Global Real Time Functions of the "Plasma System": Plasma Control and Machine Protection

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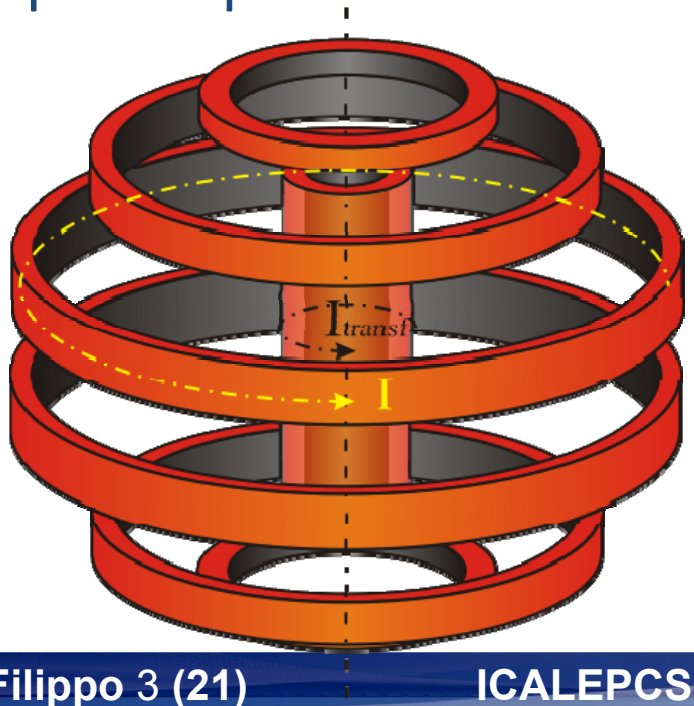
Summary

- Introduction
  - Brief description of Tokamak experiment
  - Introduce “Plasma System”
- “Plasma System” Control and Protection
  - Examples ➔ Requirements
- The “Plasma System” at JET
  - Integrated Control and Protection
- Conclusion

Tokamak

Tokamak contains the Plasma within a torus shaped vacuum vessel ➔ doughnut.

Surrounding the vessel are two sets of magnetic coils.
The PF (*poloidal*) coils create and shape the plasma.



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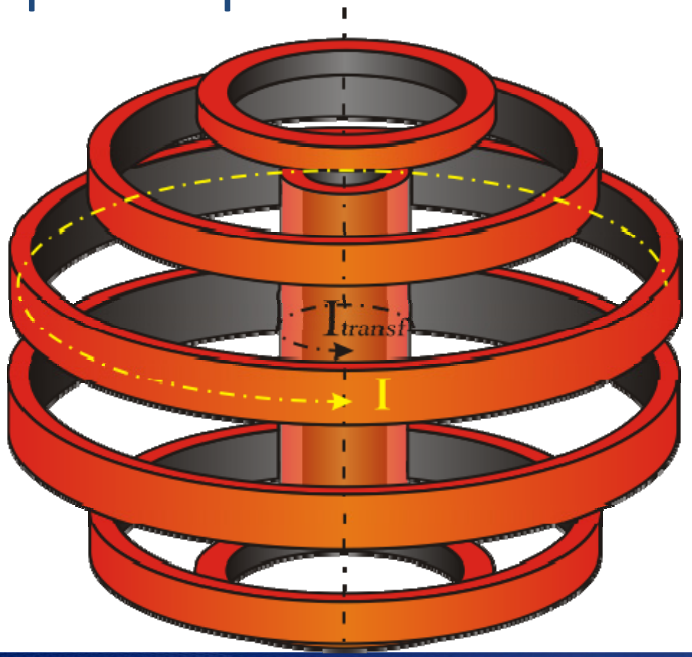

