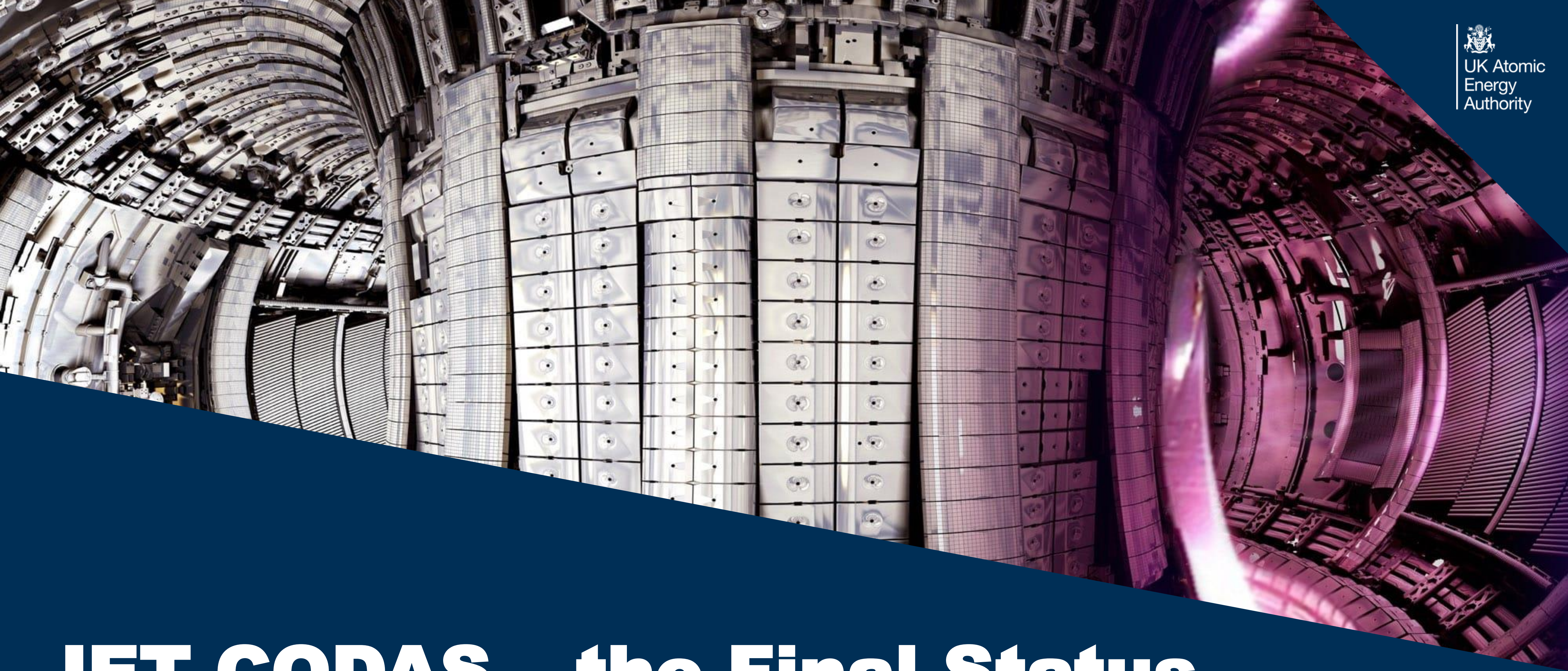

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JET CODAS – the Final Status

John Waterhouse et al, UKAEA

14th IAEA CODAC TM,

San Paulo, Brazil, 15 - 18 July 2024

UKRI Engineering and Physical Sciences Research Council

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[Grant number EP/W006839/1]

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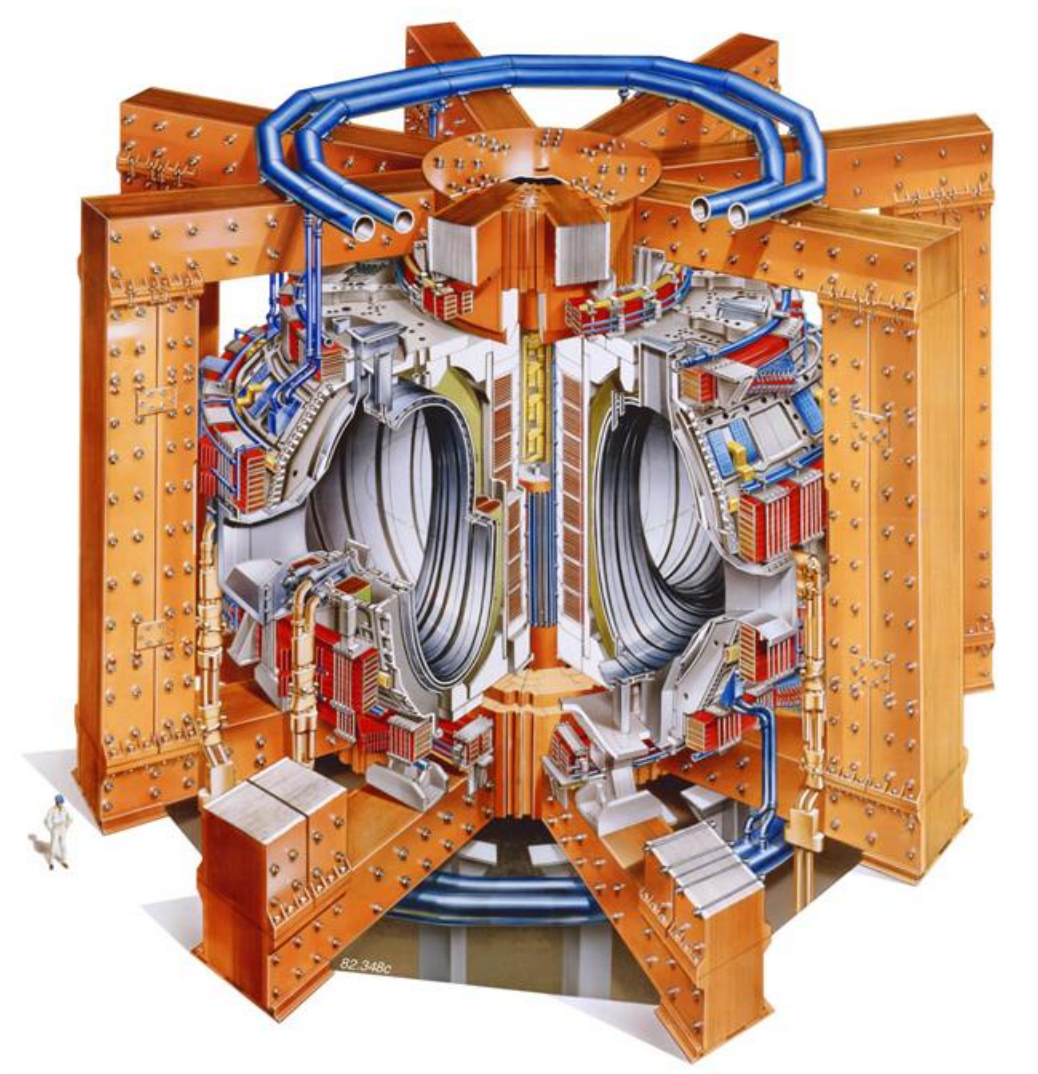
- Online system
- Data Warehouse
- Offline

Enhancements
- Diagnostic enhancement for DT operations
- Real time enhancements
- Tritium management
- Infrastructure

COVID mitigations

Recent Operations
- DTE2 and DTE3
- Desorption experiments
- Long pulse experiments

Beyond Operations



JET CODAS - Overview

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Hardware and data acquisition/control management

Continuous and pulse-based acquisition

Technologies

- Solaris sub-systems,
- CAMAC
- LSD – Line scan devices: bespoke hardware to provide control lines and monitor state signals (generally bit orientated)
- PC's/Black Box protocols
- Siemens PLC interface – hydra link
- VME
- EPICS

Infrastructure

- Solaris Servers
- Network infrastructure
- Linux Clusters
- Workstations

Hierarchy

- Level-3 – low level direct plant interfaces etc
- Level-2 – Sub-system
- Level-1 – High level collective interface & pulse management
- Data warehouse
- Data access, Analysis and Visualisation

Real time networks

- Traditional RTDN ATM
- ITER SDN/Ethernet & MARTe

Control and protection

- CISS
- Plasma control
- PTN & RTPS etc
- Local Managers

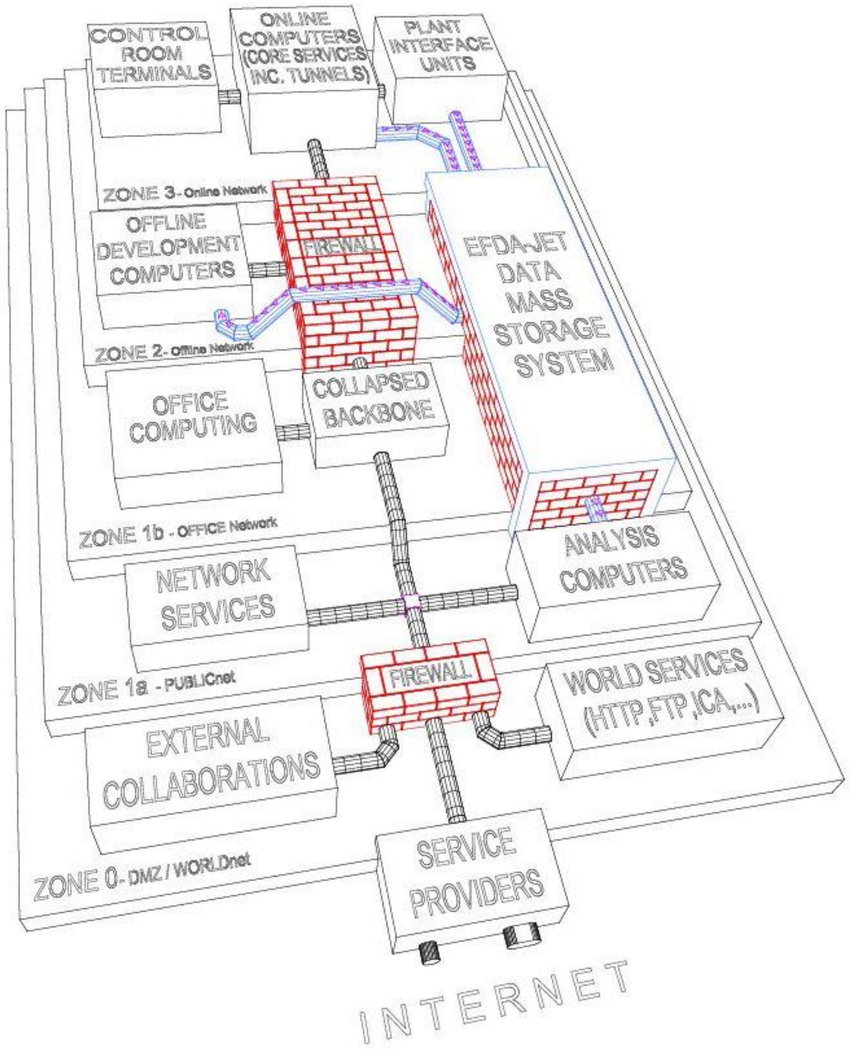
Configuration

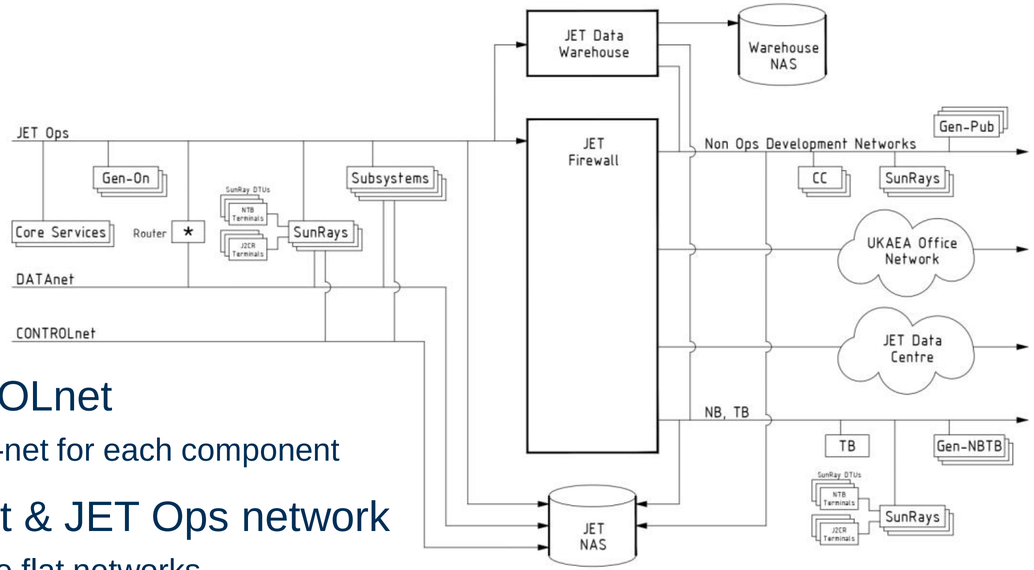
- Custo
  positio
  - M
  - S
    c

Extend Configuration Management

- *full stacked history*
- *include full signal path from sensor to analyzed data set*
- *drive data acquisition/control configuration*
- *drive offline data processing*
- *data provenance*

JET CODAS Network Architecture





CONTROLnet

- sub-net for each component

DATAnet & JET Ops network

- large flat networks

Real-time networks

- ATM and dedicated Ethernet

Timing

- star network of dedicated FO

CAMAC Loops

- dedicated FO

Private networks

- e.g CRYOnet, Tritium plant network & other smaller plant networks

Approximately 2000 devices on the operational networks

JET CODAS Sub-System Level-2

Pulse execution and data acquisition

- Included in JET Pulse or excluded,

Supervisor

- Ensure things in the right state
- Setup hardware for pulse
- Collect data after pulse

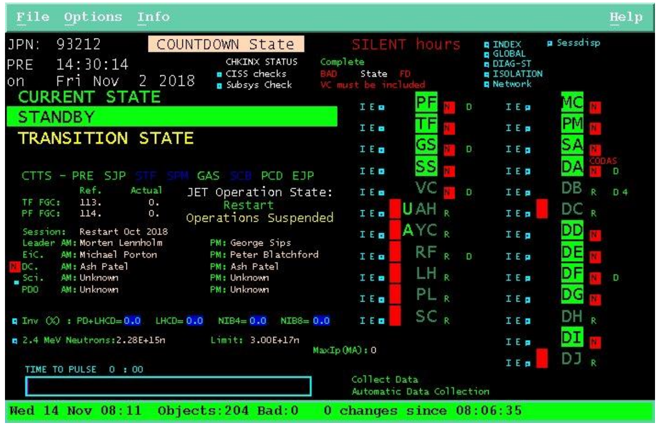
GAP – General Acquisition Program

Pulse timing system

- No actuator mode
- Central or local timing
- CAMAC timers and clocks
- Bespoke VME module
- Clock train and events
- VME reset
- PC version

Data archive

- QPF, JPF, LPF



Continuous control and acquisition

Process variables

- many formats
- scaled and unscaled
- saved state or plant state
- transport to other sub-systems and processes (Solaris) on-line and off-line (read only)
- Black Box and PLC interface
- EPICS interface

Data archive

- CGRT data
- Several trend viewer on Solaris and Linux

Mimics and touch panels

- bespoke language
- role based access control
- user action logging

Tasks and scripts

- bespoke language

Events and Alarms

- Conditioning

Startup and shutdown

Process status and monitoring

Sounds Familiar

- *pre-dates EPICS*
- *perhaps if JET developments had been more open it could have become the standard*

