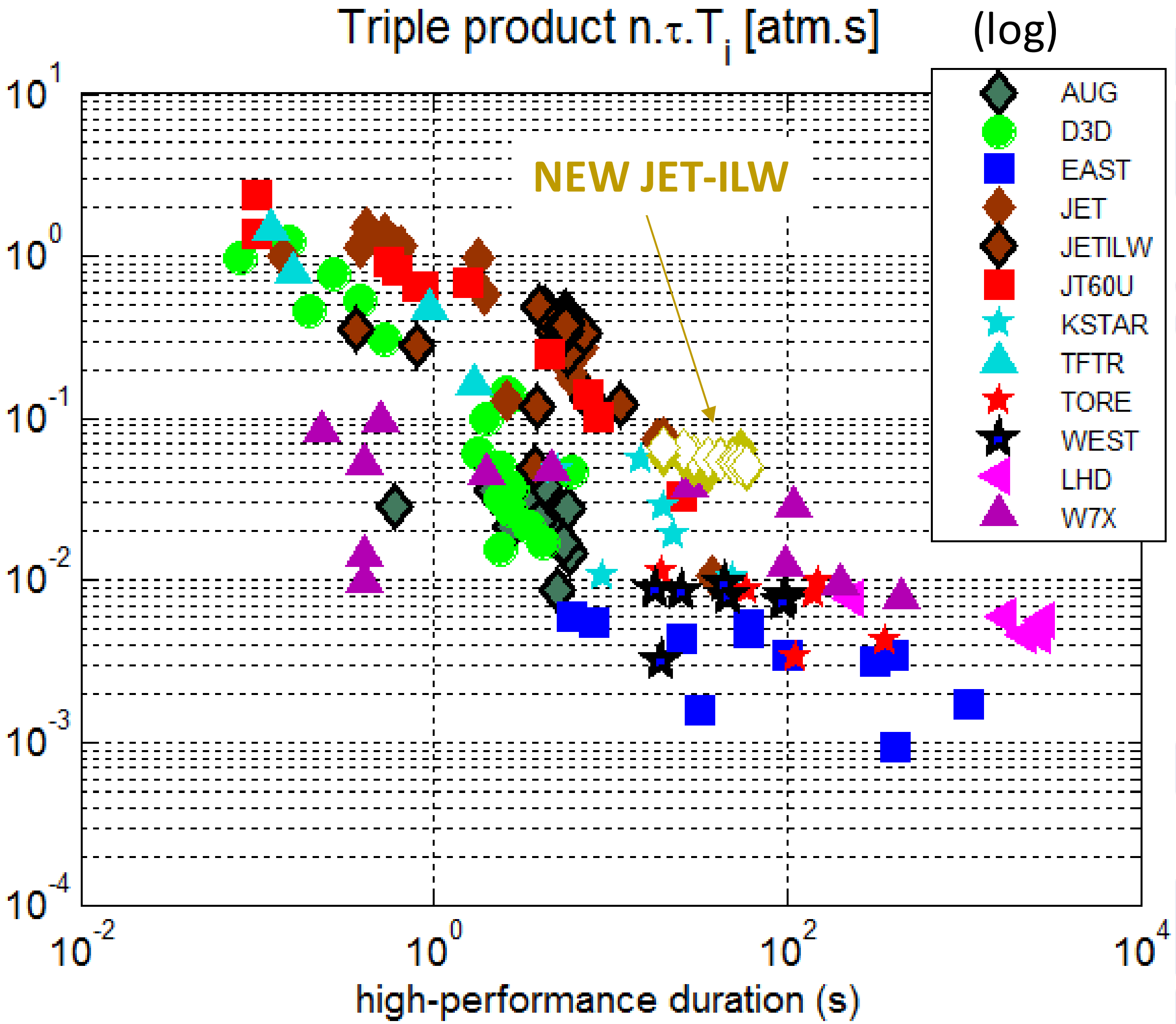
Introduction

- In last period of JET Operations there was a desire to extend CICLOP database to include 30-60s pulses on JET. Also beneficial for water activation studies.
- JET is a challenging device for long pulses, typically 5-10s main phase
- Previous pulses with 60s heating done in carbon wall with ICRH + LHCD
- Key results shown by E. Lerche earlier in this conference



X. Litaudon, Nucl. Fusion 2023

Limits for LPO: control & event handling to remain in the safe domain!

JET

Machine/Wall limits

- Available flux
- Energy (I^2t limit) or forces on the coils
- Injected power and/or Energy
  - Max Energy to be exhausted by the cooling system
  - Max. power reached
  - Max duration of injected power reached
- Power/energy/temperature for PFC
  - Limit on wall/divertor temperature
  - Limit on heating systems
- Wall/divertor erosion
  - Flakes or dusts production
  - Erosion, re-deposition and migration
  - Flakes leading to disruption
- Measurements in control system
  - Current plasma measurement drift
  - Neutron limits, Gas limits etc

Plasma physics limits

- **MHD stability (current and pressure)**
  - Pressure/Beta limits
  - Current instabilities
  - Disruption force
  - Pedestal pressure
- **Plasma radiations**
  - Core impurity (e.g. W)
  - UFO from erosion leading to radiative collapses
- **Density**
  - Uncontrolled density (wall recycling)
  - Density limits

[CICLOP and EUROfusion Operation Network E. Belonohy 2022]

Key Issues Identified to Consider and Solve

JET

- Toroidal Field I^2t
- Flux Consumption
- Heating Availability and Limitations
- Heat load management
- Pulse Development
- Control Systems/CODAS
- Diagnostics
- Approval of tests in large fusion device

Completed in last days of JET operations - pros and cons to this!

Many hurdles to overcome in a very short time!

Pulse Targets

Identified two pulse types as a target:

- **30s, H-mode pulse with maximum possible heating – meaningfully longer than standard JET pulse but with minimal changes to JET systems**

- **60s, L-mode or H-mode pulse with maximum possible heating – target for significantly extending JET database contributions, requires more substantial changes and approval**

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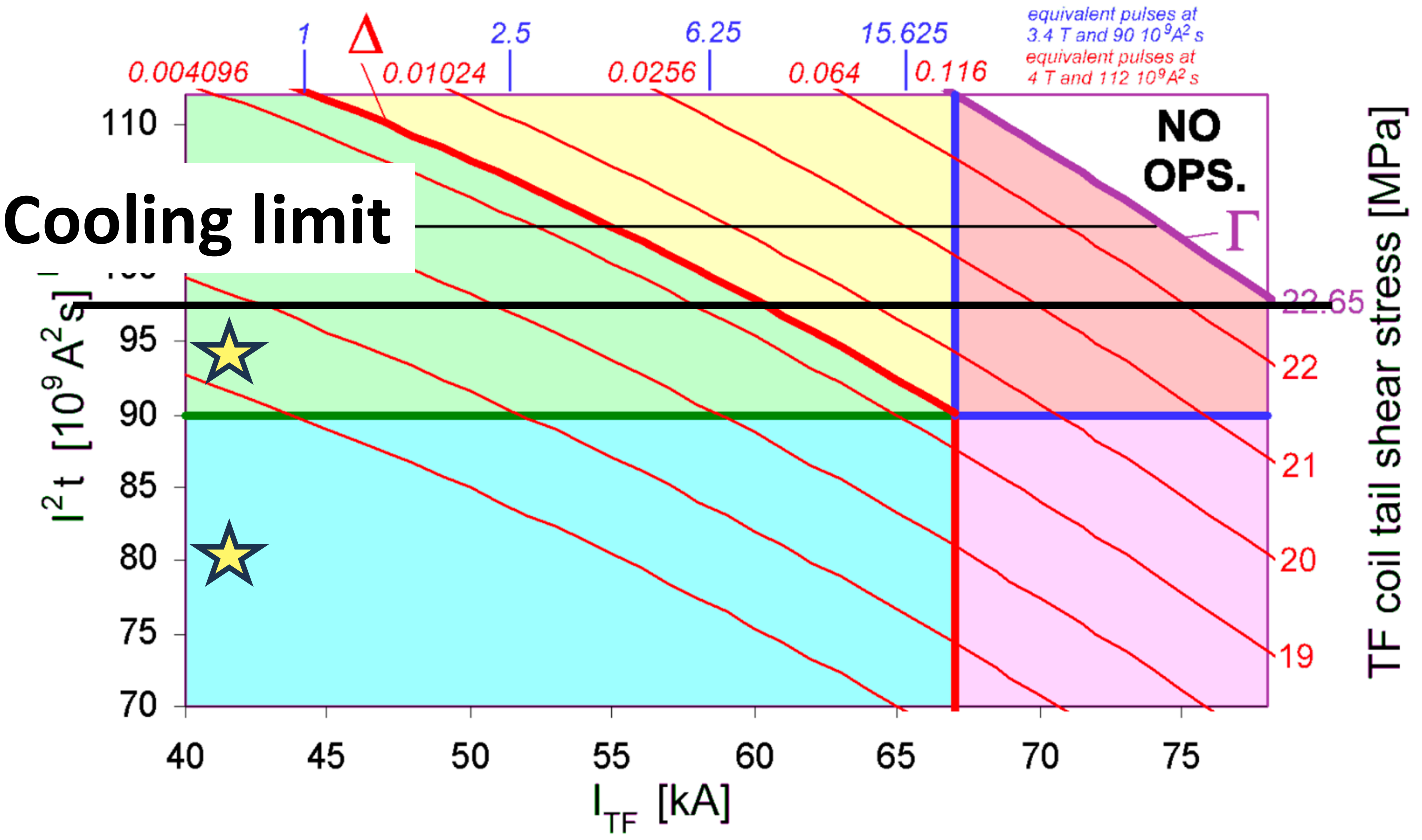
- **60s, L-mode or H-mode pulse with maximum possible heating – target for significantly extending JET database contributions, requires more substantial changes and approval**