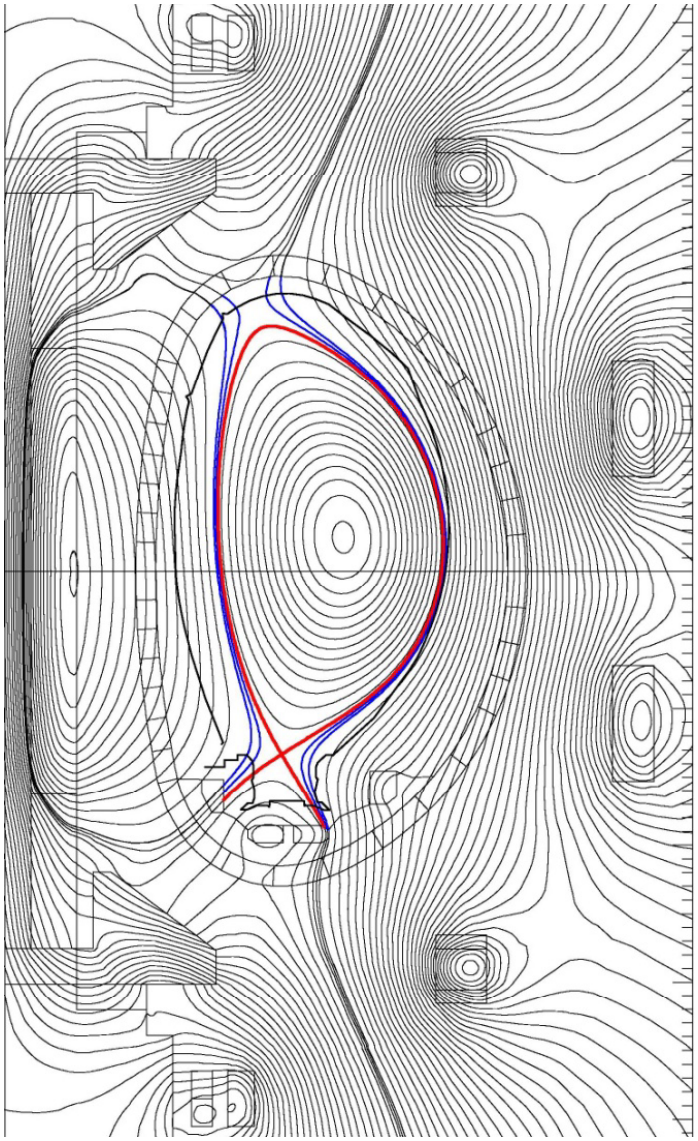

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