24 sub-systems on JET

1 sub-system on Neutral Beam testbed

1 sub-system for Network management and monitoring

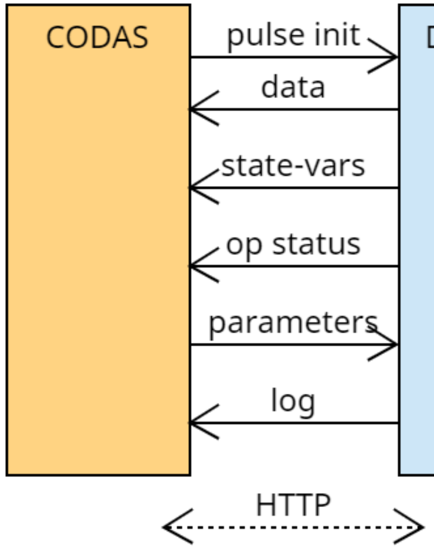
Several development sub-systems

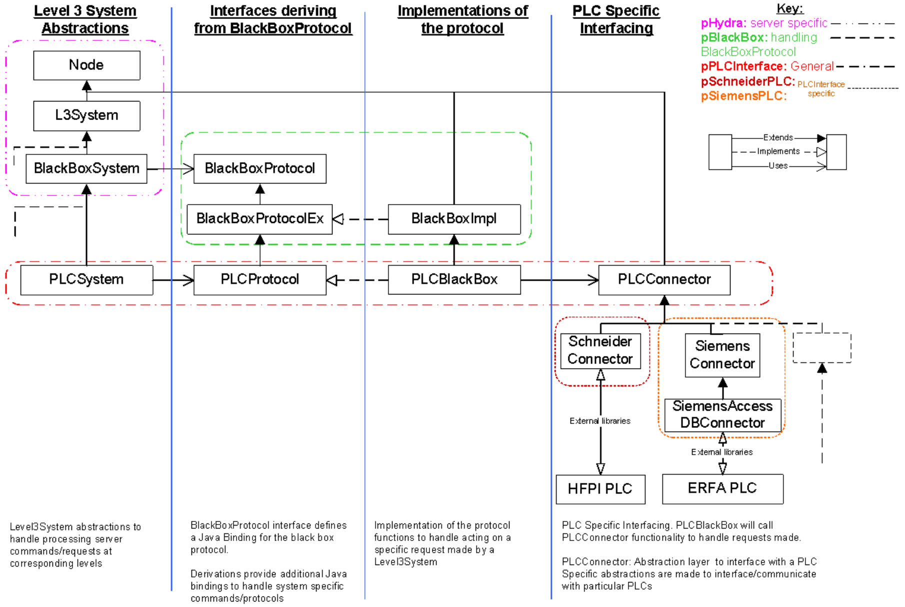
JET CODAS - Black Box Interface

Uniform interfacing to e.g. diagnostics via network

Implemented on Linux, Windows and Labview

- Layered on top of HTTP (widely supported)
- Diagnostic implements one or more facets:
  - Pulse initialisation / data collection
  - Monitoring of state-variables
  - Monitoring of operational status
    - Hierarchical set of reasons why system is not ready
  - Setting of parameters
  - Error logging
- Unlike ITER, not self-describing (so CODAS and diagnostic need to agree on names used)
- Protocol adapter for interfacing with PLCs
  - Hydra link





JET CODAS - Level-1

Collective view of the JET Plant

- Implements the JET Operating Instructions
- Captures and implements a great deal Knowledge of how things work together

Session Leader

- Prepare details of next pulse

Engineer in Charge

- Pre-pulse checks
  - Force state
    - ➢ override issues
- Load plant
- Post pulse checks

Heating system pilots/operators

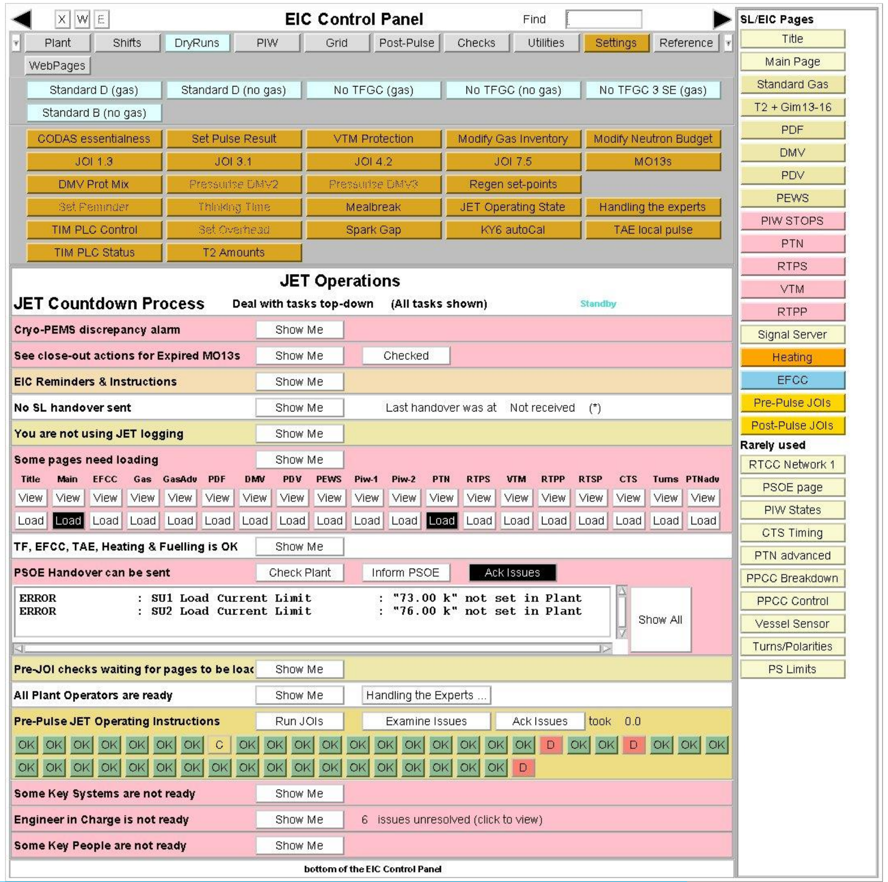
- Setup plant

Diagnosticians

- Setup plant

CODAS

- Setup and run special modes



Continuous Evolution
New plant & mitigation of removal of old plant
Experience gained
Changes to operating regime, plant limits and budgets

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User interface – xpsedit

- on-line with read/write access to the plant
- off-line read only
- Access controls

Imports data from Operational tools

- Pulse, shift, programme, campaign planning tools

Solaris application

Deamons run as processes on one of the sub-systems

Other Tools

JETLogging

Hierarchical status display

Alarm Package

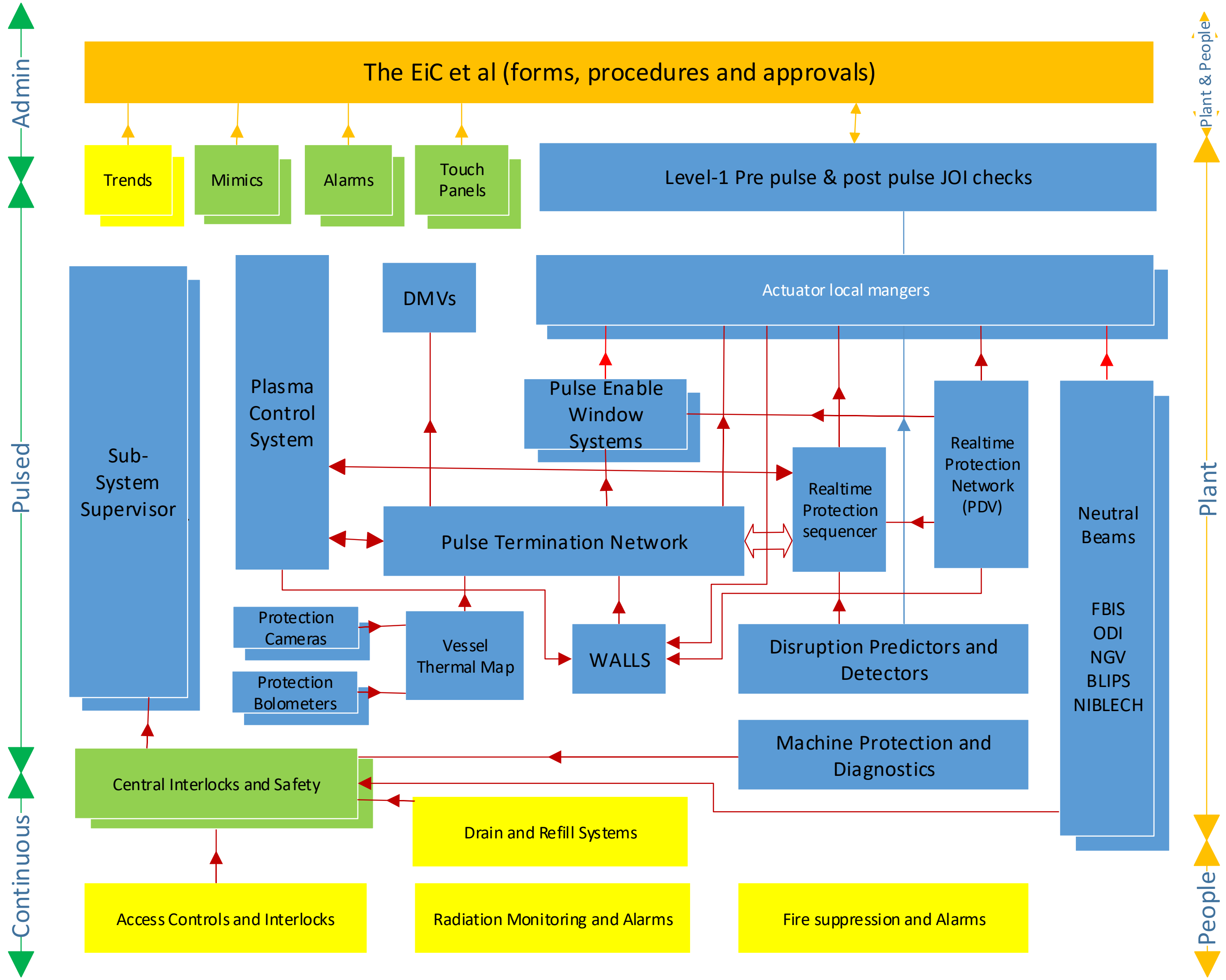
Real-time trend viewers

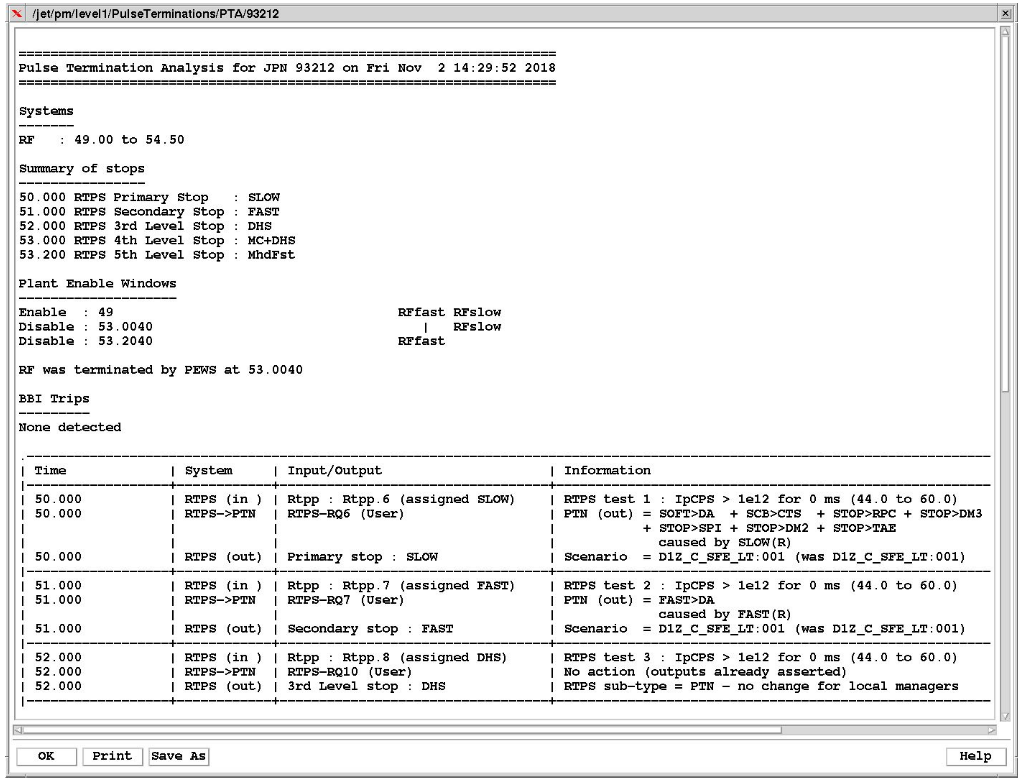
Real-time data viewers

- Video, key trends and real-time equilibrium

Data viewers

Control and Protection Systems





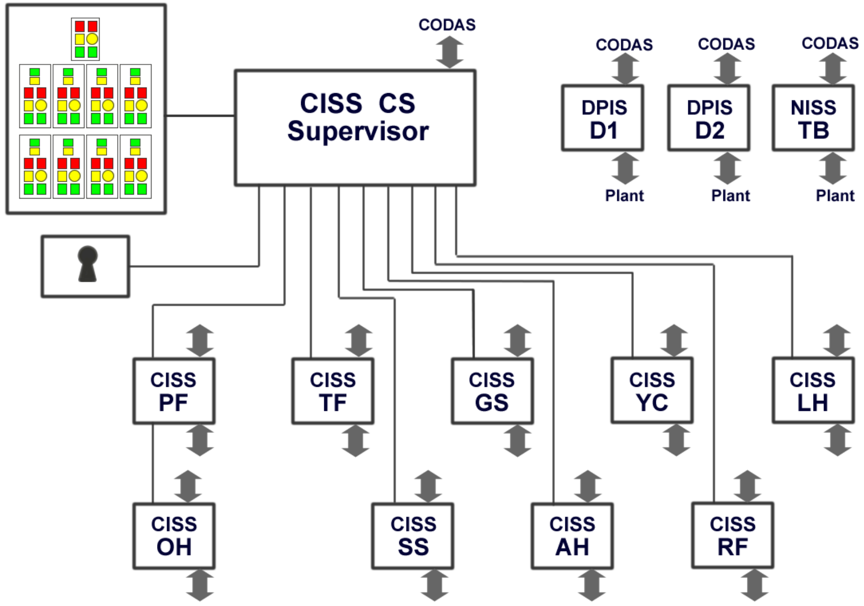
/jet/pm/level1/PulseTerminations/PTA/93212

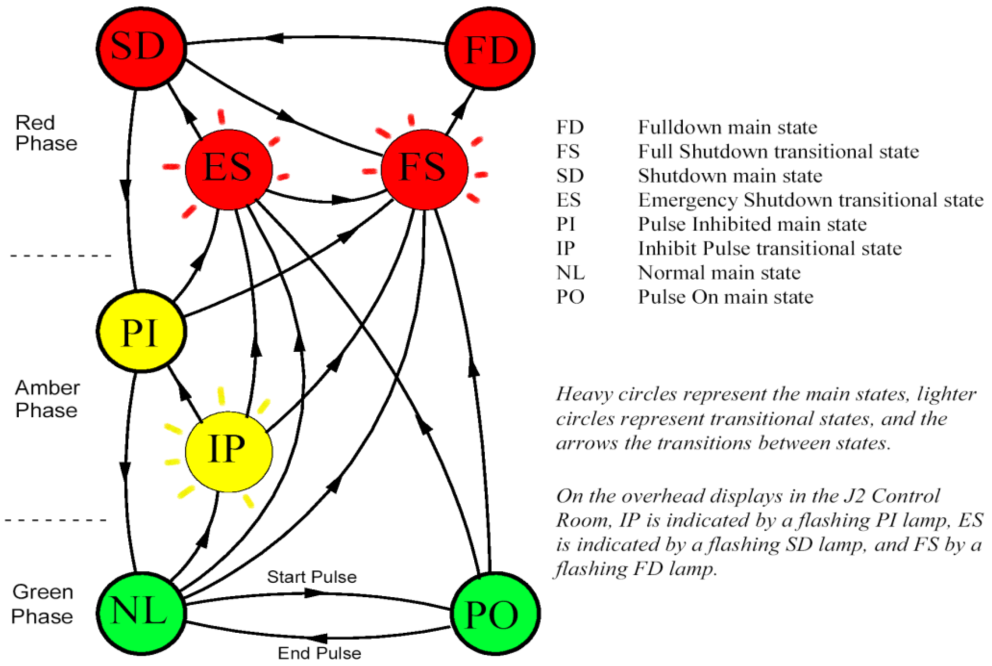
```
===================================================================
Pulse Termination Analysis for JPN 93212 on Fri Nov  2 14:29:52 2018
===================================================================

Systems
-------
RF   : 49.00 to 54.50

Summary of stops
----------------
50.000 RTPS Primary Stop   : SLOW
51.000 RTPS Secondary Stop : FAST
52.000 RTPS 3rd Level Stop : DHS
53.000 RTPS 4th Level Stop : MC+DHS
53.200 RTPS 5th Level Stop : MhdFst

Plant Enable Windows
--------------------
Enable  : 49                                        RFfast RFslow
Disable : 53.0040                                      |   RFslow
Disable : 53.2040                                   RFfast

RF was terminated by PEWS at 53.0040

BBI Trips
---------
None detected

| Time            | System      | Input/Output                     | Information
|-----------------+-------------+----------------------------------+---------------------------------------------------------
| 50.000          | RTPS (in )  | Rtpp : Rtpp.6 (assigned SLOW)    | RTPS test 1 : IpCPS > 1e12 for 0 ms (44.0 to 60.0)
| 50.000          | RTPS->PTN   | RTPS-RQ6 (User)                  | PTN (out) = SOFT>DA  + SCB>CTS  + STOP>RPC + STOP>DM3
|                 |             |                                  |           + STOP>SPI + STOP>DM2 + STOP>TAE
|                 |             |                                  |             caused by SLOW(R)
| 50.000          | RTPS (out)  | Primary stop : SLOW              | Scenario  = D1Z_C_SFE_LT:001 (was D1Z_C_SFE_LT:001)
|-----------------+-------------+----------------------------------+---------------------------------------------------------
| 51.000          | RTPS (in )  | Rtpp : Rtpp.7 (assigned FAST)    | RTPS test 2 : IpCPS > 1e12 for 0 ms (44.0 to 60.0)
| 51.000          | RTPS->PTN   | RTPS-RQ7 (User)                  | PTN (out) = FAST>DA
|                 |             |                                  |             caused by FAST(R)
| 51.000          | RTPS (out)  | Secondary stop : FAST            | Scenario  = D1Z_C_SFE_LT:001 (was D1Z_C_SFE_LT:001)
|-----------------+-------------+----------------------------------+---------------------------------------------------------
| 52.000          | RTPS (in )  | Rtpp : Rtpp.8 (assigned DHS)     | RTPS test 3 : IpCPS > 1e12 for 0 ms (44.0 to 60.0)
| 52.000          | RTPS->PTN   | RTPS-RQ10 (User)                 | No action (outputs already asserted)
| 52.000          | RTPS (out)  | 3rd Level stop : DHS             | RTPS sub-type = PTN - no change for local managers
|-----------------+-------------+----------------------------------+---------------------------------------------------------
```