Discussion in this talk primarily relates to 60s pulse

Toroidal Field

- JET has copper coils cooled by GALDEN coupled to a water cooling system
- Use of low field necessary due to I^2t limit on JET, fatigue budget approval required above $9\times10^{10}A^2s$, no operation above $11.2\times10^{10}A^2s$
- Choice of field also driven by ICRH schemes and existing plasmas



Plot of allowed TF settings from JET operating instruction

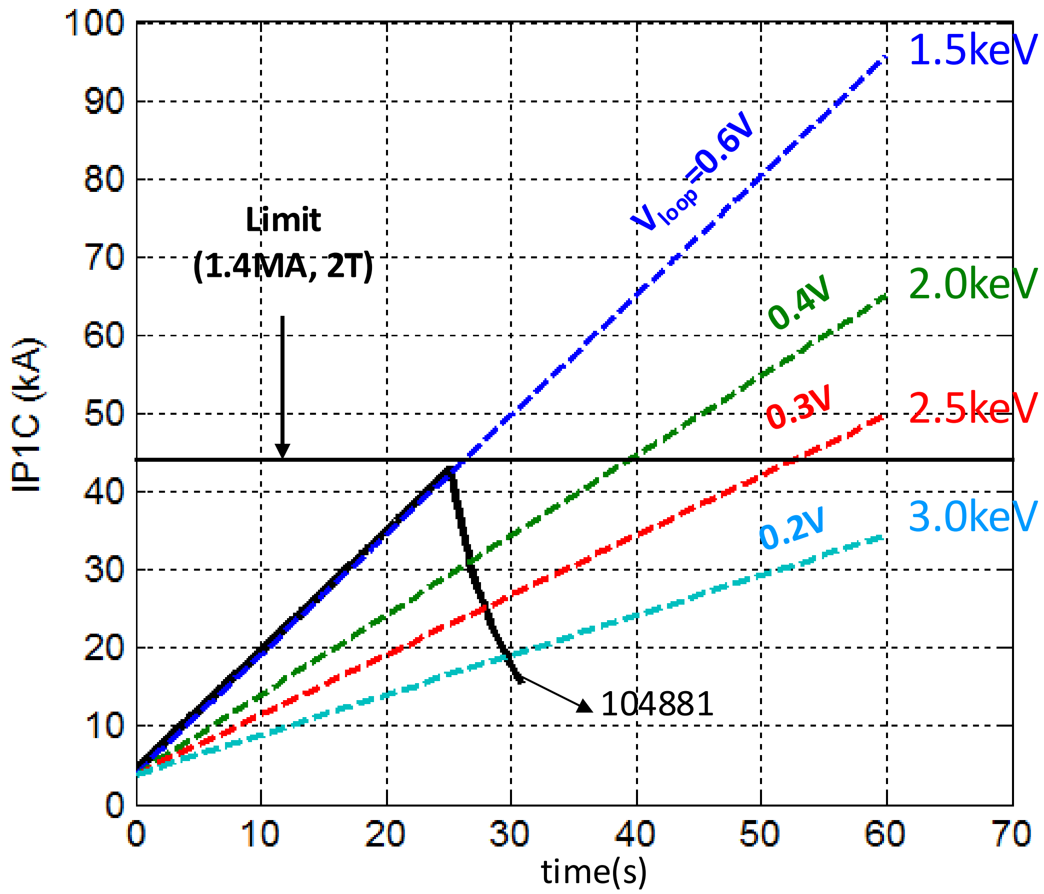
Even when within limit high I^2t restricts pulse rate and performance of chillers restricts space further

Flux Consumption

JET

- JET relies on inductive current drive hence the plasma current chosen will be dictated by this
- Requires low resistivity to achieve a long pulse on JET
- Estimate Te>2.5keV required
- Drives the pulse design to lower density -> impact on heating

P1 flux estimate (Spitzer ~ 1/Te$^{3/2}$)



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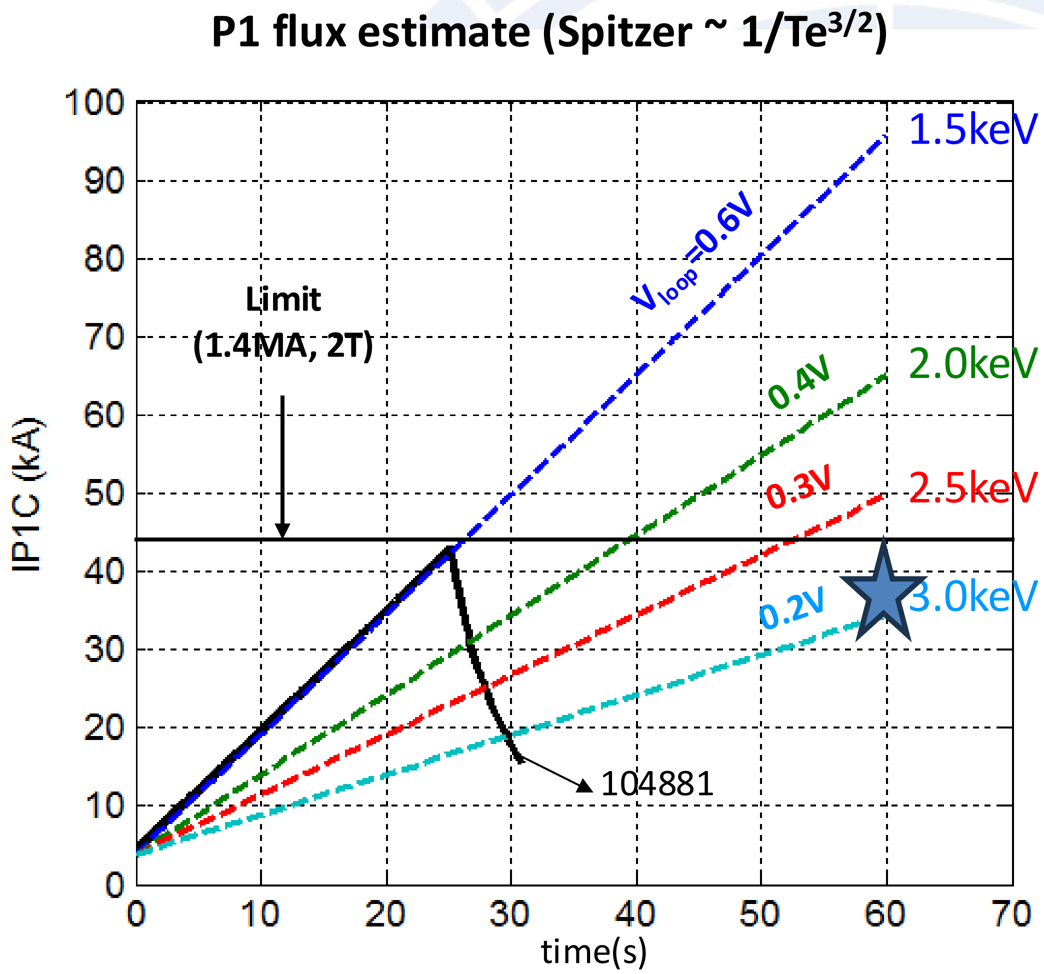
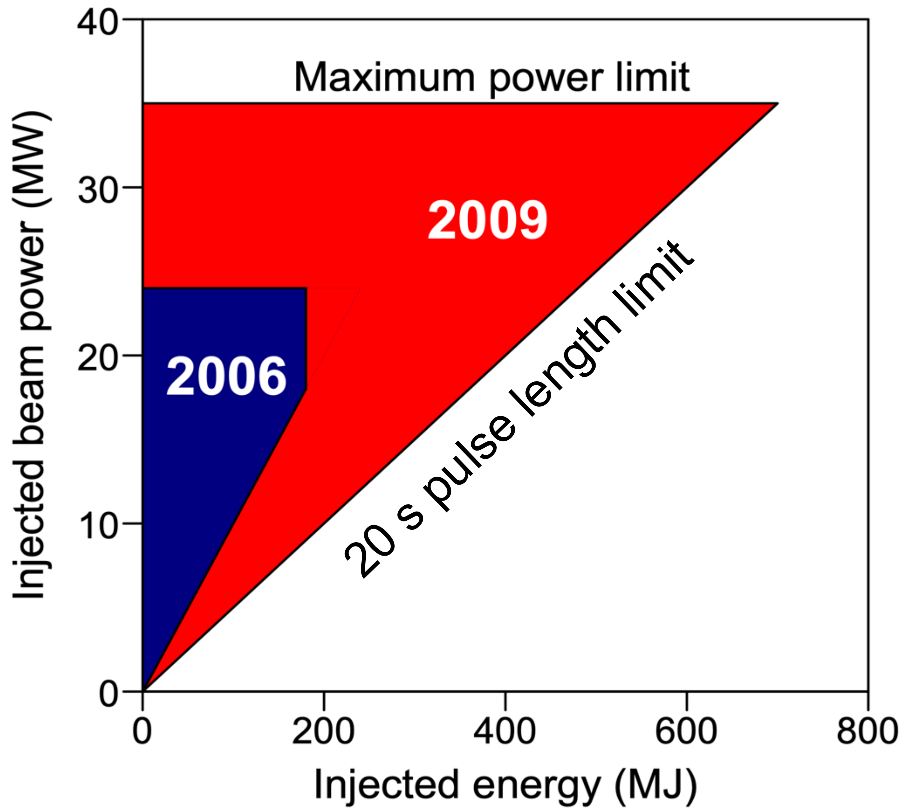
Final result!