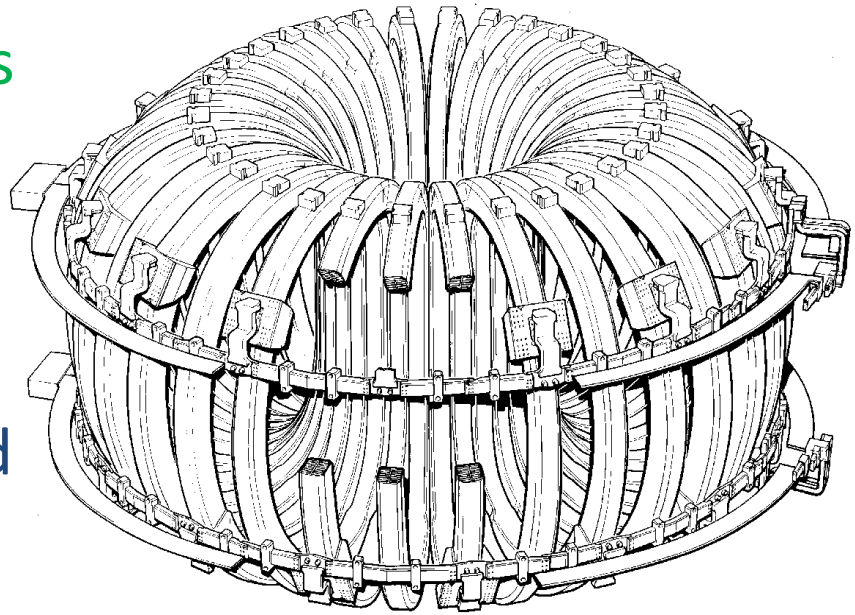