OK | Print | Save As | Help

Central Interlock and Safety System

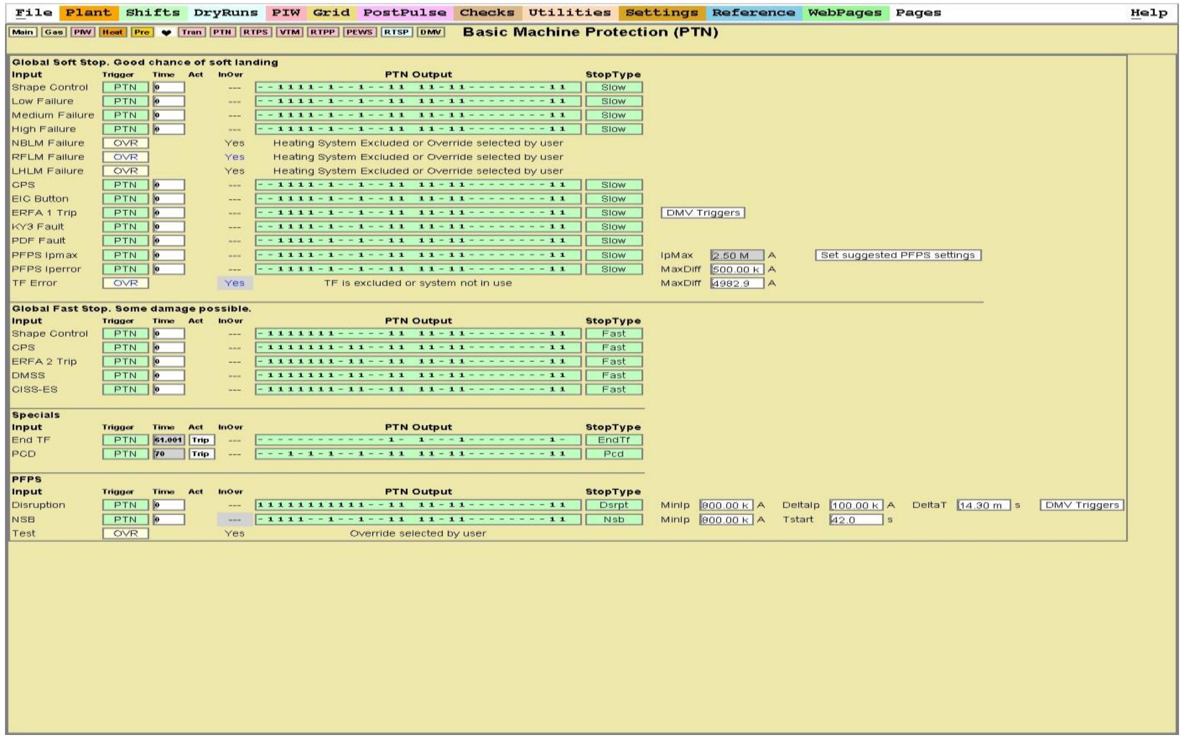
- Network of ten JET pulse-oriented PLCs
- Monitors plant/actuator state per subsystem
- Ensures that all require plant sub-systems are in the correct state to allow pulsing.
- Site on top of Personal Safety & Access Control System (key exchange & two complementary hard-wired interlocks)





- Built as a finite state machine with combinatorial input logic.
- Strong administrative controls for overrides.
- Sub-systems can be in or out of the overall CISS systems

Pulse Termination Network



Simple mapping from inputs to outputs.
Mapping set when pulse is loaded and remains constant throughout the pulse.
Hardwired inputs and outputs implemented using pulse trains over fibre optics.
Output enable/disable timers & time stamping.
Build on CAMAC CAC technology

Pulse Enable Window System

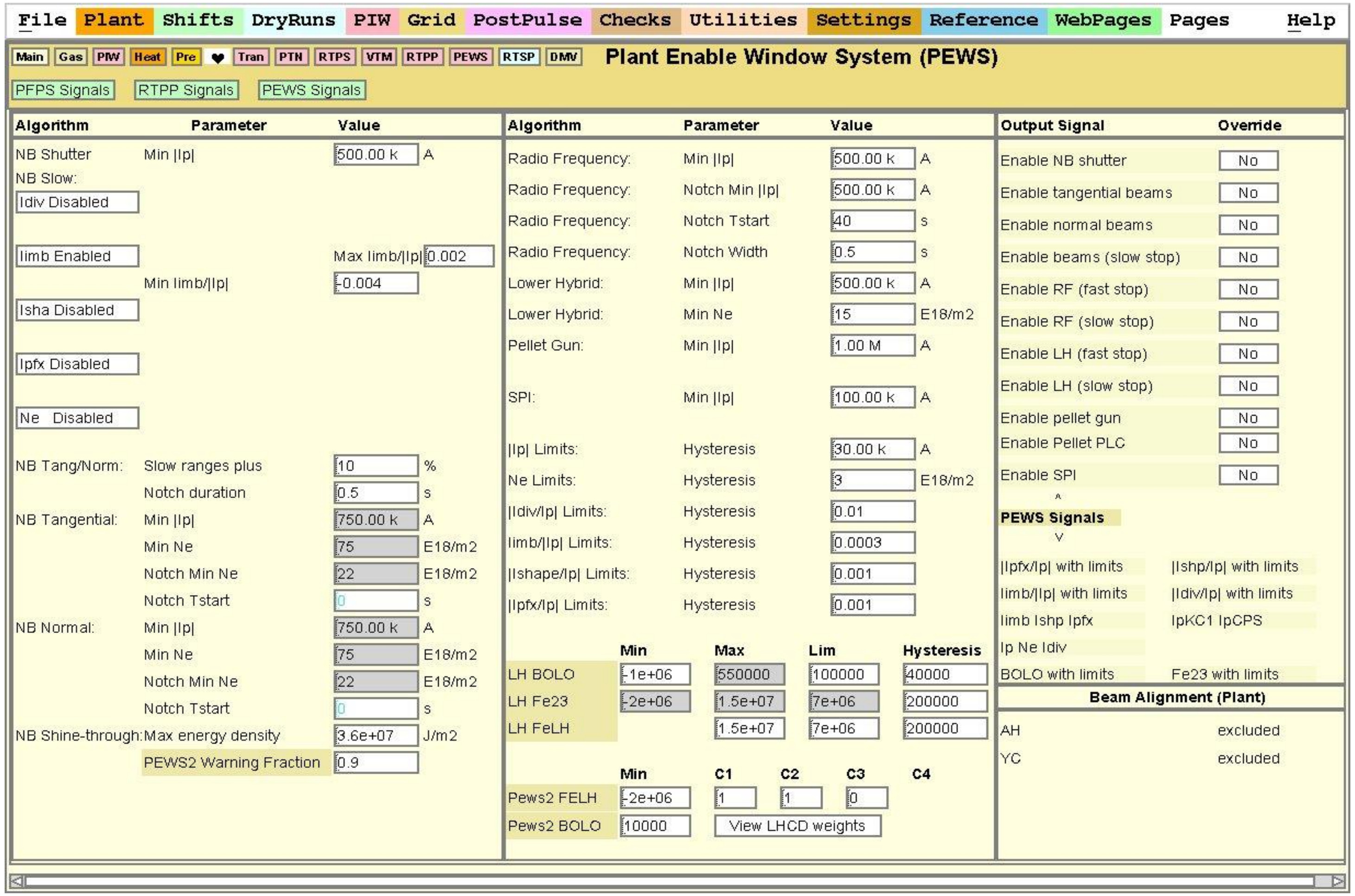
Provides enable windows (pulse trains over FO links) to heating systems plant based on time and basic plasma conditions.

PEWS

- CAMAC CAC based control

PEWS2

- VME/PowerPC based control
- Enhanced neutral beam shine-through calculations
    - PINI by PINI
    - Warns neutral beams local manager



Protection of the ITER like Wall

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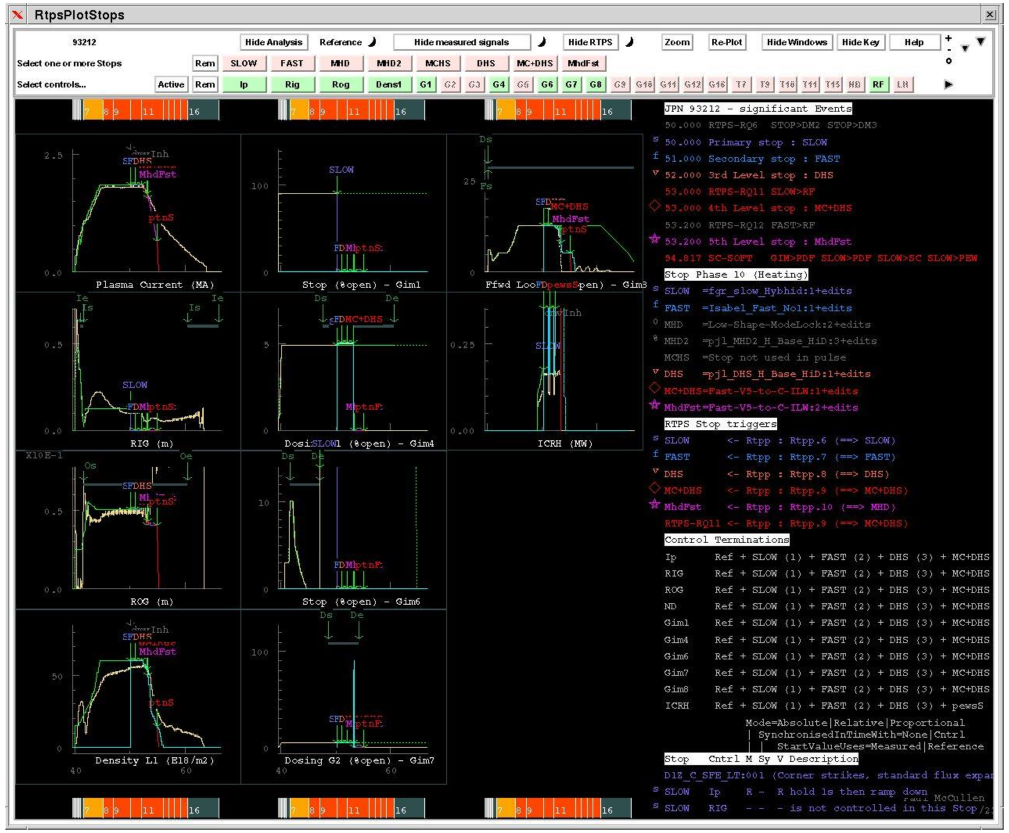
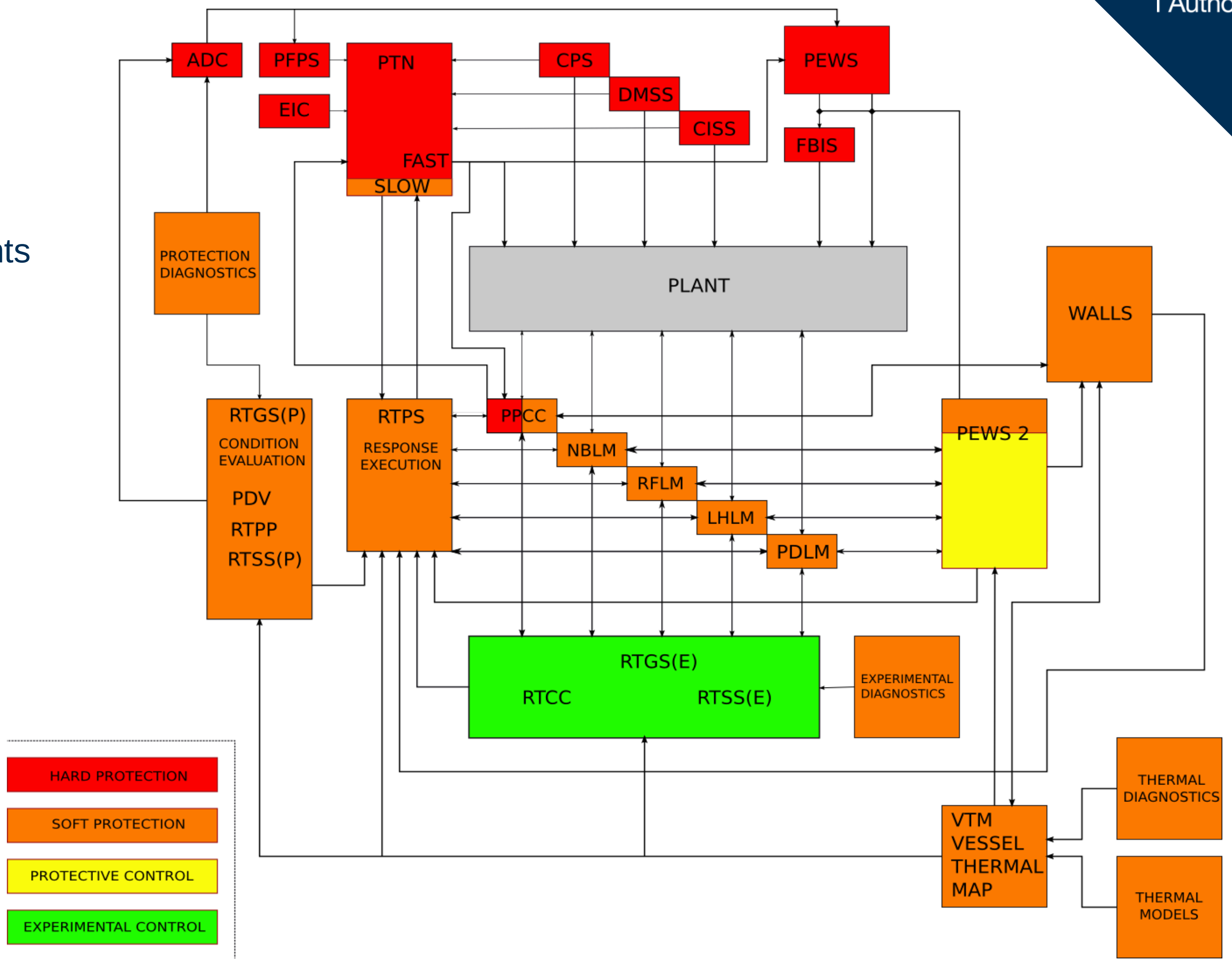
VME/Power PC
ATM networks
Data logging – XG
Data viewer
Data replay through individual components