Neutral Beams

JET

- Previous attempts at >30s on JET used wave heating only
- JET NBI upgrade allows up to 15s per PINI*
- By stacking PINIs appropriately can build 30s or 60s pulse with maximum possible power
- Safe operating limits on the beamline prevent longer operation for various reasons but shinethrough is major limit on power



*originally 20s, revised from 2020 onwards

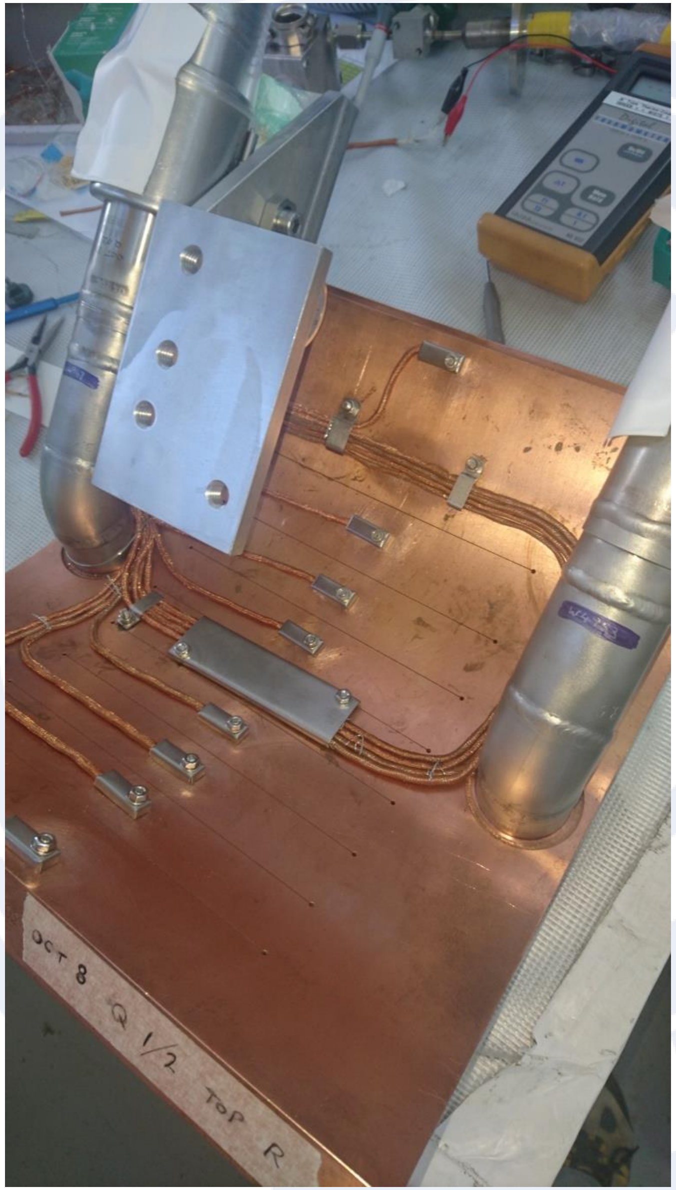
Neutral Beams: Limitations

JET

Main limiting components on JET beamline are:

- **Molecular ion beam dump (J-plate)**
- **Inertially cooled scrapers on beamline**
- **Transformer ratings on some HV power supply**

(more beyond to prevent *continuous* operation but these are limits for 15s)



Neutral Beams: Shinethrough

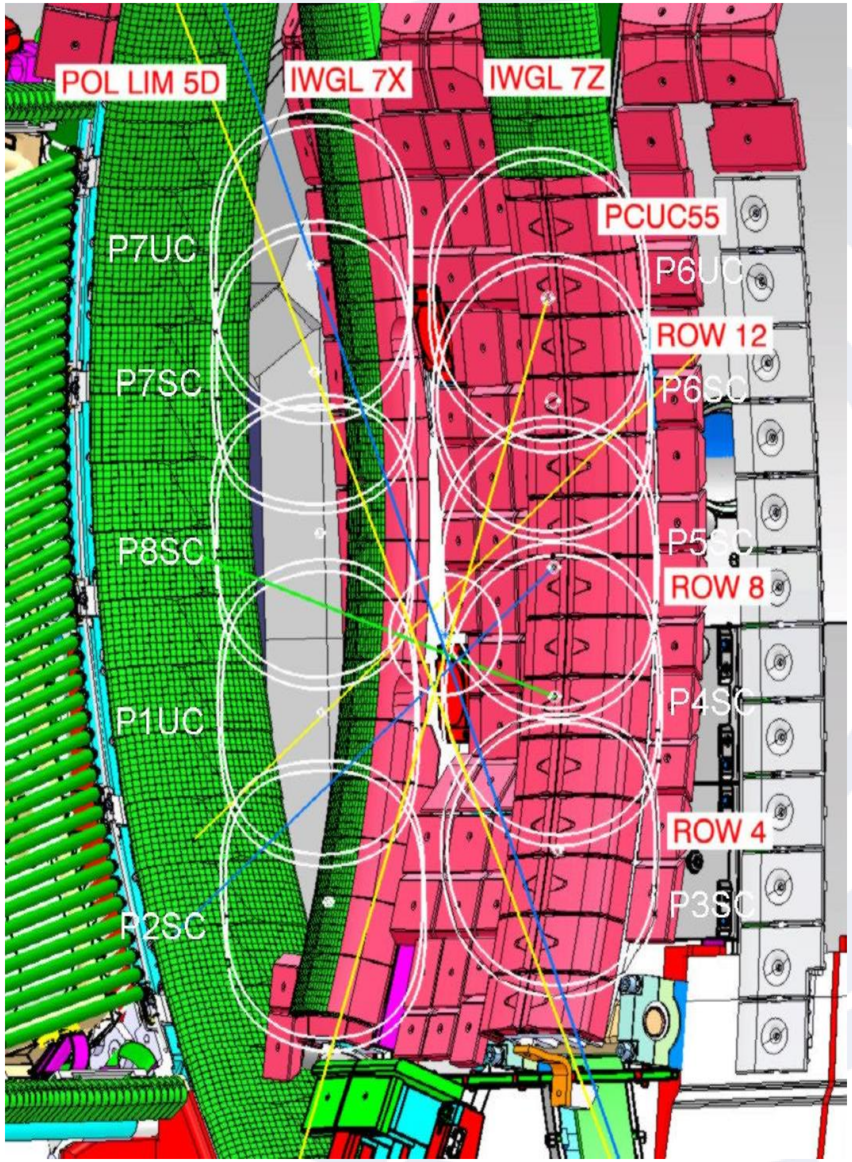
JET

JET NBI power was increased at the same time the metal wall was introduced

Increased issues with beam shinethrough

Multiple interlocks exist to ensure adequate plasma density to ensure no damage to wall