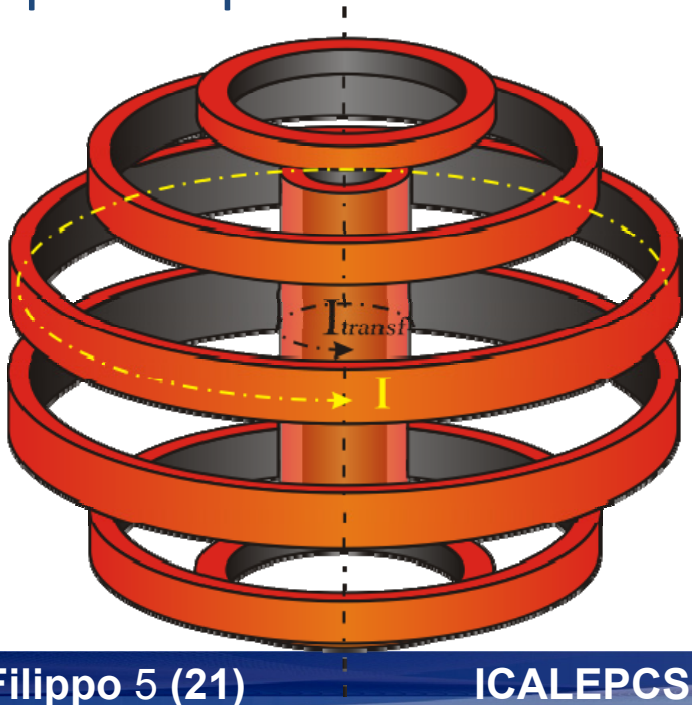
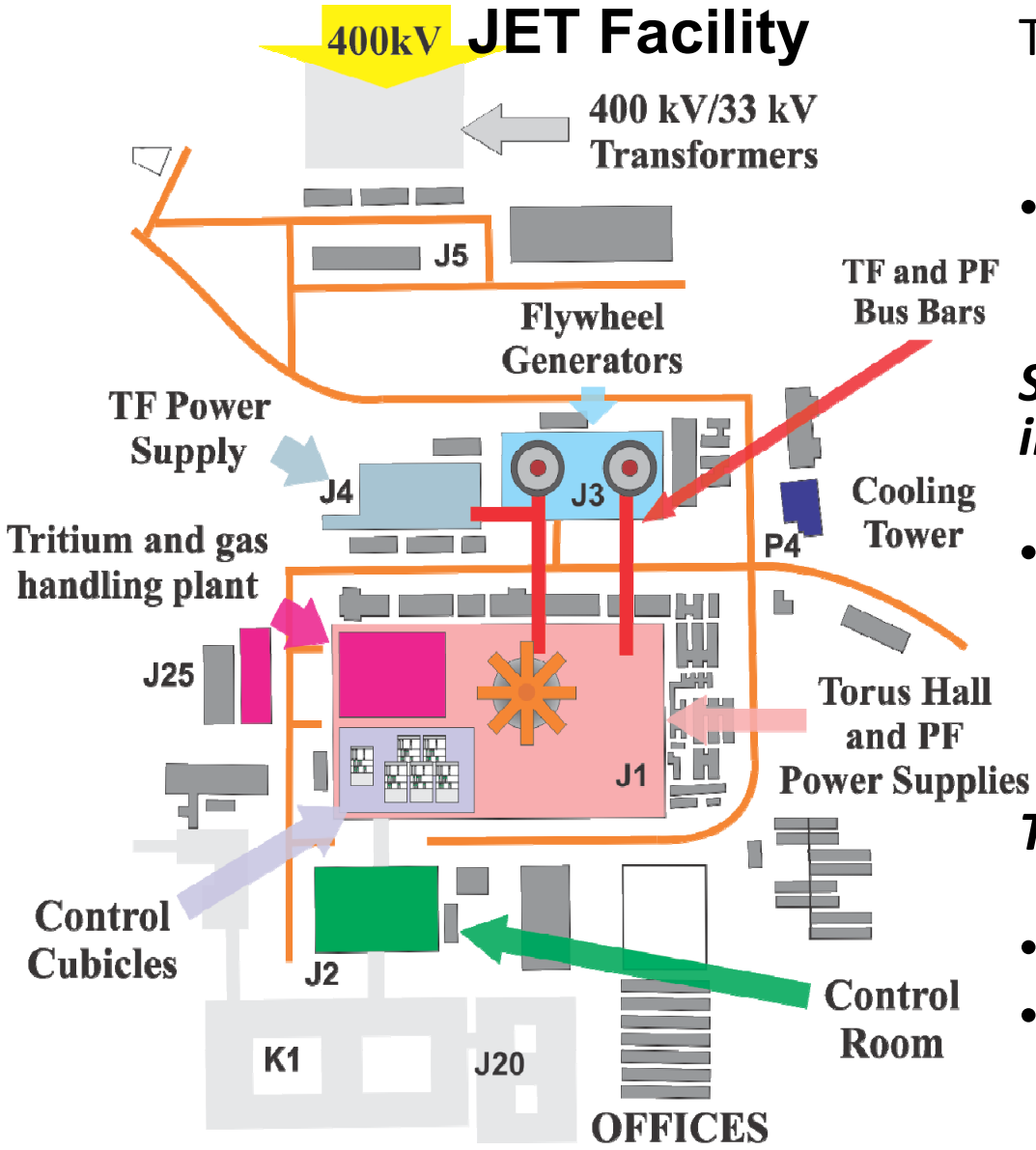