Real-time Protection Sequencer

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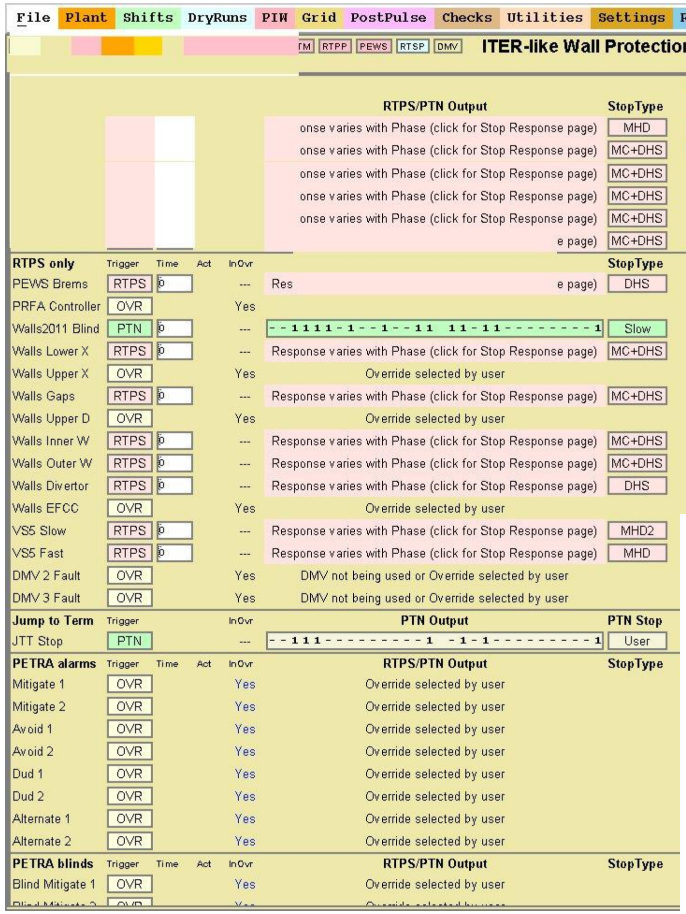
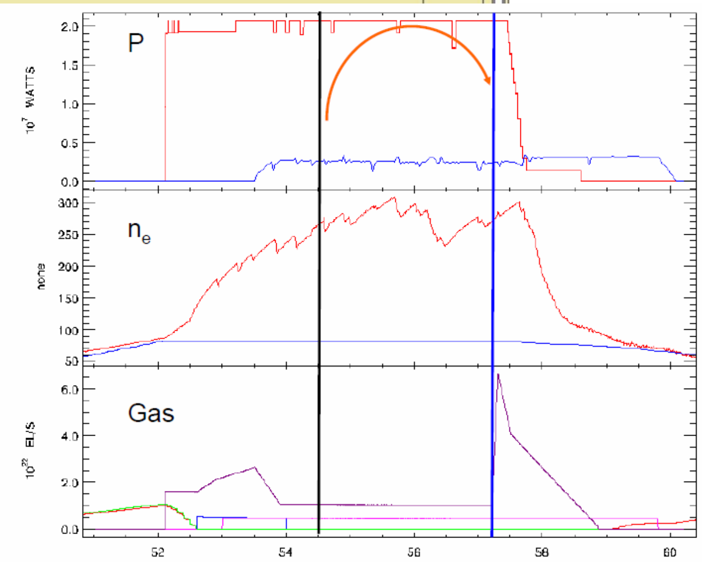
- Aware of plant inputs to PTN
- Can drive plant stops through PTN
- Real time network connections to other event detectors, RTGS, PPCC, and heating systems local managers
- Can initiate ‘Jump to Termination’
  - intended for protection but sometime ‘miss-used’ as experimental feature
- Hierarchical application of stops
- Can take over control of pdlm and nblm etc





Plan:
- Steady-state 52.5-57.4
- Termination: 57.4-62.0

If event occurs any time in steady-state phase jump to 57.4

In case RTCC control: jump out of RTCC time window

Jump to Termination
Need good language
Otherwise gets confusing

Other Protection Systems

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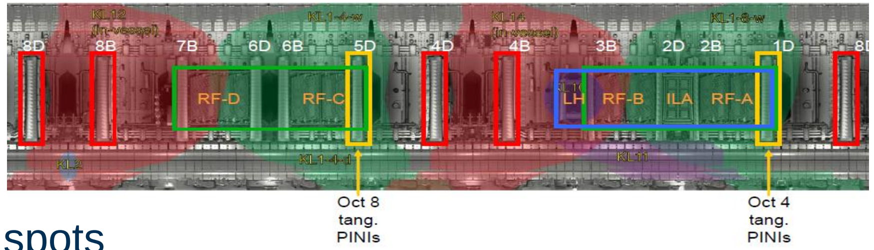
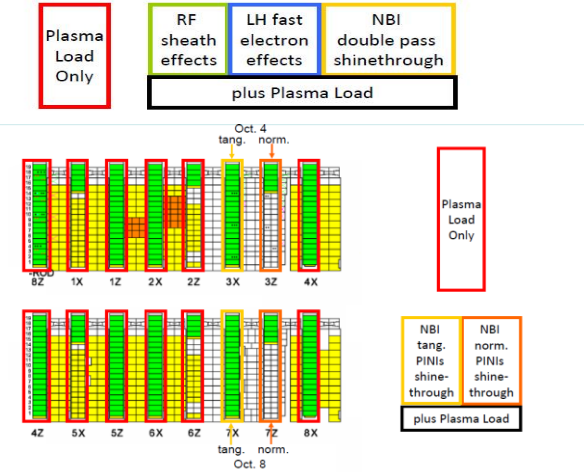
Vessel Thermal Map

- Takes thermal diagnostics (cameras and bolometers) as inputs.
- Implements thermal models
- Protection against NBI and RF induced hot spots is done by setting a lower temperature limit in VTM for Regions of Interest where these may occur. If this is reached
  - the offending heating systems (individual PINI, RF antenna etc is stopped by the local manager
- If temperature in the Region of Interest continues to rise a global stop is requested when the next higher temperature limit is reach:
  - Main changer hot spot
  - Divertor hot stop
  - Both





Protection aspects of Real-time networks

- RTPP
- PDV
- RTSS(P)

APODIS & RAPTOR

- Disruption predictor

PETRA

- Dud detection
- Disruption avoidance
- Disruption mitigation

Alarms go to Realtime Networks & RTPS to be actioned

WALLS

Inputs from

- Magnetics diagnostics
- Plasma control system
- Heating system local managers
- PDV
- Bolometry
- Thermocouples

Model based algorithm computing plasma wall loading

- The position of the strike points of the plasma in tiles
- The penetration of the plasma between tiles
- The angle of incidence of power on tiles
- The plasma power load on tiles
- The bulk and surface temperature of tiles due to plasma power loads

WALLS alarms go to RTPS to be actioned

This provides a backup when cameras in VTM are blind

JET Data Warehouse

Oracle Solaris based system using ZFS

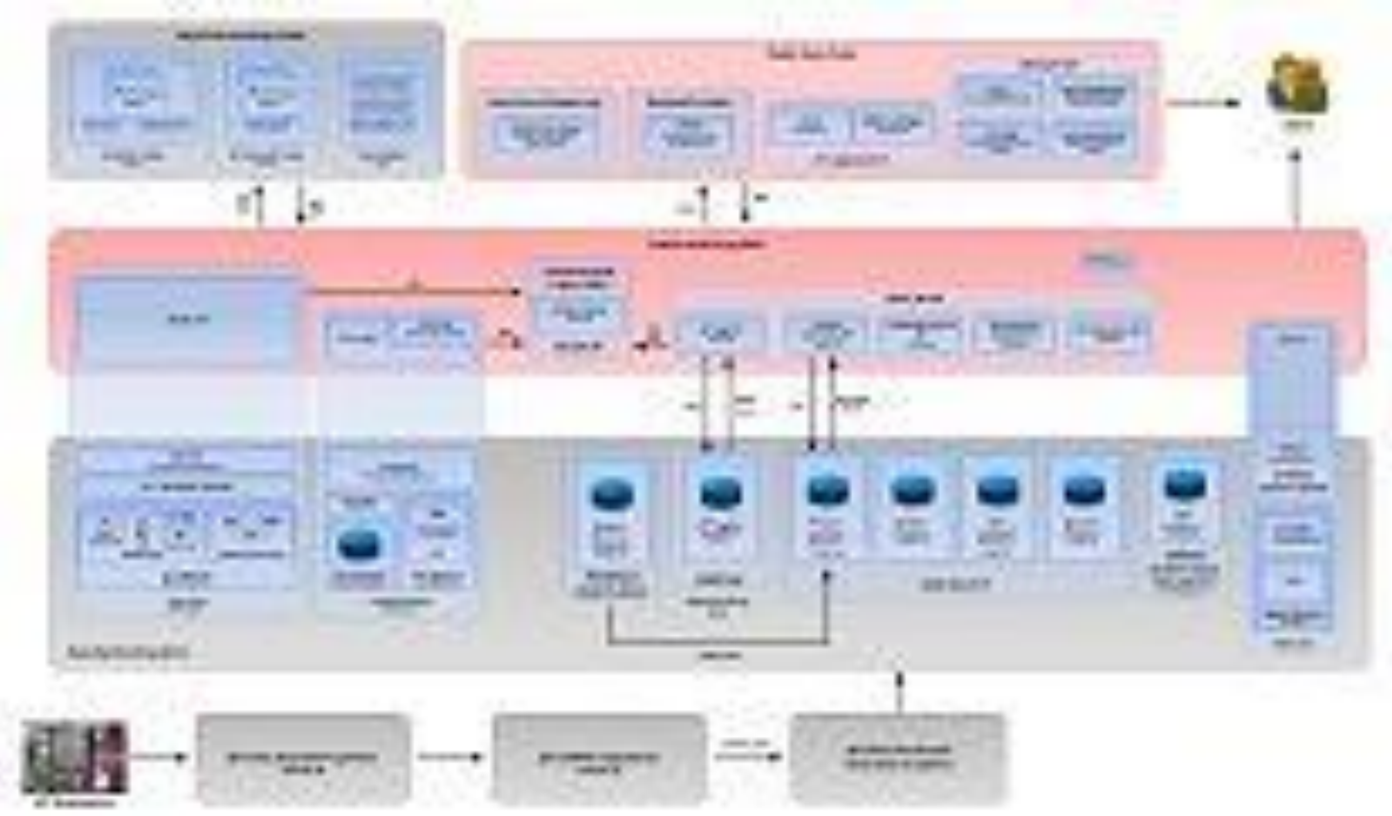
Several upgrades

- Hardware
- Operating system

40 years of data can still read

the early data with the standard tools

Keep all data on-line and 3 copies of data offline inc. cloud storage



JET Data Automated Analysis

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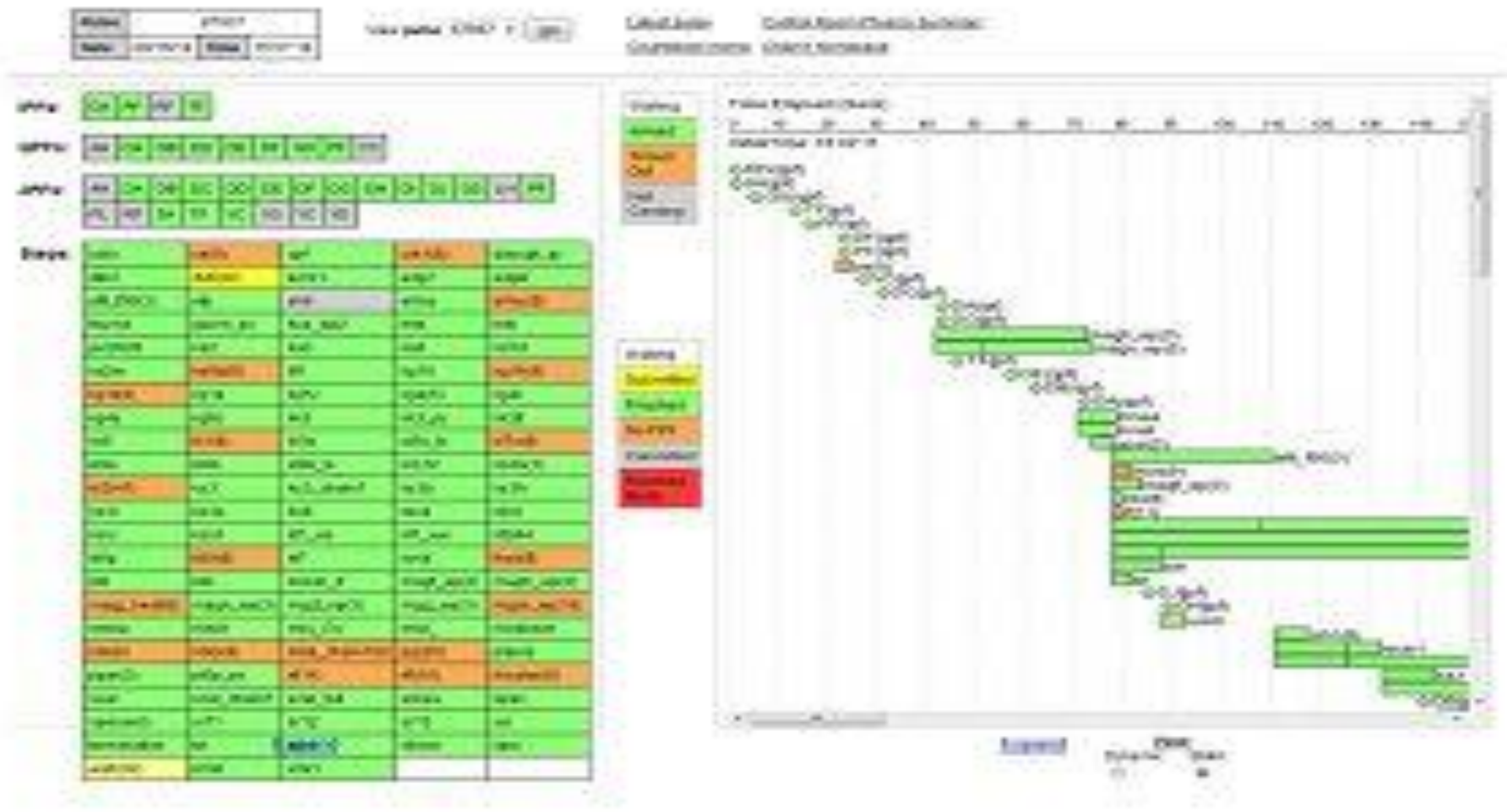


Generates PPF data stored on the data warehouse

JET CODAS Enhancements

Norsk Data -> Solaris
VME
Protection of the ITER like wall
Black Box protocol & PLC interface
Virtualisation of Solaris sub-systems & split
CAMAC access layer
Adoption of ITER relevant technologies
- EPICS, SDN, MARTe V2

DT enhancements
- Tritium introduction
- Tritium tracking
- PSACS Key monitoring and interlocks

Disruption Mitigation
- DMV's & SPI

Real-time Control
Covid driven enhancement

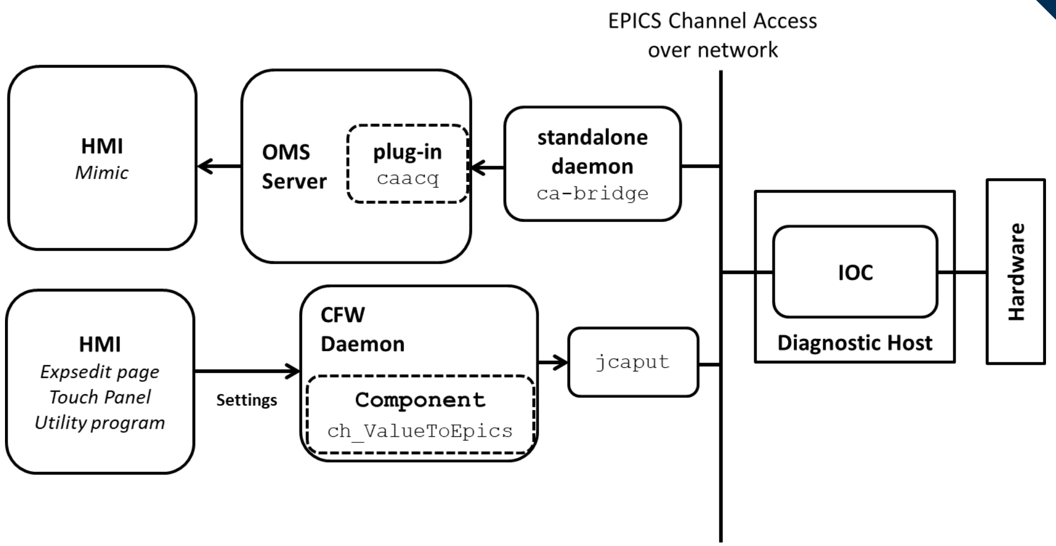
EURO*fusion* enhancements for DT – CODAS integration	
Gamma ray camera	Gamma ray spectrometer
Vertical compact neutron spectrometer NE213	Vertical compact neutron spectrometer CVD
Correlation reflectometer	Charge Exchange diagnostic upgrade
Time of Flight upgrade	Neutron camera upgrade
Single diamond spectrometer	Viewing systems upgrades