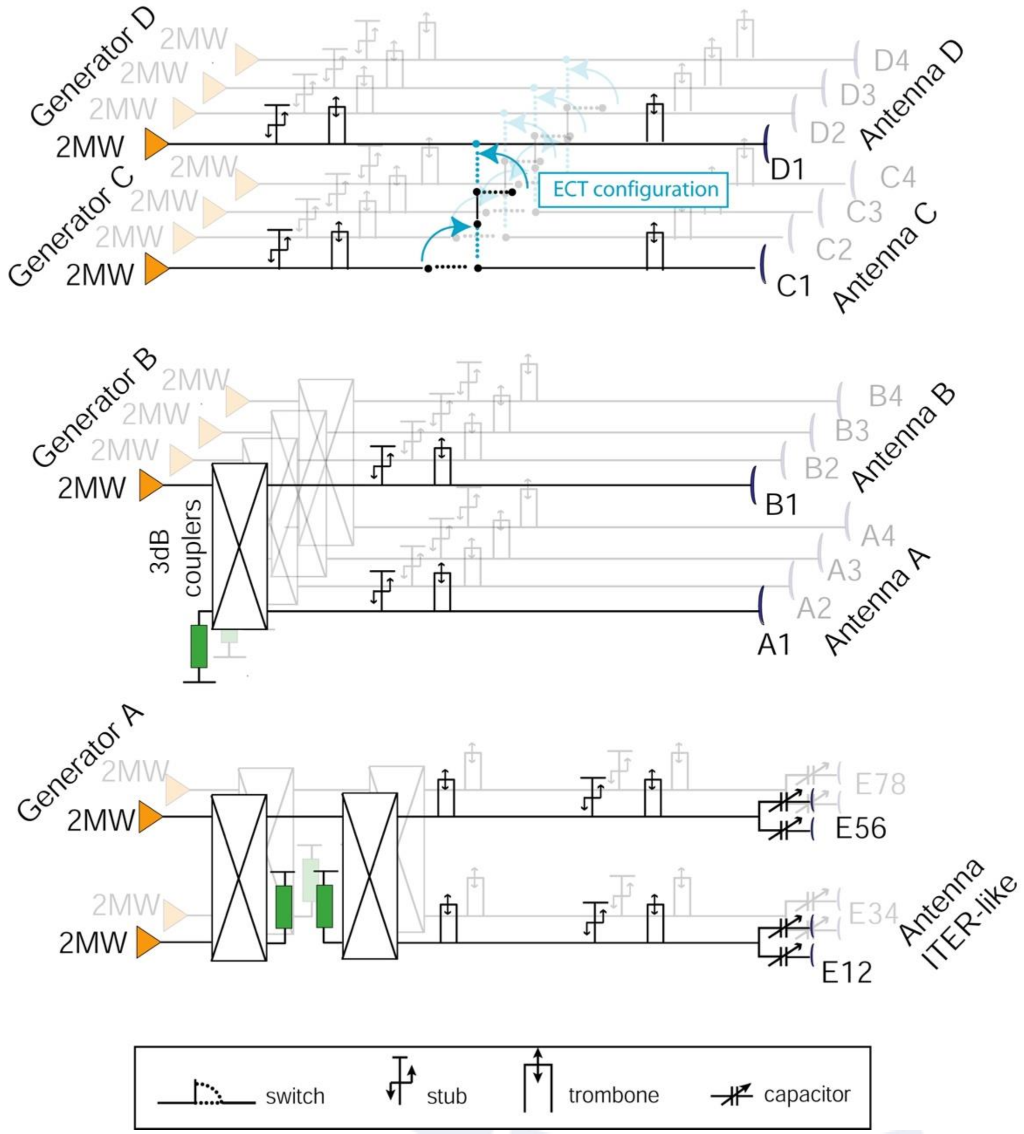
Calculations performed at range of beam energies ->
Desired density sets the beam energy ->power



ICRH

JET

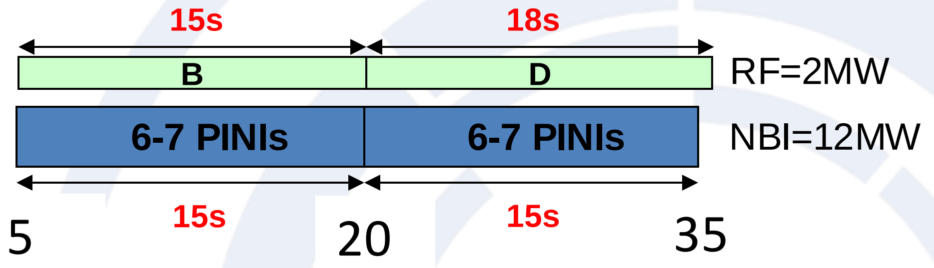
- JET ICRH has multiple antennas with various configurations over decades.
- Two of the generator systems were available at the time of the experiment, ‘B’ and ‘D’
- While the majority of the plant could operate longer, the power supplies had a limit of 18s -> max 36s of ICRH possible
- The system operates in a range of 25->57MHz but becomes less reliable at the extremes
- 29MHz, H-minority operation provides good compromise between performance and lowest possible field



Planned Heating

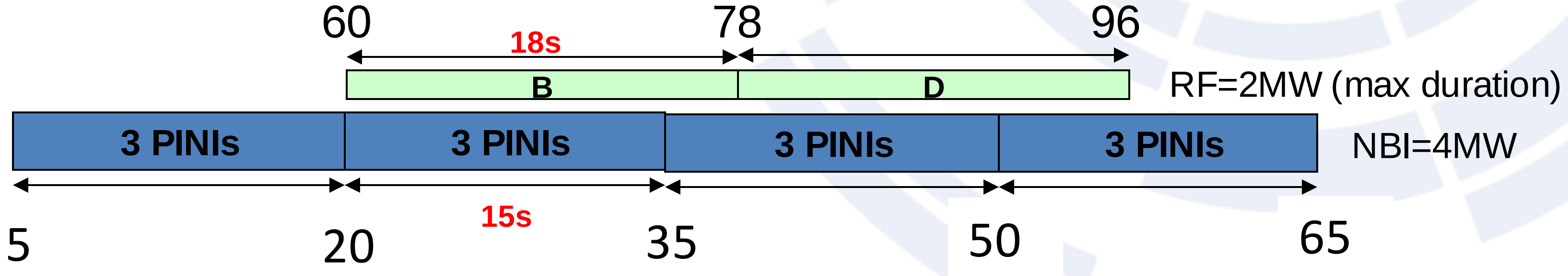
JET

Once the constraints above are considered the best achievable heating setup would be as shown*



Further decisions taken:

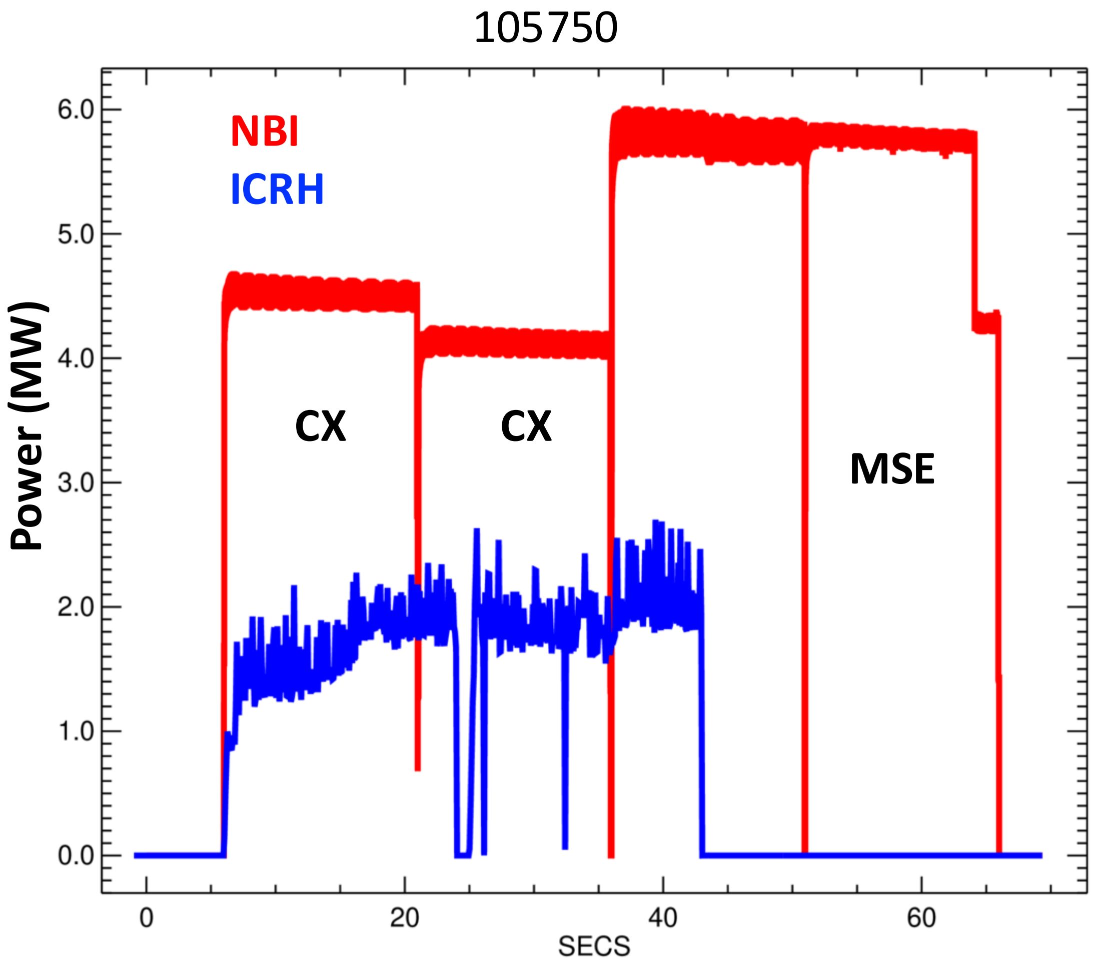
- **on when during pulse to use diagnostic beams**
- **how to cope with reliability**
- **when to use the limited RF power…**