The TF coils create a *toroidal* field which helps avoiding instabilities.

Tokamak Facility



Tokamak operation requires large plant with many systems.

- Some *provide essential services*:
  - Electrical distribution, Vacuum, Cryogeneration, Cooling, …

Similar to other experimental or industrial facilities.

- Some *play an active role* in the plasma experiment:
  - Magnets, Additional Heating, Gas Fuelling, Diagnostics

These + Plasma = Plasma System.

- *Unique to the fusion world*
- *Subject of fusion research…*

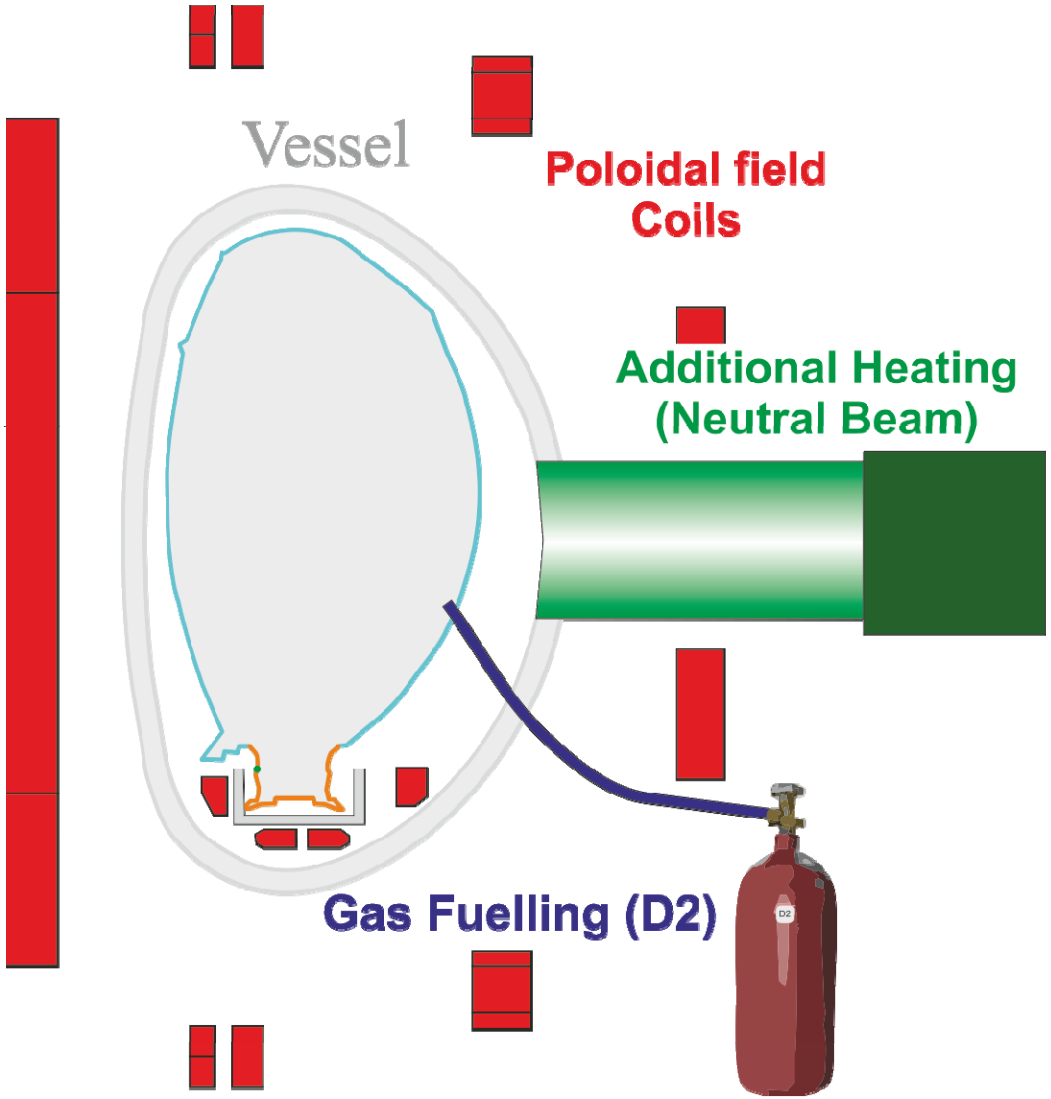
The Plasma System

The Central solenoid creates an electric field. GAS is added and ionised → plasma.

During plasma growth PF coils control plasma radial position.