Driven by technology obsolescence/refresh and new requirements/enhancements

Adoption of ITER relevant technologies EPICS

Introduce EPICS to augment our traditional system

- Access to a vast body of well supported (open source) software
- Cross platform support (Windows and Linux)
- ITER compatible
- Introduce some compatibility with MAST
- Contribute back to the community



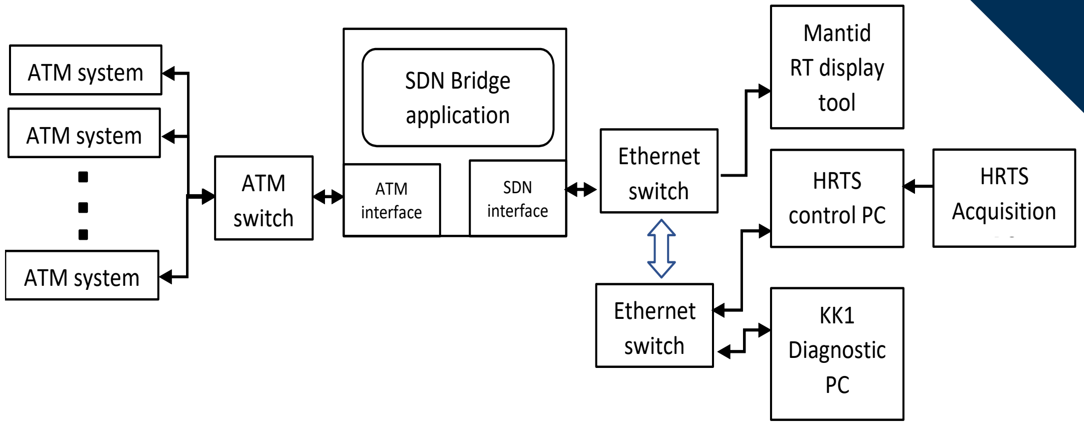
Target applications

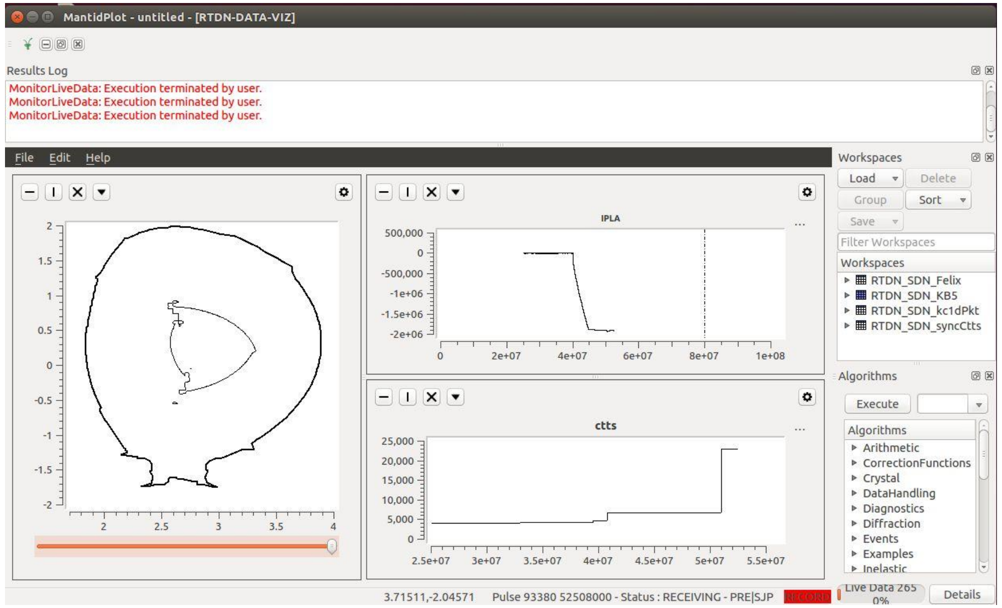
- Filter wheel controller for cameras/spectroscopy
- Turbopump controllers
- Radiation Protection Instrumentation

One of my software/control engineers said *“its great, I have integrated this device into CODAS without writing a single line of code”*

Adoption of ITER relevant technologies SDN

- JET real-time network/ATM – ITER CODAC Ethernet/SDN bridge
- MARTe application
- Initially unidirectional
  - Real-time Flux surface reconstruction and real-time display based on Mantid
- Extended to bidirectional
  - Loopback through the existing real time signal server
  - Real time High Resolution Thomson scattering (HRTS) reconstruction (KE11), a MARTe V2 application
  - Real time ECE Michelson interferometer (KK1)
  - RTCC2
  - Release spares for real-time protection system
- Were JET to have run for a few more years
  - Move local actuator managers & other control/protection systems to Ethernet/SDN





Neutron Tolerance

Bit errors, noise, latch-up, FO darkening
Some viewing systems moved out of Torus Hall and some left in
Heated jackets on fibre optics for several diagnostics
Remote controllable power switches to mitigate for thyristor latch-up
Rad-hardened passive vacuum gauges, RGA electronics on extra long cables, turbomolecular pumps adapted for high radiation environments & shieled
Si diode detectors lost sensitivity, higher leakage current with hall effect characteristic.

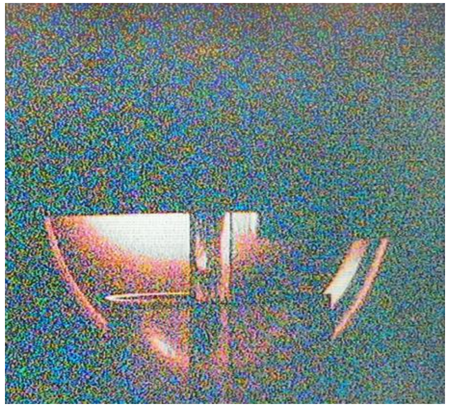
- neutron rate of order 3×10^{11} /cm2/s in DTE2 pulses

Digitiser issues on top of the machine

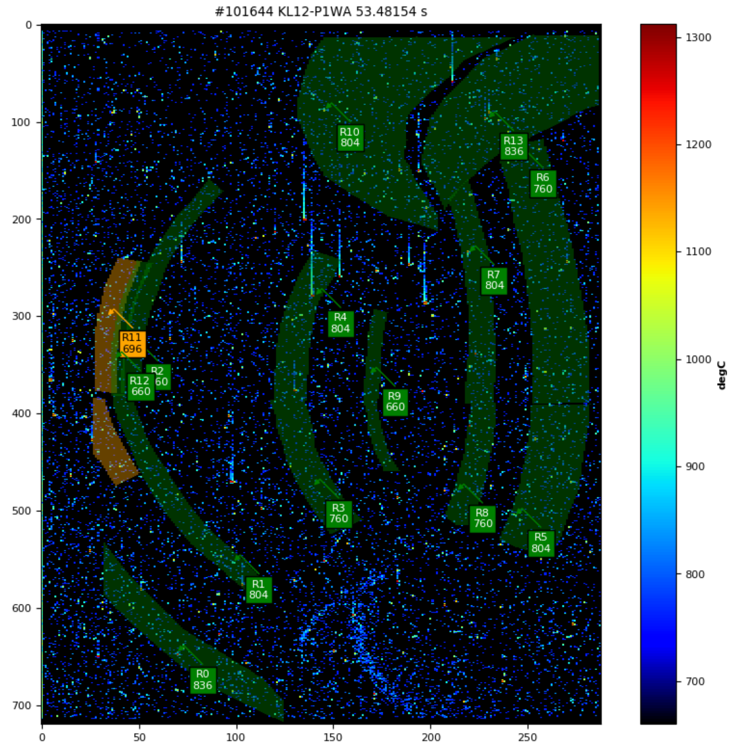
- able to reset whilst network connection remained live
- then network connection died

1 n/cm2/s limit for modern high-density electronics and people

Pellet injector camera on top of the machine



- shieled with 20 mm polyethylene – hard errors
- Normally changed every 2 years



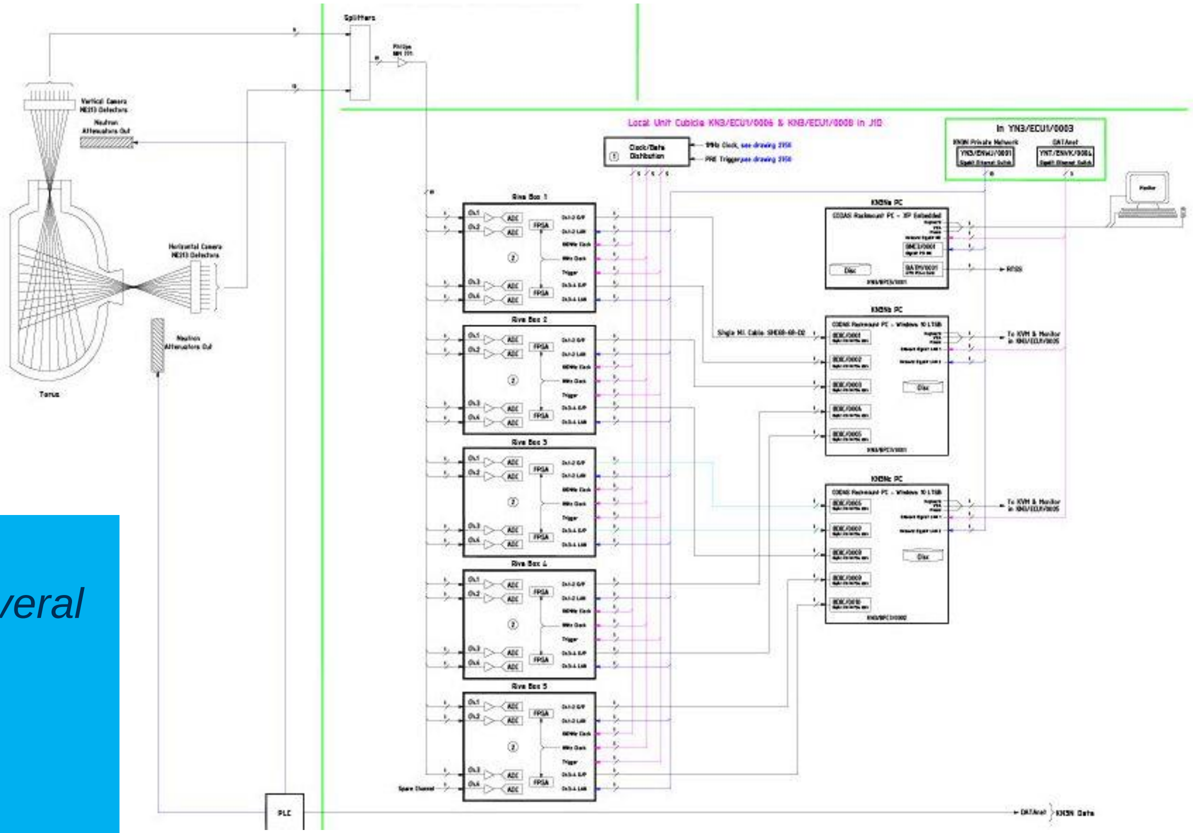
Mid-plane protection camera removed for DTE2 so run ‘blind’ replaced after DTE2 but 1 year on residual Tritium 0.3% 30×10^{15} n in a pulse -> 1.6×10^{9} n/cm^2/s and still noisy

DT enhancements
Neutron and gamma diagnostics

Two groups of 20 single board TSB7053 PCs

Most cases support four PCs

Not standard CODAS PCs so custom Embedded Windows OS support to include device drivers



Set good technical standards

One of the Neutron diagnostic enhancements came with several chassis each containing 4 vertically mounted PC's

It overheated and had to be replaced with several of our standard rack mount diagnostic PC's

Spares and maintainability

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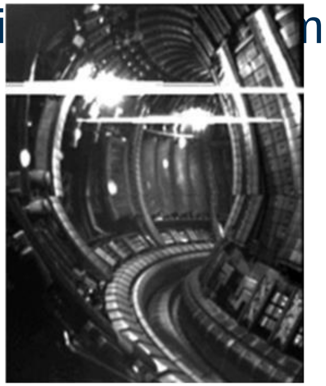
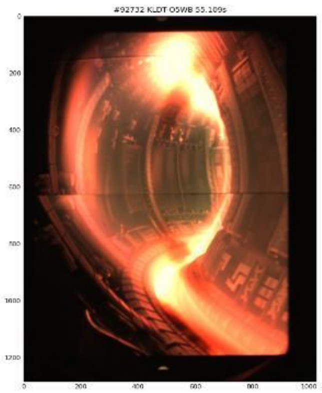
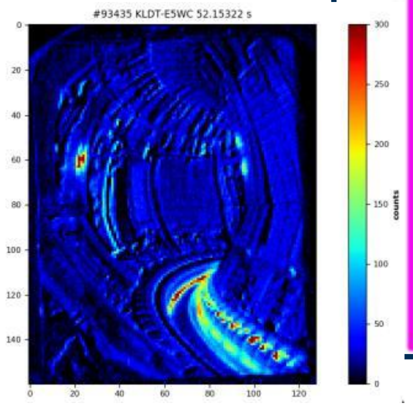
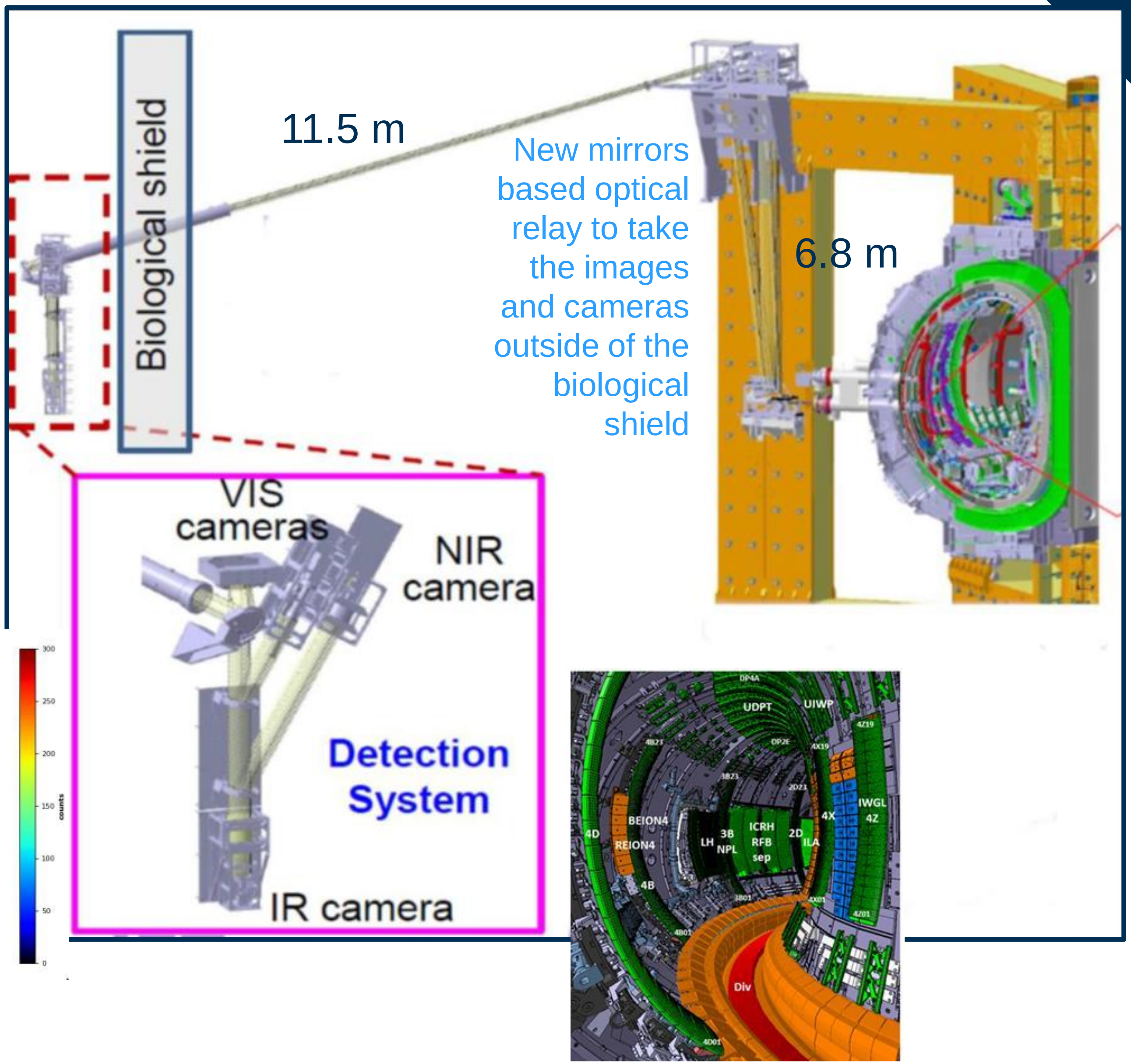
DT enhancements Viewing systems and Protection

Relocation of camera systems outside the Torus Hall
Cameras named "KLDT-xxxx" installed for DTE2/3 as part of CDT2 project.
All other cameras were removed.
New high resolution operational camera, KLDT-O5WB.
Using a cooled ZWO astronomy imaging camera.
An IR protection camera with the same view
Protection and Scientific IR cameras: Divertor vi na









DT enhancements - Spectroscopy

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Development of real-time software for H/D/T ratio measurement for use in experiment.