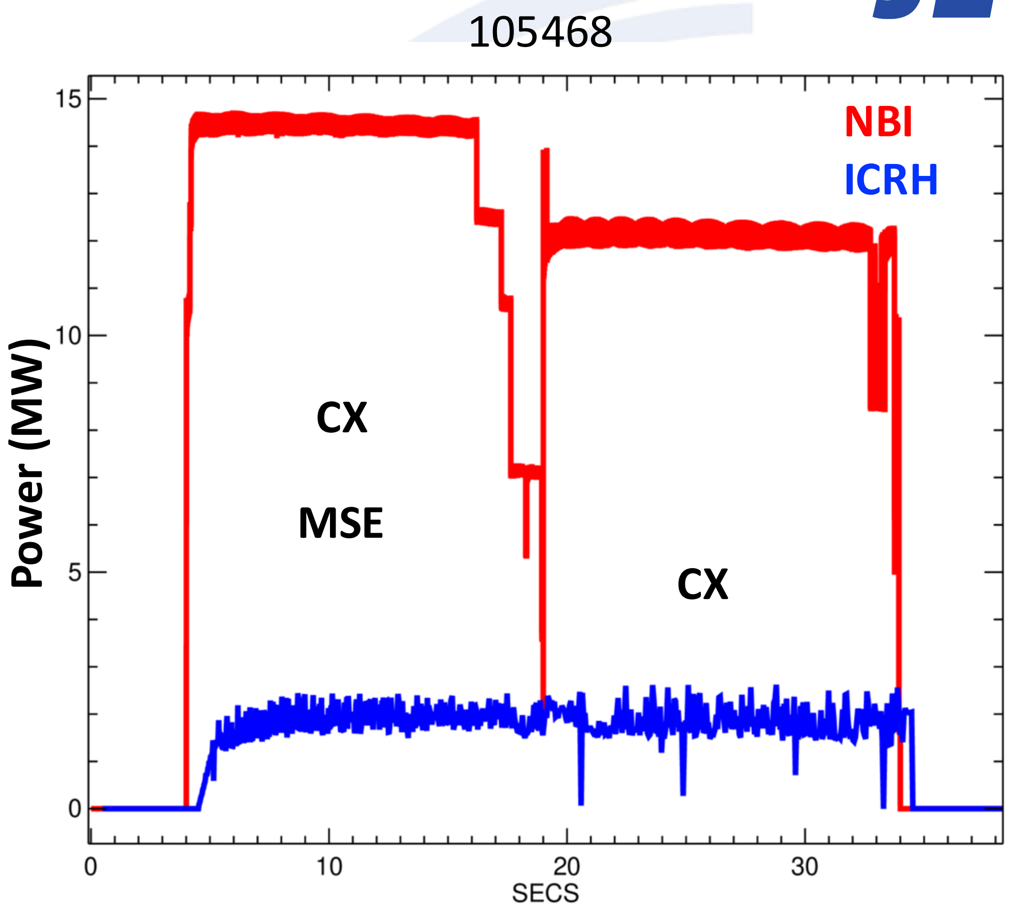


***only 15 PINIs available in 2023**

Achieved Heating

60s pulse used RF at beginning in final option with higher NBI at end to compensate

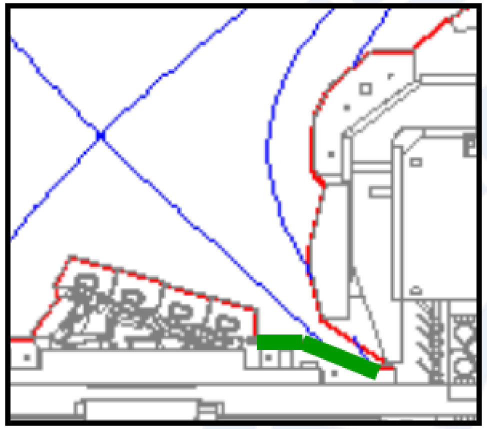




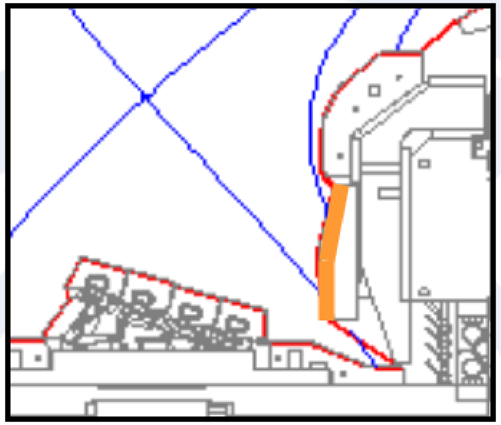
30s achieved higher power than expected but suffered drops in NBI power due to shinethrough protection

Tile Heating

- The divertor structure on JET has limits on surface temperature and deposited energy
- Max surface temperature of 1,200°C
- The tiles are not directly cooled and hence the total energy is important to consider – tie rod structure
- Permission required for orange or higher band



Tile 6 (horizontal)



Tile 7 (vertical)

- Main chamber heating not found to be an issue in this pulse (apart from shinethrough)

Table 3 Tile energy limits to limit tie-rod fatigue

Label:	*Green*	*Yellow*	*Orange*	*Red*
Life in shots:	*>33333*	*>3333*	*>333*	*<333*
Energy deposited on Tile 3 [MJ]	<17.1	17.1-23.2	23.2-32.4	>32.4
Energy deposited on Tile 4 [MJ]	<15.5	15.5-21.3	21.3-30.3	>30.3
Energy deposited on Tile 6 [MJ]	<32.4	32.4-50.3	50.3-94.6	>94.6
Energy deposited on Tile 7 [MJ]	<48.8	48.8-73.7	73.7-133.1	>133.1

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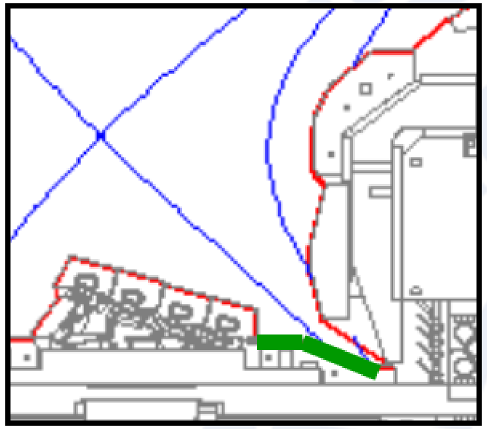
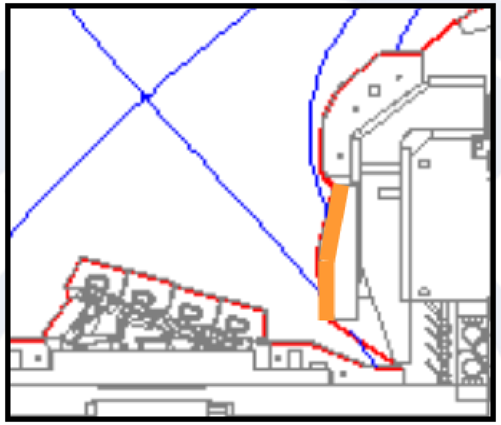


Tile 6 (horizontal)



Tile 7 (vertical)

Did enter red zone for first (and last) time on JET!

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Tile Heating - Tools

- Some tricks available to aid in the heat load management
- Divertor strike point sweeping common on JET, helps hotspots but not bulk temperature
- Can move the strike point to another tile, plasma can be affected (pump throat)
- Can use seeded impurities – problem here for flux consumption and pulse development!