Other PF coils shape the plasma into diverted shape

Additional heating heats the plasma



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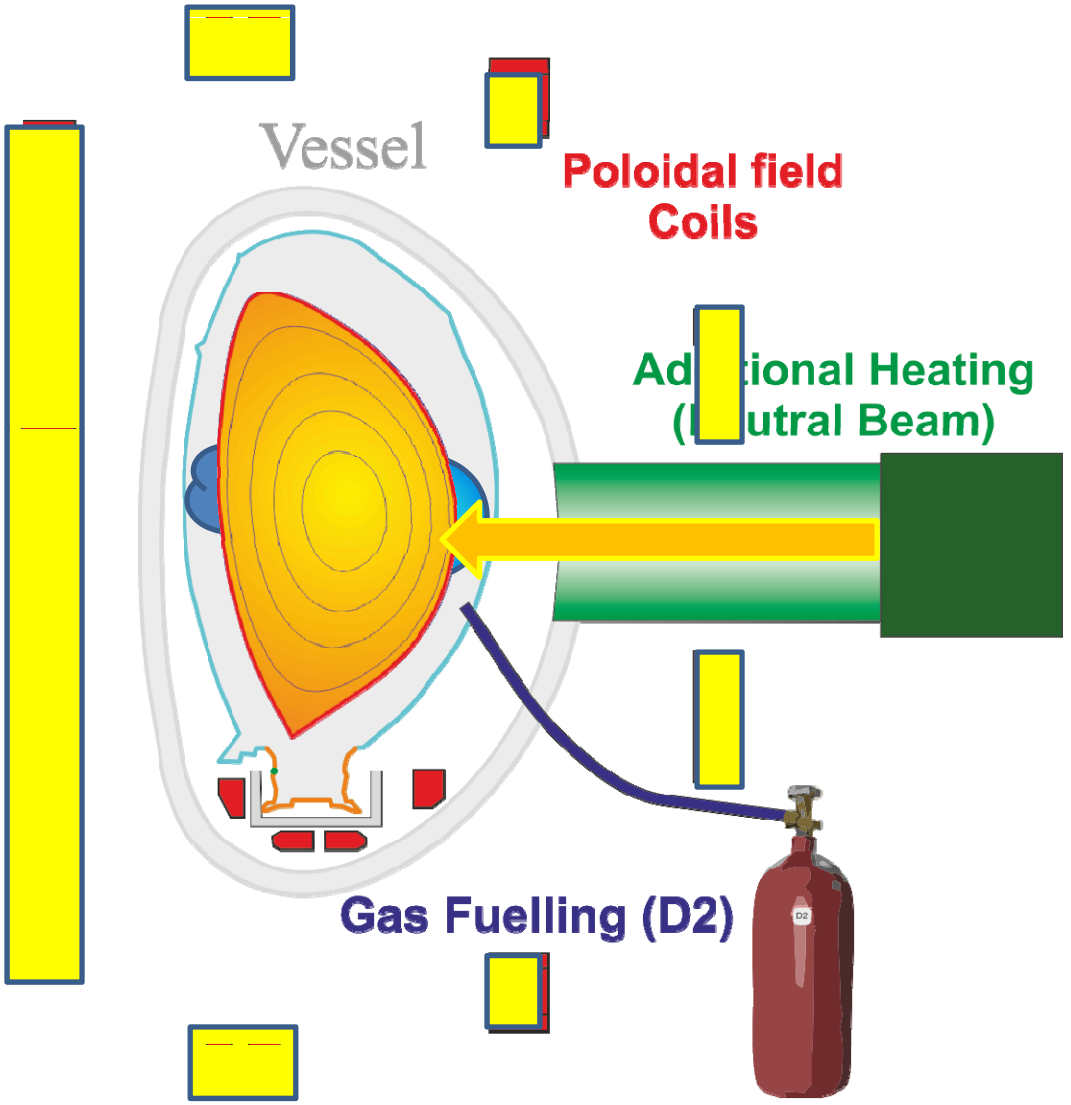
The conditions for fusion are reached!



Main Challenges

In the next slides examples to show :

- Real-Time functions involving multiple Plant Systems
- Protection actions ➔ Control functions
- “Plasma System” Diagnostics ➔ Low Reliability!
- Complex algorithms