Fit four or six Gaussian functions to the data.

- 4 if only D and H present
- 6 if T also present.

The relationship between some of the parameters of the fit are constrained.

- A Levenberg-Marquadt solution is carried out to evaluate the free parameters defining the Gaussian functions. At each stage of the iteration the full set of Gaussian parameters are calculated based on the current best fit of the free parameters. These parameters are used to generate an estimate of the source spectra, and the derivatives with respect to intensity, position and width in order to guide the solution.

Running at reliable 40ms cycle time

DT enhancements Real time systems

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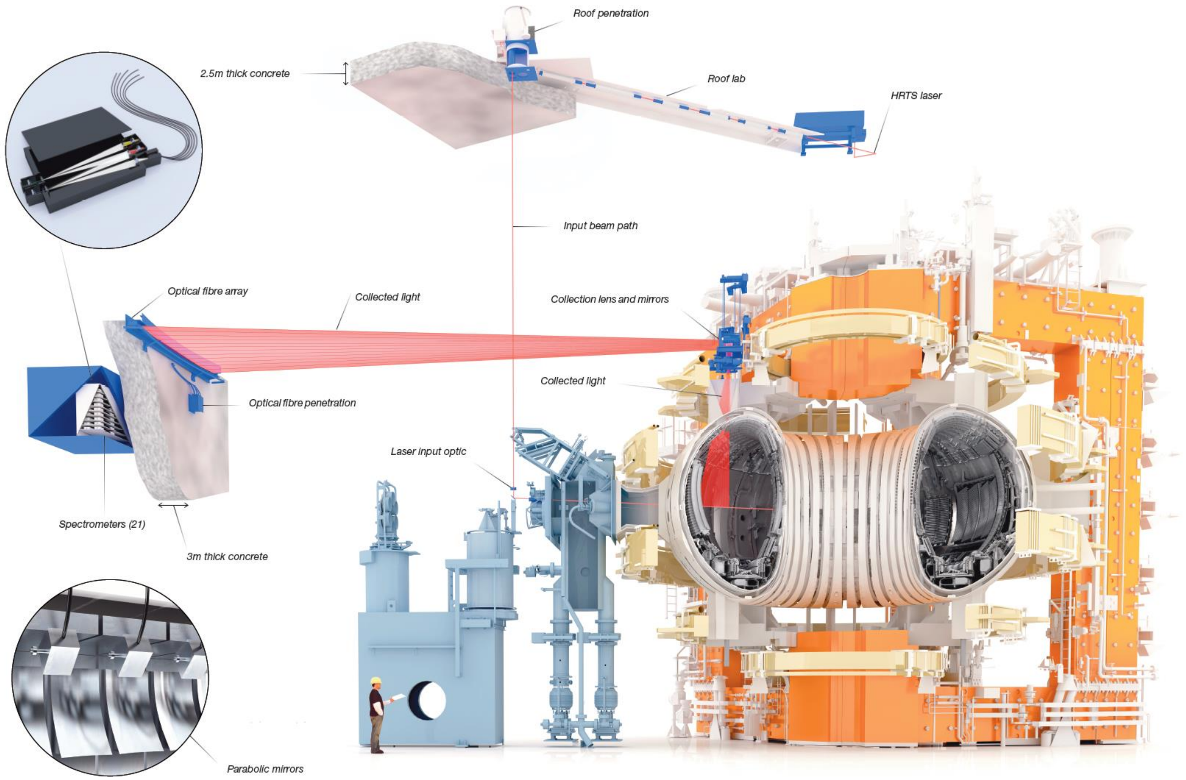
KE11RT is a MARTe V2 application running on lin-ke11-rt

- Reads in data from KE11DAQ each time the HRTS laser fires
- Produces real-time estimates of the Te and ne profiles.
- The laser <~20Hz
- The KE11RT output package is sent on the SDN/Ethernet at 2ms cycle with the data in the body of the packet only updating after each new laser pulse has been processed
- The temperatures and densities are used by PETRA, which tries to fill in any gaps where certain groups weren't available or had bad data.
- This is currently then stored as XG data points



DT enhancements
Tritium Management, Introduction and Tracking

5 new TIMS in addition to the 12 existing GIMS

Neutral Beam PINI grid gas D_2 or T_2

PDLM duplicated for the TIMS

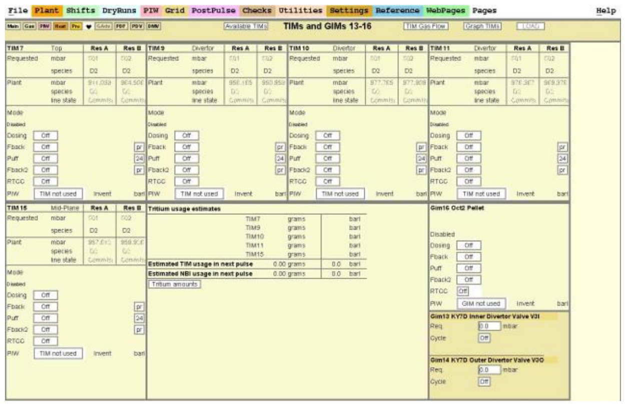
- Density feedback control
- Valve opening
- Flow control

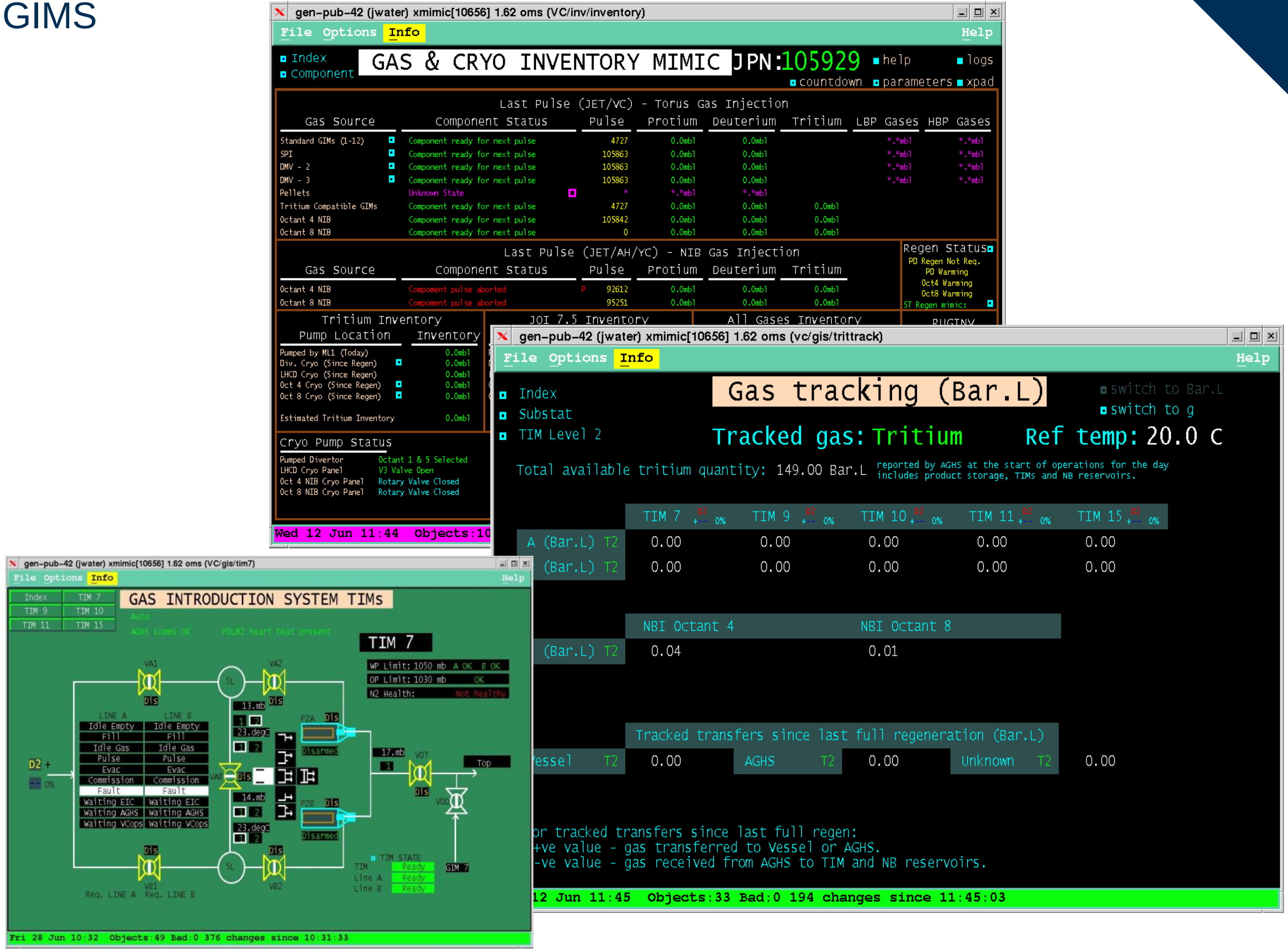
Gas inventory and tritium tracking

Level-1 controls

- Communication with Tritium Plant
- Configuration
- Budget management

TIM Level 2 controls and communication





Real-time Control Enhancements

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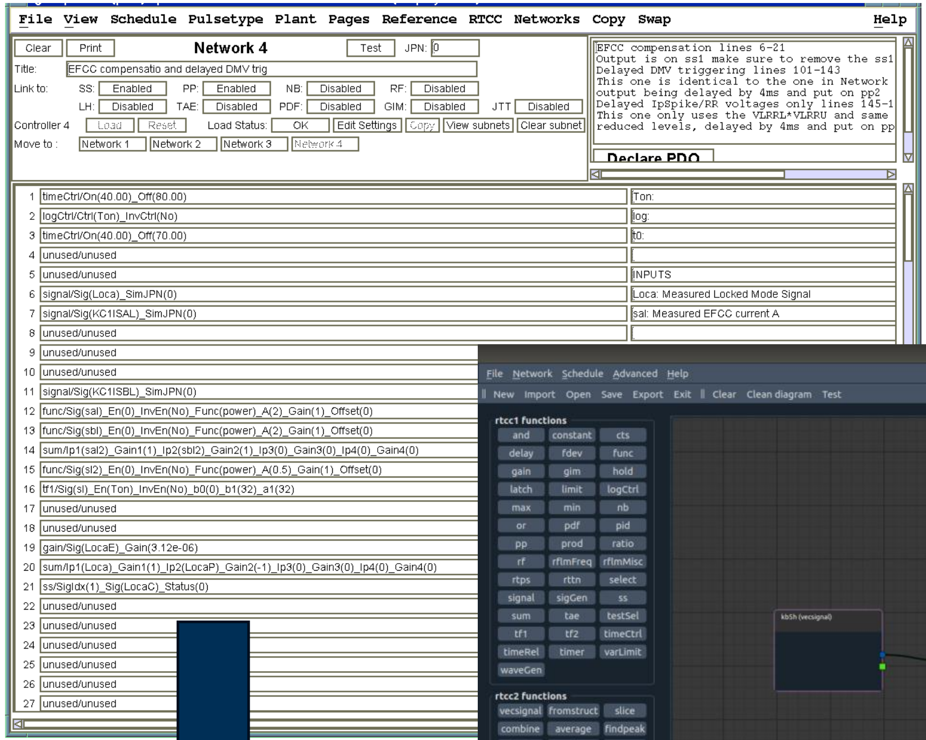
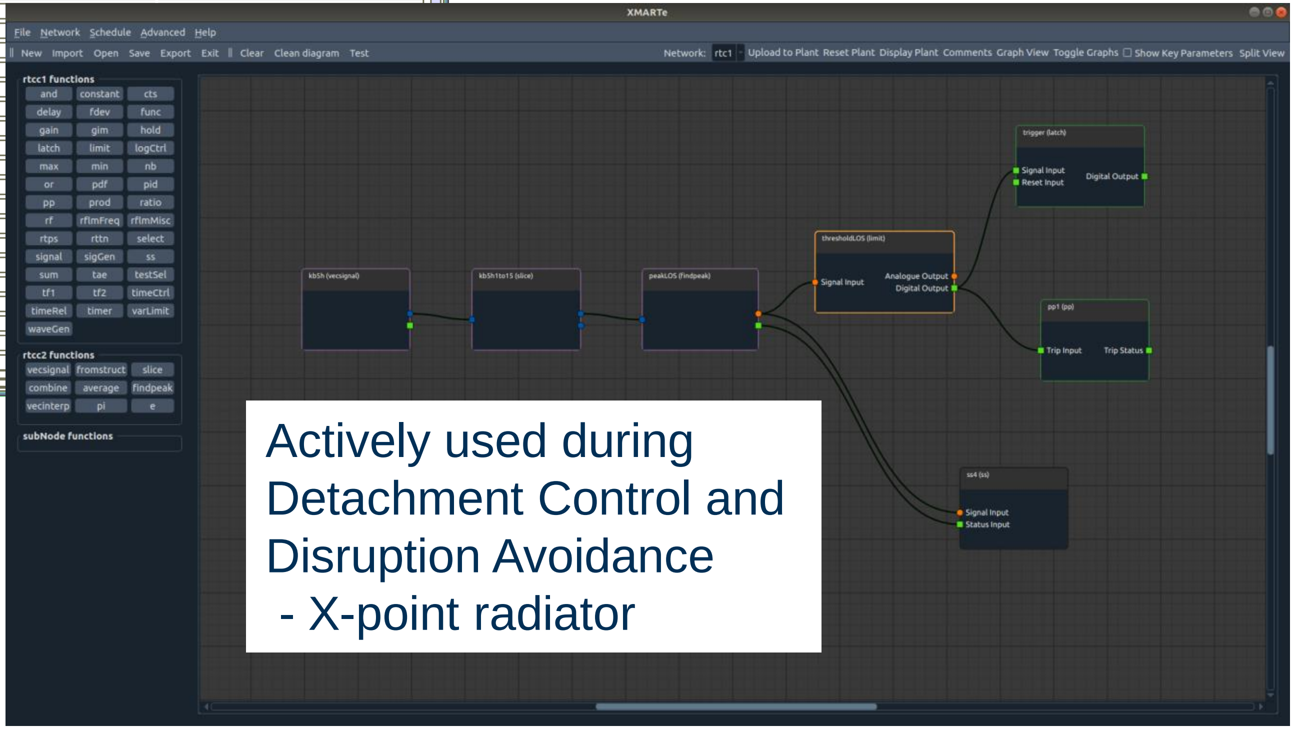