Tile 6 (horizontal)

Tile 7 (vertical)

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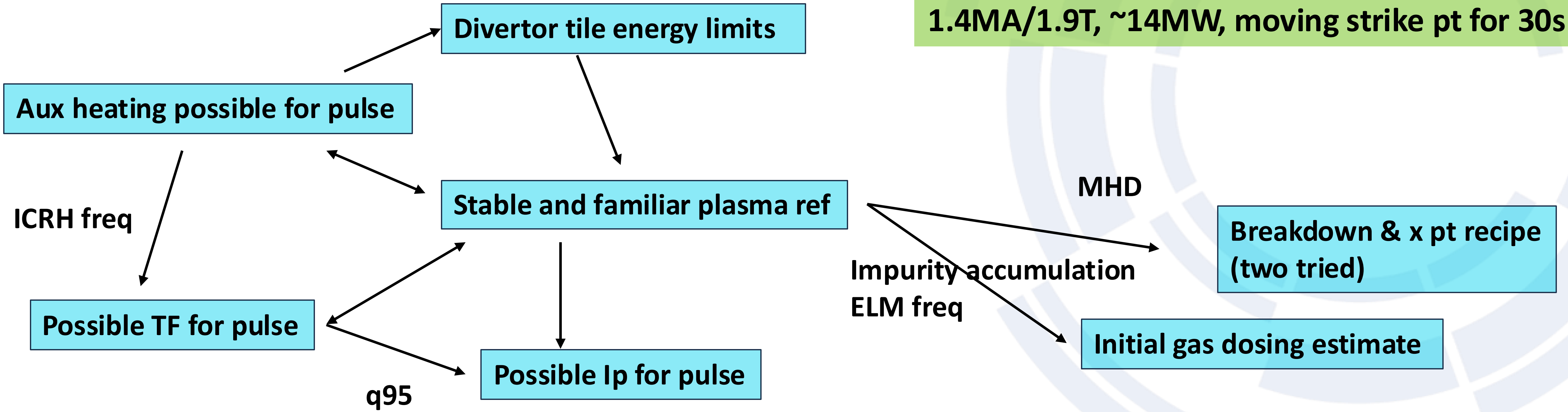
JET

Limited available machine time due to end of JET life, therefore existing, well developed plasmas should form the basis of experiment

End result:
1.4MA/1.9T, ~4MW, static strike pt for 60s
1.4MA/1.9T, ~14MW, moving strike pt for 30s



Control Systems

JET

- A standard JET pulse has breakdown at 40s and has an end <80s (called PCD)
- To complete a 60s heated phase PCD of 120s was required
- Majority of control systems capable of achieving *>80s however*, this value is hard coded in numerous places
- The control of each individual subsystem had to be considered and checked for compatibility
- Earlier work on 60s pulses long time ago – helped but many systems needed fixes
- The CODAS team took on the majority of this work, checking systems offline and in tests
- Interaction of CODAS with each subsystem required

"no one will ever need a pulse longer than 80s!"

Control Systems

JET

JET Supervisor Software	High level control system known as ‘level 1’
TF settings and control	Controller and TF hardware – use of flywheel and user settings
Heating Control	Software for NBI + ICRH
Magnetics	Diagnostics and control system
CODAS	Overall control system for JET, sets parameters for other systems
Thermal protection	Cameras and their interaction with the control system
Plasma control	Diagnostics and control system
Real time protection	Controller to protect against all off-normal events, many layers
Density control	Diagnostics and feedback loop controller
Vertical stabilisation amplifier	Concern over controller and amplifier overheating
DMS	Require MGI in pulse for protection
Plasma protection	More simplistic event handler
Hard wired protection	Even more simple protection directly on essential hardware

Control Systems

JET

- As these systems are related to machine protection care had to be taken and tests performed. No changes that required major recommissioning allowed!

- Systems worth noting in these are:
  - Level 1 included the parameter ‘PCD’ that was fed to all parts
  - Heating controls only fully exposed in final attempts at 60s
  - TF required special expert mode to correctly use no-flywheel
  - Concern that integrators for magnetics control could be affected
  - Changing all the numbers by CODAS took ~30 minutes before pulse
  - The standard plasma density control interferometer was not available for long pulse, only the older system could be adapted with different laser controller
  - The density controller itself also needed adapting

- Similarly to (and integrated with) the control systems most diagnostics required work to resolve

  - In almost all case the settings had to be altered by the coordinator or RO to allow for long pulse
  - In many cases either the time window available was reduced or the acquisition rate slowed down
  - Limitations on storage, hardware and design assumptions found
  - Required 10-20 people to be available for pulse to set up and check

A lot of sweat over these settings but successfully managed to set all up appropriately!

Approvals, Processes and Sequence

JET

Preparation for the pulses began during the post-DTE3 cleanup phase

Many bugs and surprises that cannot be found until last one overcome

To make progress carried out 'dry runs' in time found over weeks to find the next issue

Each attempt required a completed approval form and a checklist to ensure each subsystem ready

Checklist for Long Pulse operations

Test sequence

1. Dry run test of systems (has PCD >80s)
2. 30s pulse at low power
3. 45s pulse at low power (has PCD >80s)
4. 60s pulse at low power (has PCD >80s)
5. 60s pulse at higher power (if available)

Systems to confirm before starting JET pulse with PCD > 80s

System	Ready	Returned to standard
PCD		
NBI		
RF		
RTPS		
PETRA		
VTM		
KG1		
NBLM		
RFLM		
KC1		
Cameras		
Gas		
PPCC scenario		
ERFA (duration limit)		
DMV		

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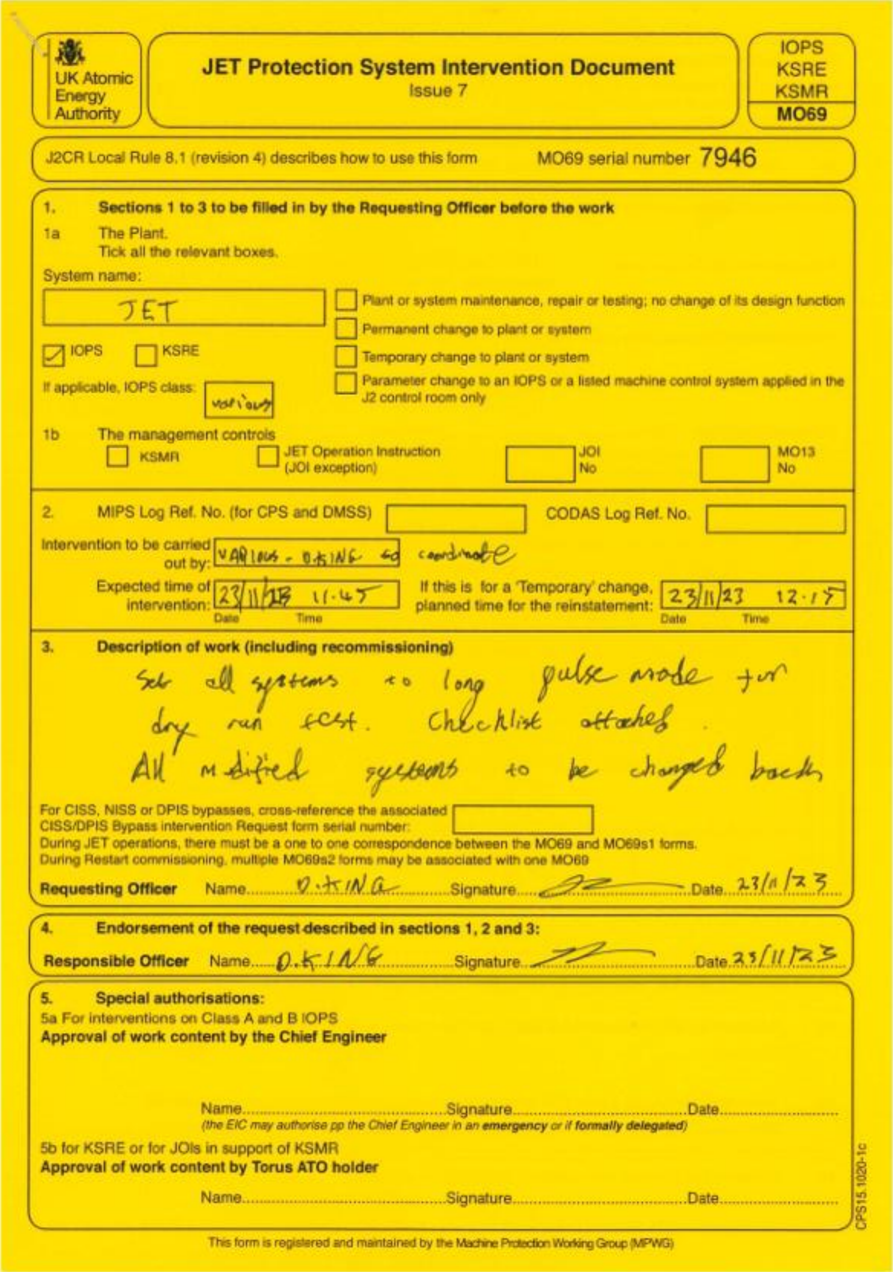


UK Atomic Energy Authority

JET Protection System Intervention Document
Issue 7

IOPS
KSRE
KSMR
MO69

J2CR Local Rule 8.1 (revision 4) describes how to use this form — MO69 serial number 7946

1. **Sections 1 to 3 to be filled in by the Requesting Officer before the work**

1a The Plant.
Tick all the relevant boxes.