Shape Control

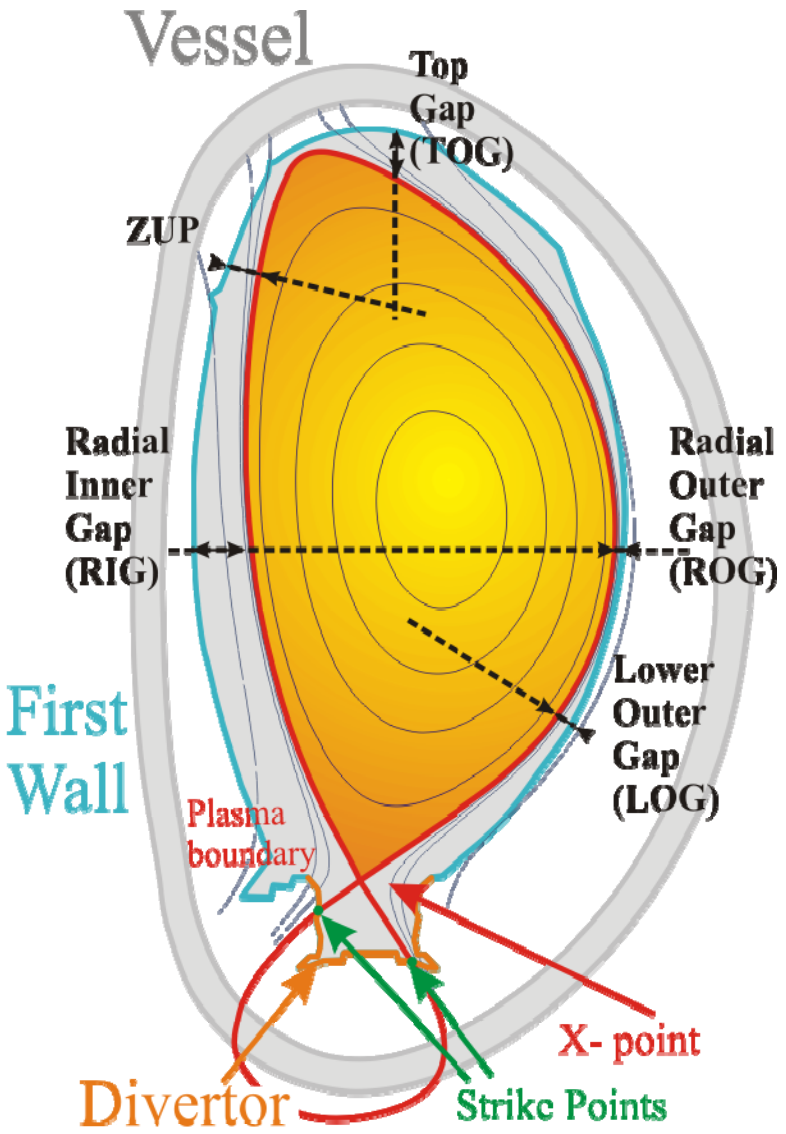
Problem:
Plasma shape ➔ performance and interaction plasma-walls.
But: plasma pressure varies ➔ shape variation.

Actuator: **PF Magnet System**
Adjust PF currents ➔ shape corrected
JET: *9 PF coil currents*

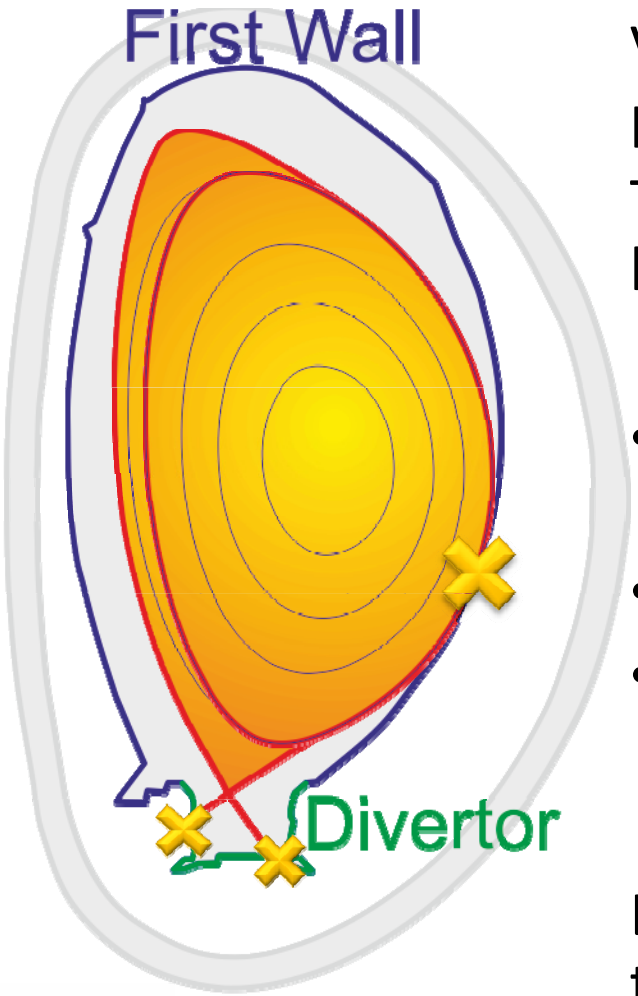
Diagnostic: **Magnetic diagnostic System + Equilibrium Code**
JET: circa 200 magnetic signals

Real Time Control System:
Calculates voltages to be applied to coils.
Complex: Time-variant, Non linear, Multi-Variable control problem.