RTCC – VME/Power PC running VXWorks with RTDN over ATM build on MARTe

Level-1 configuration editor



Actively used during Detachment Control and Disruption Avoidance

- X-point radiator

RTCC2 – Linux PC with ITER/SND over Ethernet

Built on MARTe V2

New graphical user interface

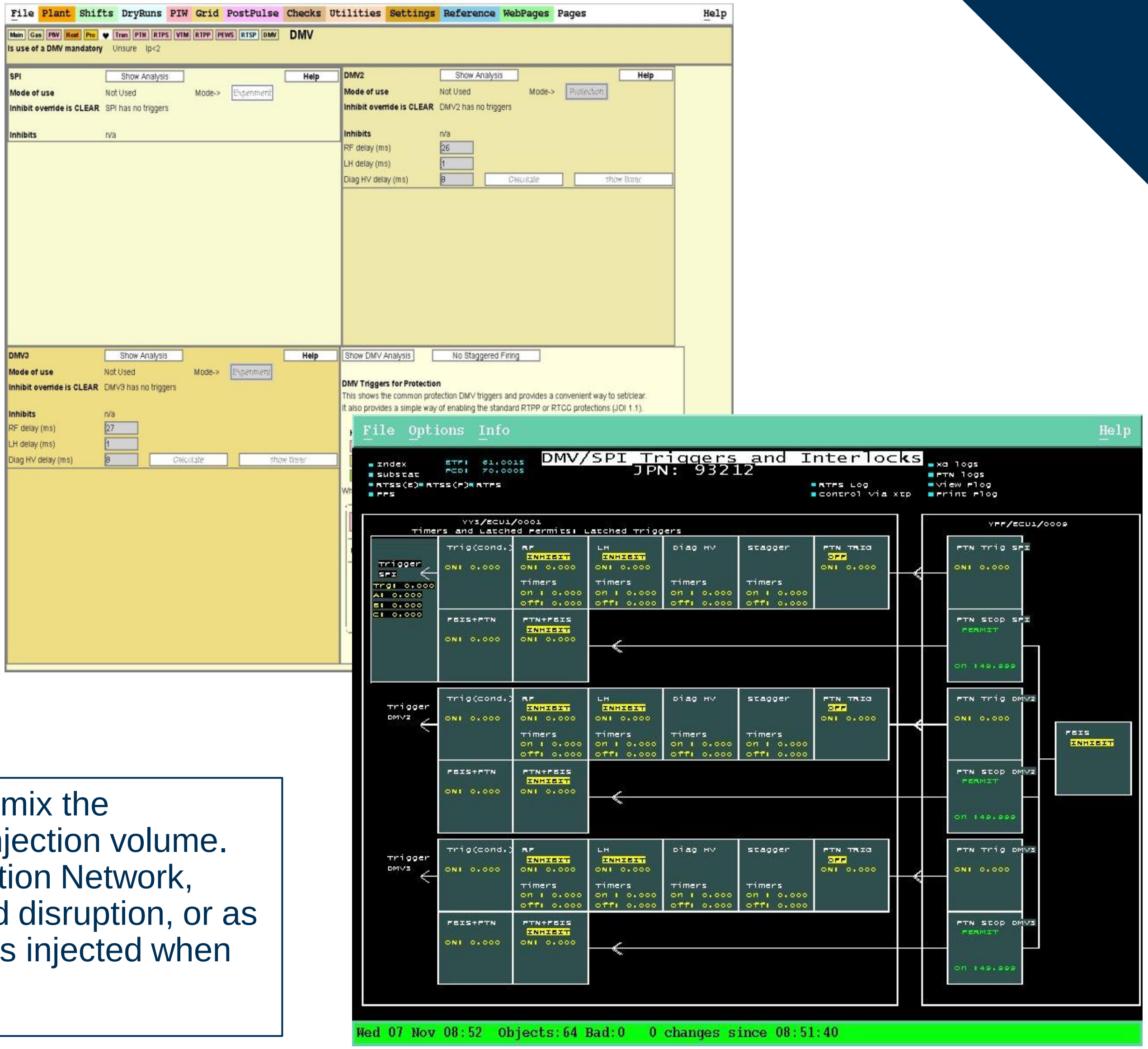
Would like to have implemented statistical selection and derivation of control signals

- *plasma density in PDV for gas feedback control*

Disruption Mitigation Systems - DMV

Disruption Mitigation Valve

- Originally an ITER related experiment
- Later mandatory protection for high current/energy pulses
- Poses risks to plasma facing systems
- Neutral beam interactions catastrophic
- Timing/Trigger system using PTN with fail-safe interlocks to additional heating systems
- Automation of routine operation
- Level-1 interface
- Expert user required for special cases
- PLC data extracted over ethernet for logging and display in JET control room
- Integrated into Gas Inventory



Each DMV system is controlled by its PLC to mix the appropriate gas species and pressurise the injection volume. The trigger originates from the Pulse Termination Network, either in response to a disruption, or predicted disruption, or as part of an experiment. A large volume of gas is injected when triggered

Disruption Mitigation Systems - SPI

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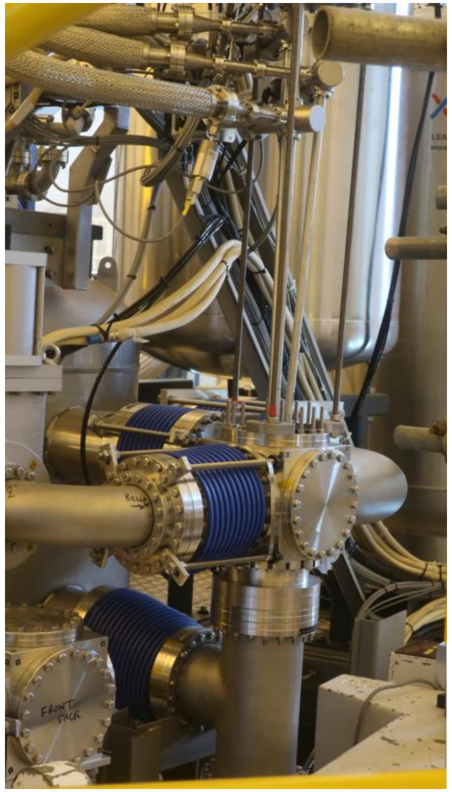
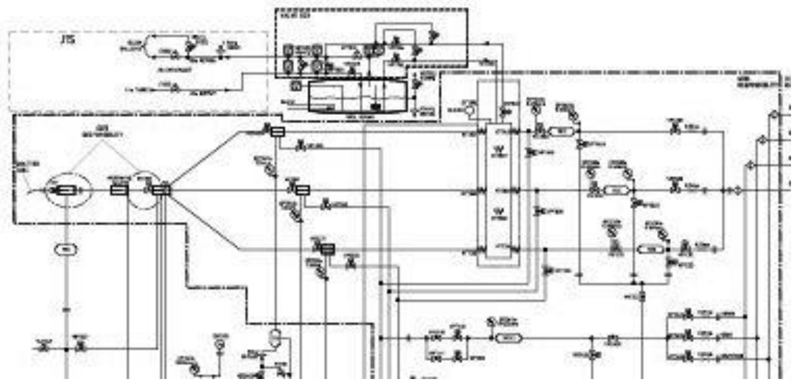
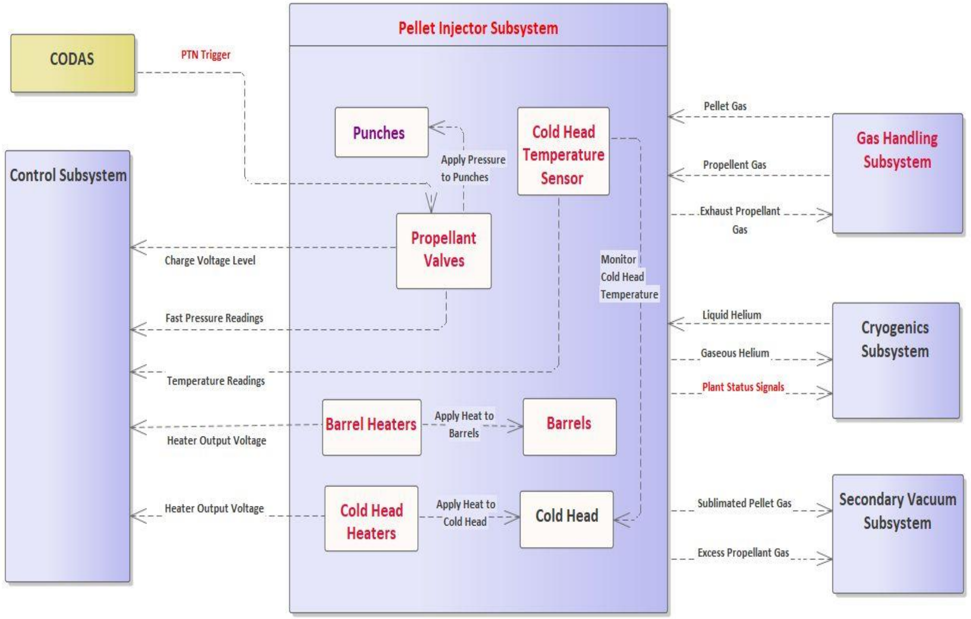


Shattered Pellet Injector

- Shared gas supply with DMVs
- Integrated into DMS interlocks
- Gas species frozen to form pellets
- Cold head cooled to 10K
- Propellent gas typically D at 60bar
- Partial automation to support export users
- An ITER related experiment
  - NOT a protection system
  - but also used for runaway experiments
- Possible damage to inner wall if no plasma
- Failure modes: no fire, premature injection
- Integrated into Gas Inventory
- Trigger via PTN with interlocks





The pellet shards penetrate the plasma more rapidly than a DMV gas puff, and SPI technology will be used on ITER.

Developments to mitigate for COVID

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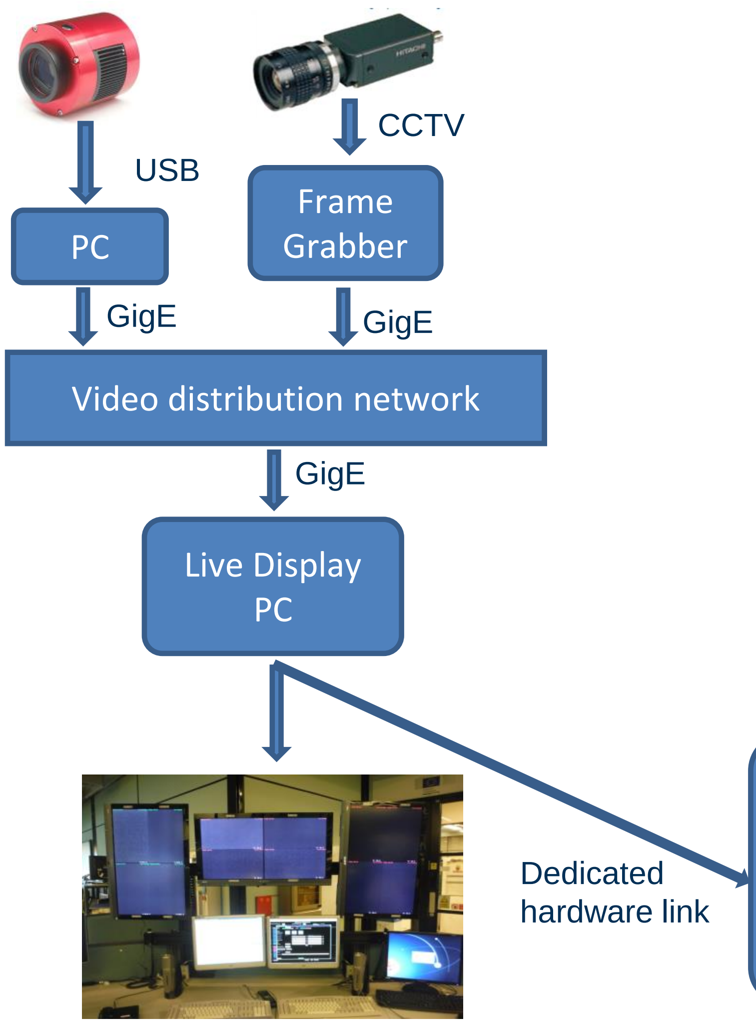
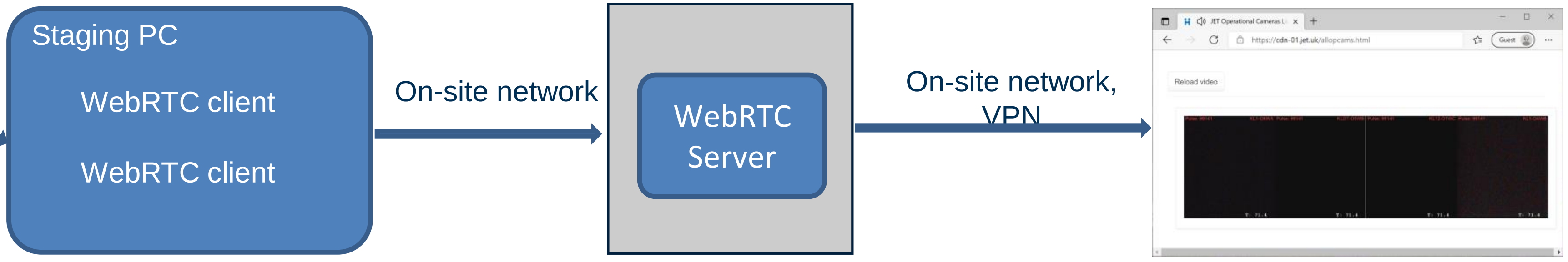


Web browser access to JET Mimics
Improved remote access to operational systems
Video stream intercept and serve in real time through the web

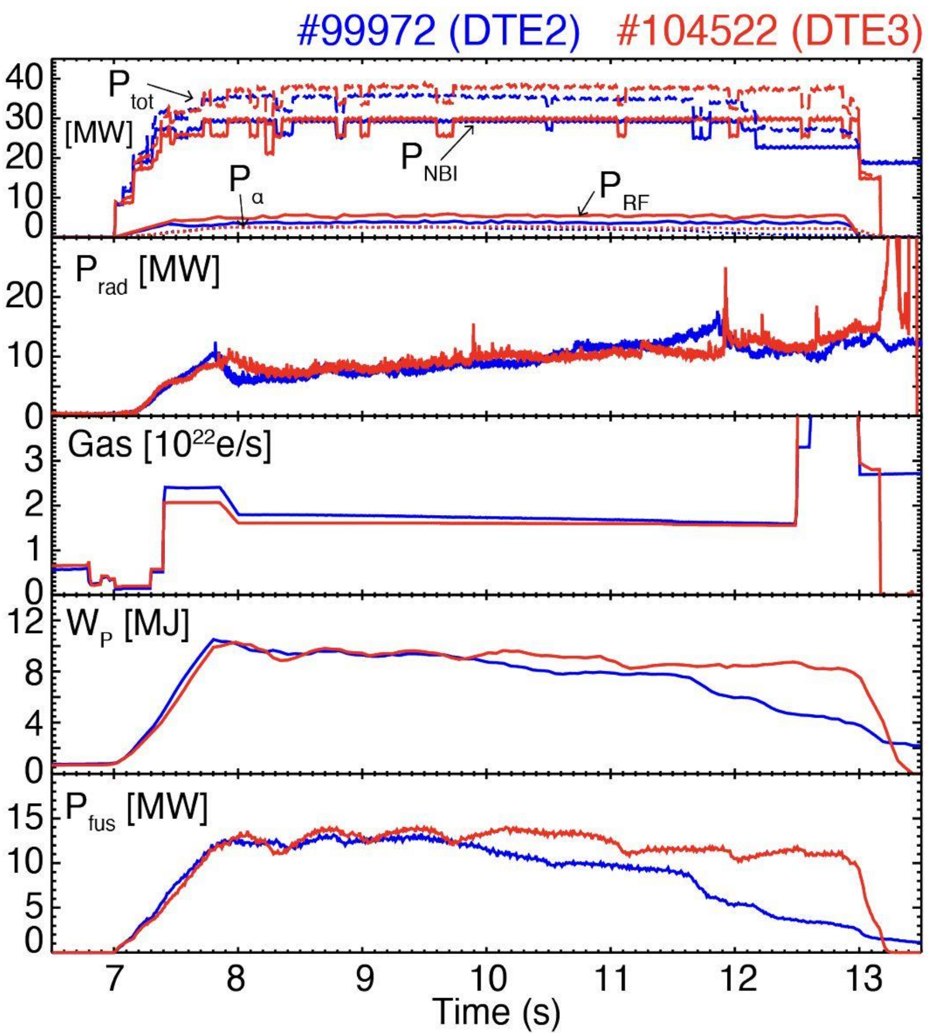
- Colour Operations Cameras only
- Re-use control room live software, running on a dedicated PC, to generate the live/rolling replay views for remote users
- The Staging PC grabs the monitor output and presents it to a WebRTC server