System name: JET

- [x] IOPS
- [ ] KSRE

If applicable, IOPS class: various

- [ ] Plant or system maintenance, repair or testing; no change of its design function
- [ ] Permanent change to plant or system
- [ ] Temporary change to plant or system
- [ ] Parameter change to an IOPS or a listed machine control system applied in the J2 control room only

1b The management controls

- [ ] KSMR
- [ ] JET Operation Instruction (JOI exception)

JOI No

MO13 No

2. MIPS Log Ref. No. (for CPS and DMSS) — CODAS Log Ref. No.

Intervention to be carried out by: VARIOUS - D.KING to coordinate

Expected time of intervention: 23/11/23 (Date) 11.45 (Time)

If this is for a 'Temporary' change, planned time for the reinstatement: 23/11/23 (Date) 12.15 (Time)

3. **Description of work (including recommissioning)**

Set all systems to long pulse mode for dry run test. Checklist attached.
All modified systems to be changed back

For CISS, NISS or DPIS bypasses, cross-reference the associated CISS/DPIS Bypass intervention Request form serial number:
During JET operations, there must be a one to one correspondence between the MO69 and MO69s1 forms.
During Restart commissioning, multiple MO69s2 forms may be associated with one MO69

Requesting Officer Name D.KING Signature ... Date 23/11/23

4. **Endorsement of the request described in sections 1, 2 and 3:**

Responsible Officer Name D.KING Signature ... Date 23/11/23

5. **Special authorisations:**

5a For interventions on Class A and B IOPS
Approval of work content by the Chief Engineer

Name........ Signature........ Date........
(the EIC may authorise pp the Chief Engineer in an ***emergency*** *or if* ***formally delegated****)*

5b for KSRE or for JOIs in support of KSMR
Approval of work content by Torus ATO holder

Name........ Signature........ Date........

CPS15.1020-1c

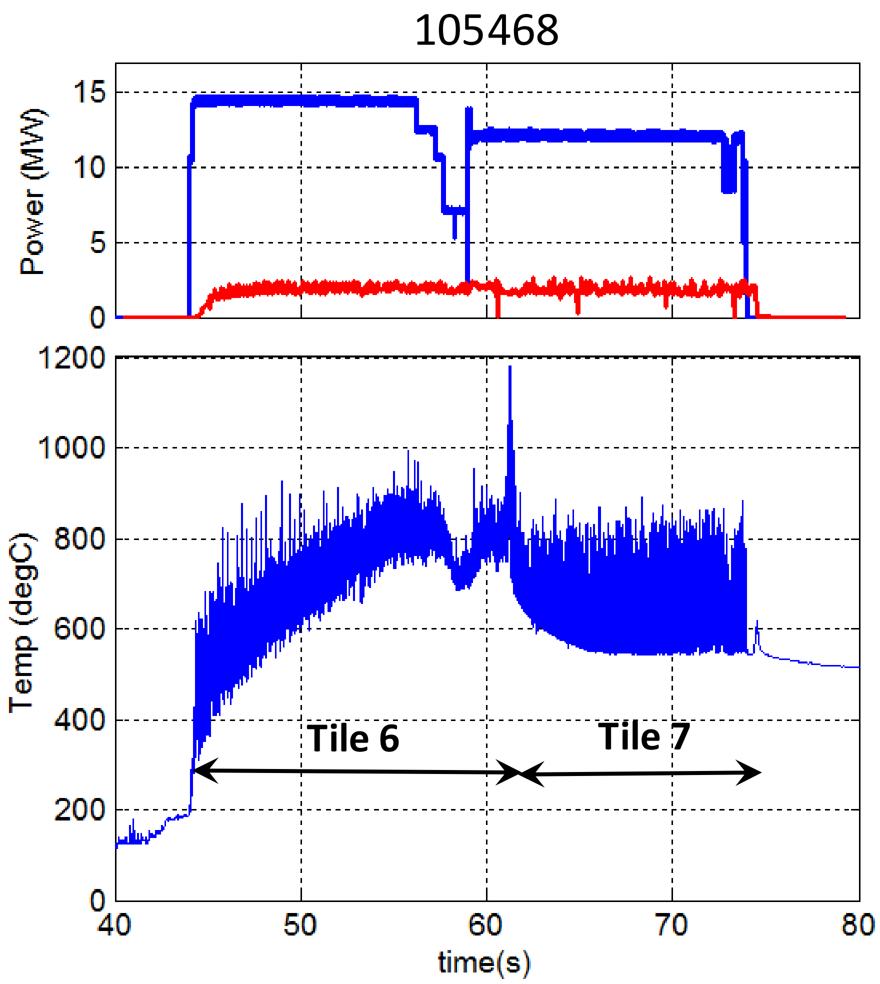
This form is registered and maintained by the Machine Protection Working Group (MPWG)

Outcome – 30s pulse

The 30s pulse provided no control or setup issues relative to a ‘normal’ pulse

Primary issue was in resolving the tile heating situation while achieving best performance (see Ernesto’s talk)

Using evidence from first attempts it was possible to obtain approval for remaining on the optimum divertor position



Outcome – 60s pulse

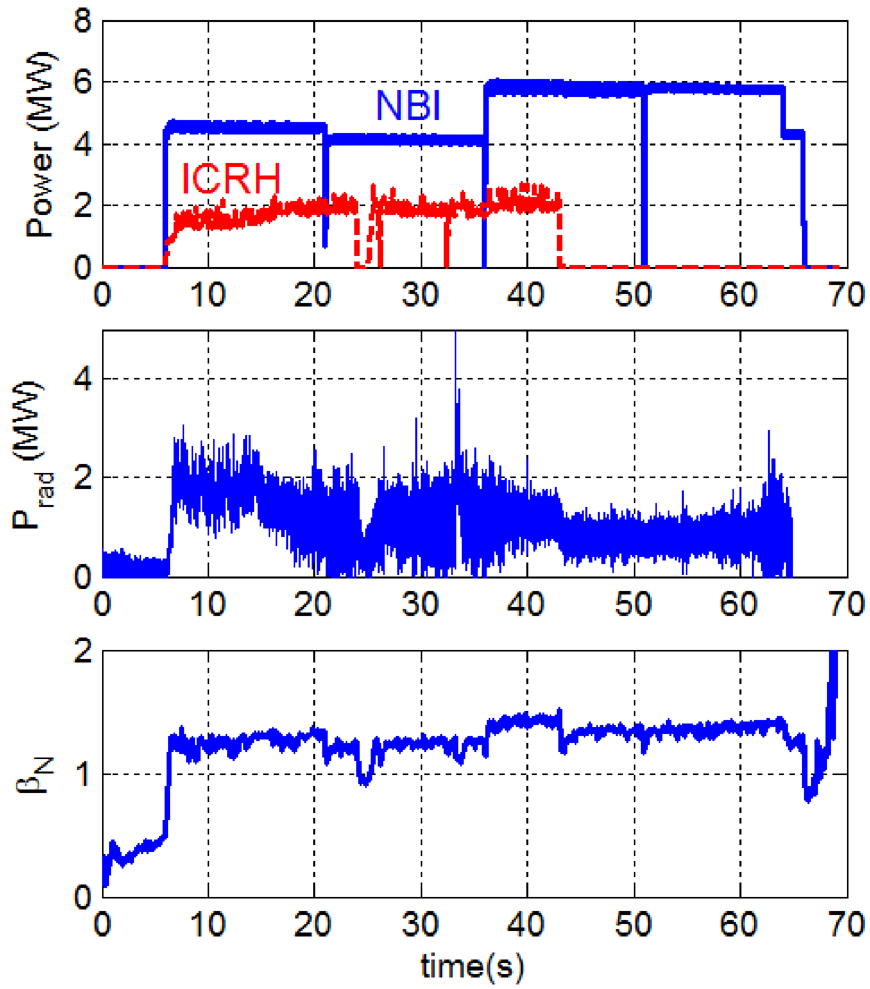
JET

As expected, the main problems in the 60s pulse development was related to settings in various control systems

As these were tested in various dry runs there was some confidence it would work in a real pulse

Many systems however could not be completely tested in dry runs (plasma control, heating…)

105750, 1.4MA, 1.9T



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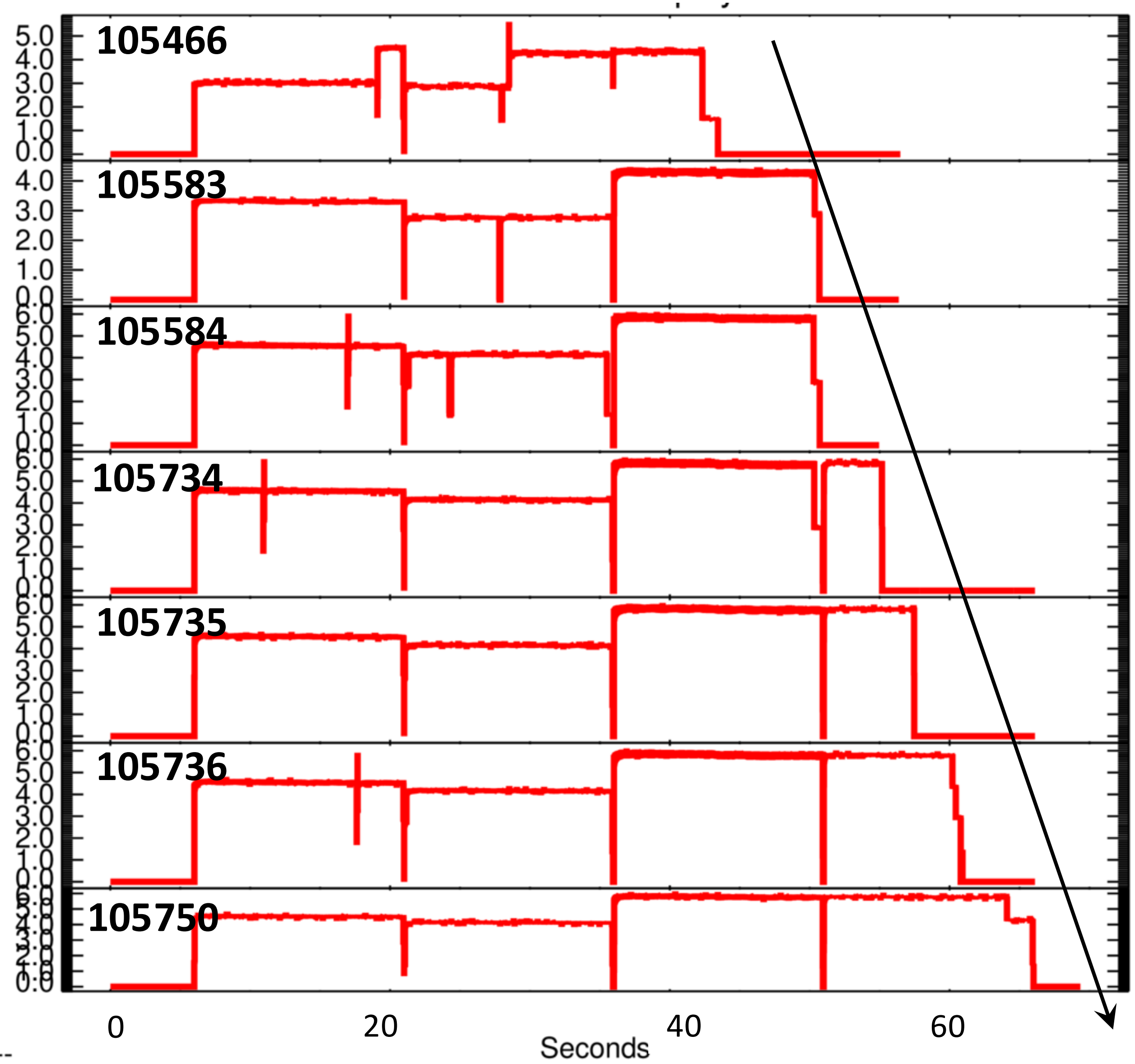


NBI + RF not possible to set beyond 43s (control system)

Stopped by unidentified plasma current control issue

Plasma current control again, stop identified as related to measurement comparison and a setting

Helium affecting resitivity, stopped by NBI magnetic field compensation system

Helium affecting resitivity, stopped by NBI MFC (unresolved) and shinethrough system (unnoticed due to MFC)

Helium removed, stopped NBI shinethrough system

Made it the whole way!

Pulses very good at helium removal!

Outcome 60s pulses

JET

Most notable bugs resolved:

- **Plasma current measurement comparison, this prevented two pulses due to a correction process stopping at 80s**
- **High and low level control parameters on the heating systems – particularly on NBI that was only shown when reaching >100s**
- **Many post-pulse checking algorithms failed (e.g. gas total for cryo-panel loading), did not stop pulse but causes issues**
- **Diagnostic settings were in best possible shape but took a huge effort by many people on each attempt**
- **Divertor strike point control drifted in pulse due to saturation, not so far as to cause an issue**

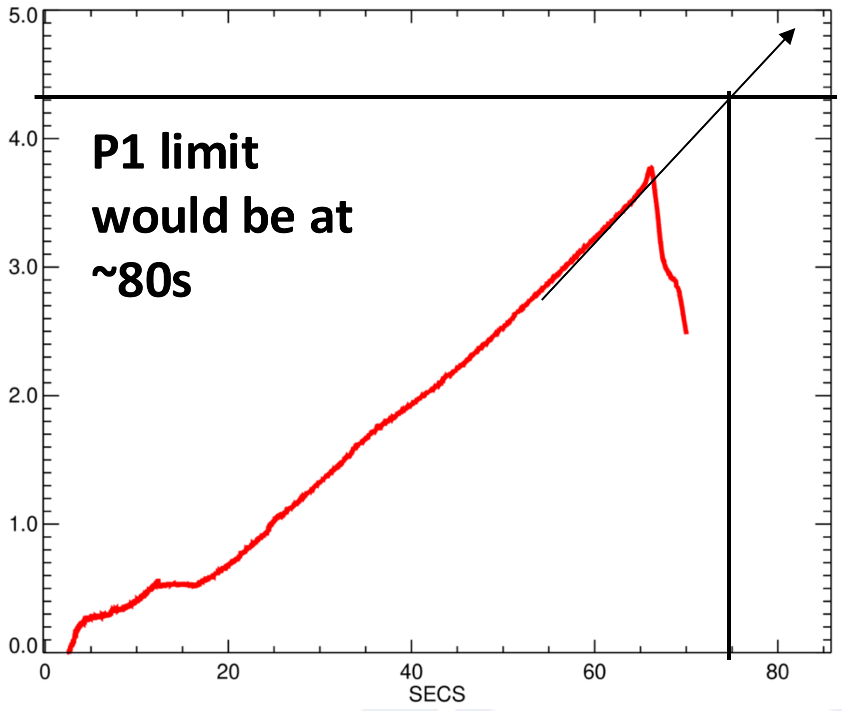
Limitations in the final results

JET

- Primary limitation ended up being Heating windows possible
- Could not have done much longer, I2t limits on TF, P1…
- Could have improved performance - focussed on getting to end of pulse!
- Diagnostics failed/timed out and could not repeat (not directly LP related)

- Important to foresee pulse length in design - engineering limited the pulse length but was easily defined, *>90% of effort here related to software*

- Approval and commissioning process in large scale device must be considered



Summary: Limits for LPO: control & event handling to remain in the safe domain!

JET

Machine/Wall limits

- Available flux ✓
- Energy (I^2t limit) or forces on the coils ✓
- Injected power and/or Energy ✓
  - Max Energy to be exhausted by the cooling system ⧗
  - Max. power reached
  - Max duration of injected power reached ✓
- Power/energy/temperature for PFC
  - Limit on wall/divertor temperature ✓
  - Limit on heating systems ✓
- Wall/divertor erosion
  - Flakes or dusts production ⧗
  - Erosion, re-deposition and migration
  - Flakes leading to disruption
- Measurements in control system
  - Current plasma measurement drift ✓
  - Neutron limits, Gas limits etc ⧗

Plasma physics limits

- **MHD stability (current and pressure)** ⧗
  - Pressure/Beta limits
  - Current instabilities
  - Disruption force
  - Pedestal pressure
- **Plasma radiations** ⧗
  - Core impurity (e.g. W)
  - UFO from erosion leading to radiative collapses
- **Density** ⧗
  - Uncontrolled density (wall recycling)
  - Density limits

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END

Control Systems

JET

JET Supervisor Software	High level control system known as 'level 1'
TF settings and control	Controller and TF hardware – use of flywheel and user settings
Heating Control	Software for NBI + ICRH
Magnetics	Diagnostics and control system
CODAS	Overall control system for JET, sets parameters for other systems
Thermal protection	Cameras and their interaction with the control system
Plasma control	Diagnostics and control system
Real time protection	Controller to protect against all off-normal events, many layers
Density control	Diagnostics and feedback loop controller
Vertical stabilisation amplifier	Concern over controller and amplifier overheating
DMS	Require MGI in pulse for protection
Plasma protection	More simplistic event handler
Hard wired protection	Even more simple protection directly on essential hardware

Outcome MHD

- No issues with MHD in this pulse
- First sawtooth within ~2s of heating start time
- This is unsurprising in this case as the pulse parameters were chosen conservatively to avoid issues

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