Future Machines/Power Plants

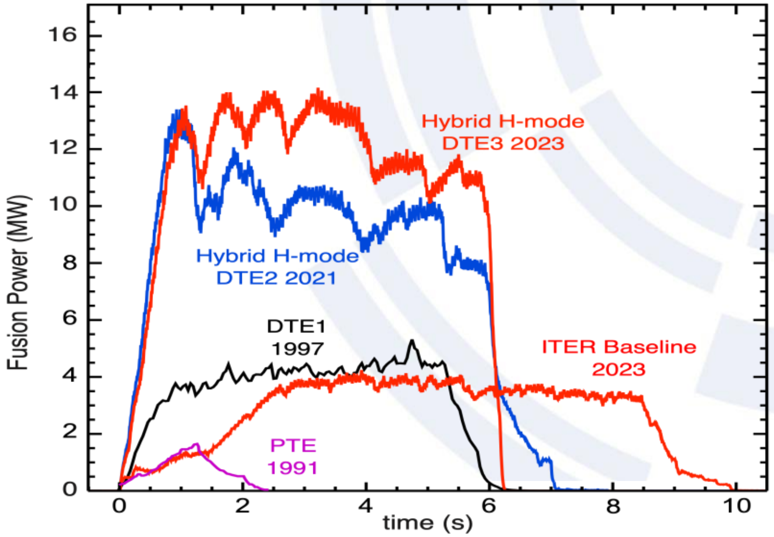
- Few people on site and in Control Room
- How do you manage remote access
    - Monitoring & Plant Control



Deuterium Tritium Results



- T-rich hybrid scenario experiments revisited:
  - repeat the highest performance pulse
  - with improved resilience to high-Z impurity accumulation, achieved via higher P_{ICRH}
  - Higher power, optimised gas



Very long heated pulse
A CODAS challenge

Traditional JET pulse

- 80 s of TF
- 40 s of plasma
- 10 s NBI heating 30 MW

Plant limits

- Central solenoid Vs
- Power supply limits
- Thermal limits

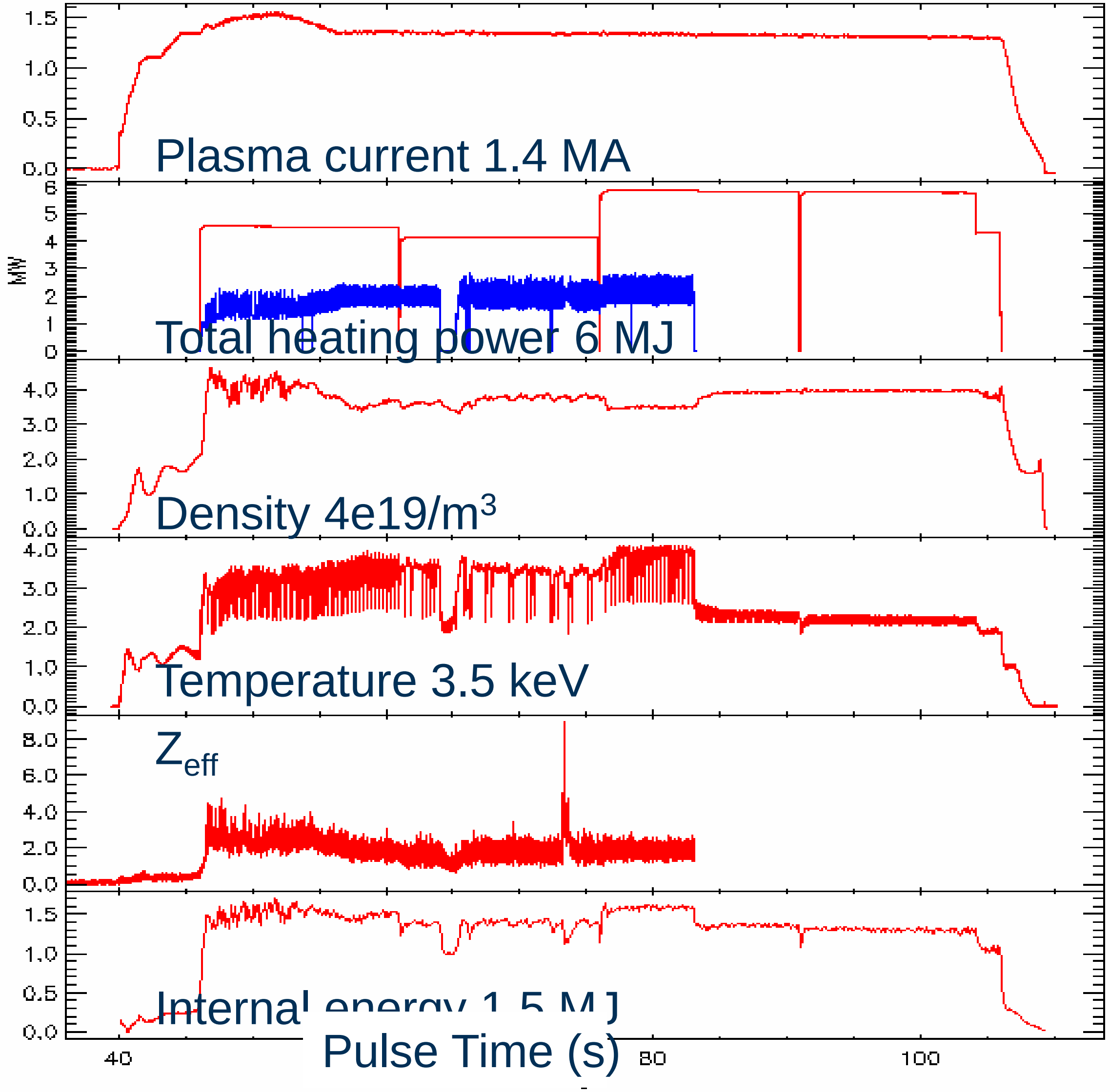
CODAS Limits:

- Explicit timing settings
  - Plant enable windows
  - Protection limits
- Implicit assumptions
  - Timeouts
  - Sampling rates/number of samples

Long Pulse

- 110s TF
- 60 s of plasma at 1.4 MA
- 60 s of NBI heating at 4 - 6 MW
- 40 s of RF power at 2 MW

Be aware of your explicitly and implicit limits



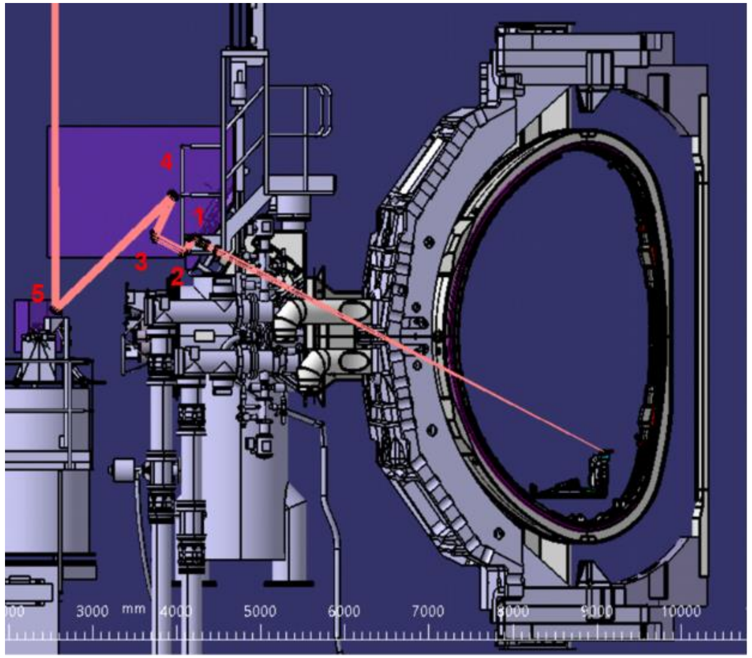
LID-QMS
Laser Induced Desorption Quadrupole Mass Spectrometry

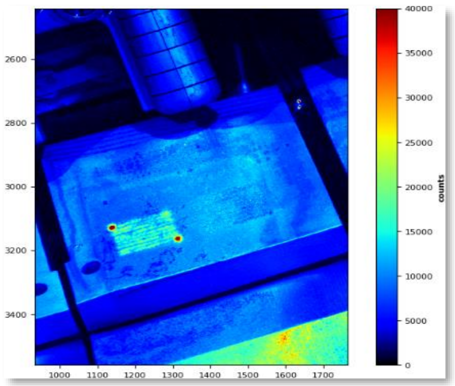
Usual key exchange and primary safety circuit
- To ensure no one is in controlled areas – Torus Hall

Special CODAS Pulse Mode:
- No checks on Central Interlock and Safety System
- Limited subsystems enabled to speed up readout

Enhancements required:
- Repurposing Cameras to view tile being used
- Laser control/triggering system
- Articulated mirrors to steer incident point
- High level (Level-1) controls
- Mode setup and return to normal scripts in Level-1

Operating mode
- Initially in pauses in operations – meal breaks
- Later whole shifts inc. Saturdays





Gas analysis : QMS

Laser scan on tile

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Last Ever JET Pulse....105929

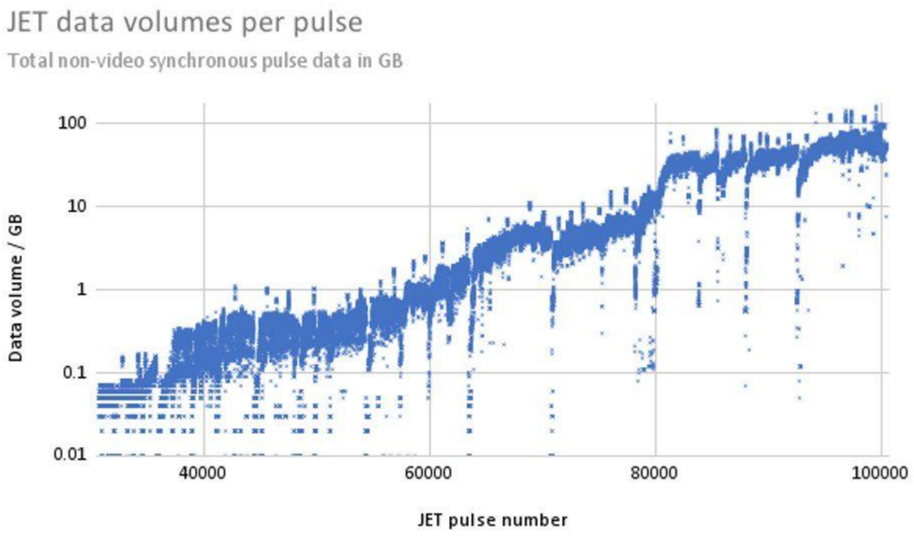
LID-QMS pulse with JET pulse announcement message

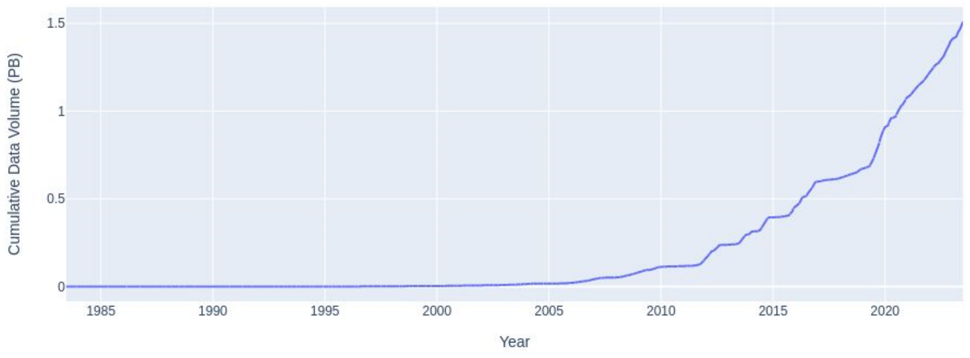
JET Data Centre

Politics
- BREXIT
- Who owns the JET Data
- Are we a member of
- Who has access to the data
- Who is funding

Proposal to lift and shift the JET Data Centre
- Separation of operational systems from the data warehouse
- Local caching for data new data and visualisation/analysis and local resilience
- Very high bandwidth connection
- ❖ Failed - so stays local

Future access to JET data by others (DTT, CFS and other)?
- Data mining
- IMAS interface
- Virtual-JET – to develop and test future control and protection systems





Beyond Operations

Plasma operations ceased at the end of 2023

Much of the plant is still running:

- Vacuum pumping and plant monitoring
- Environment monitoring
- Radiation protection instrumentation
- Access Controls

Forthcoming activities:

- Power down to reduce electricity bill
- Diagnostic calibrations
- In-vessel sample retrieval
- Detritiation
- Decommissioning and repurposing

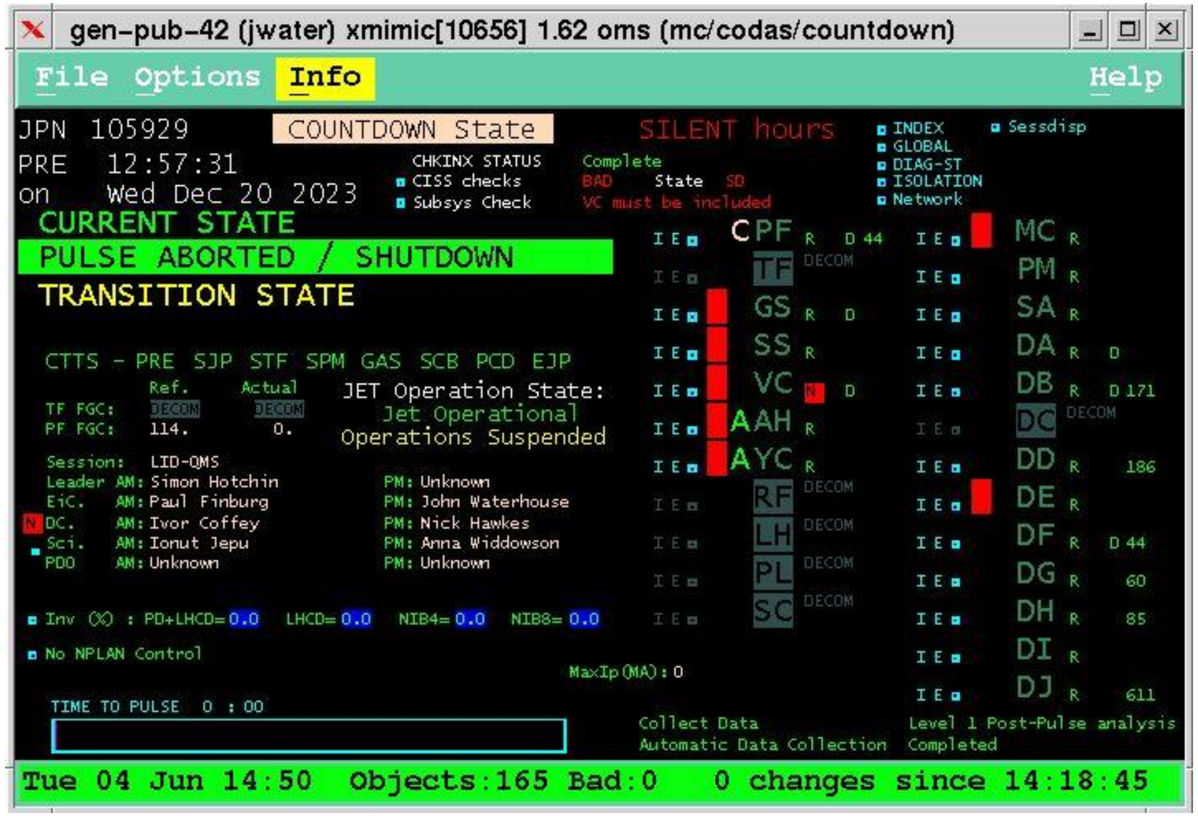
CODAS Sub-systems powered down when associated plant it turned off

- ➢ Greyed out and marked Decom

Parts of CODAS will have to remain operational for several years until functionality replaced

Maintain Configuration Control & Documentation

- Decommissioning
- De-planting



Conclusions

JET Control and Data Acquisition has stood the test of time and supported a very successful programmes on JET.

- Much of the architecture from 40 years ago still in use
- Evolution to meet experimental needs and changing technology
- Much technology development in the early period as components were not commercially available and continues at a diminishing rate right through to the end
- High standard, administrative controls, documentation
- Adoption of new technologies as appropriate
- Maintenance of old technologies where appropriate (ex Data to Solaris computers)
- Supply in-kind and interfacing to CODAS – some intere

Aspects of JET CODAS live on

- JET Data Centre continues to provide access to all (>4 data
- Support for diagnostic calibration
- Support for plant & environment monitoring, radiation protection instrumentation and access controls
- Possible support for detritiation
- CODAS plant facing system are being shut down when no longer required
- De-planting and Repurposing to follow

JET is a research machine

- Very flexible

Future large machines will be different

- Commissioning will be more like a research machine
- Then repetition of pulses to build up statistic
- Reliability & Maintainability
- Technology refresh

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Acknowledgement

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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.

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