➔ Poster MOPMU035 "Shape Controller Upgrades for the JET ITER-like Wall"



Wall protection: problem



The problem:

Vessel is lined with tiles designed to stand, the power exhausted by the plasma.

The majority is, typically, concentrated in two locations in the divertor. (particles)

- **power density** too high → tile melts (metal) or sublimates (carbon) → disruption.
- **total energy** too high →supports weakened
- particles' **angle of incidence** too steep or too shallow → tiles edges damaged.

Larger risk exists if the main plasma body touches the First Wall: not designed to take much power nor energy.

Wall protection: diagnostic

Diagnostics:

Surface temperature: IR cameras, pyrometers…

- Formation of dust layers → Heated →False alarms

Bulk temperature: thermocouples…

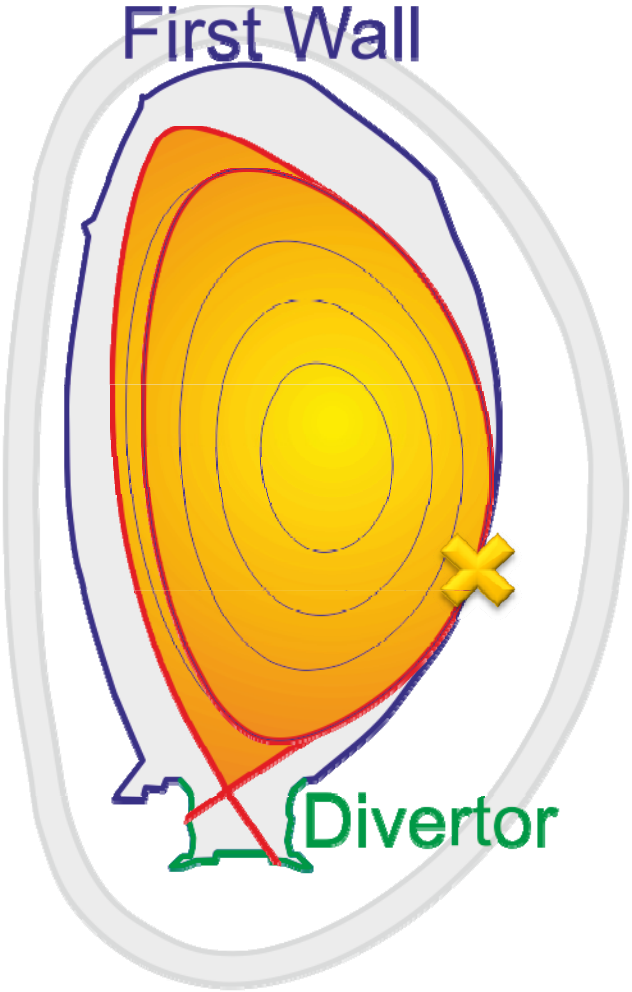
- Electromagnetic pickup → fake temperature swings

Reliable diagnostic → a challenge!

→ Poster WEPMN014: "The Software and Hardware Architectural Design of the Vessel Thermal Map Real-Time System in JET"

→ Poster WEPMU018: "Real Time Protection of the "ITER-like Wall at JET"

Wall protection: action



Protection Action:

- Fast Stop plasma ➔ all plasma energy on point of contact
- Stop additional Heating power ➔ disruption

Correct solution:

- Change point of contact
- Slowly reduce power and terminate discharge

Solving the problem requires control!

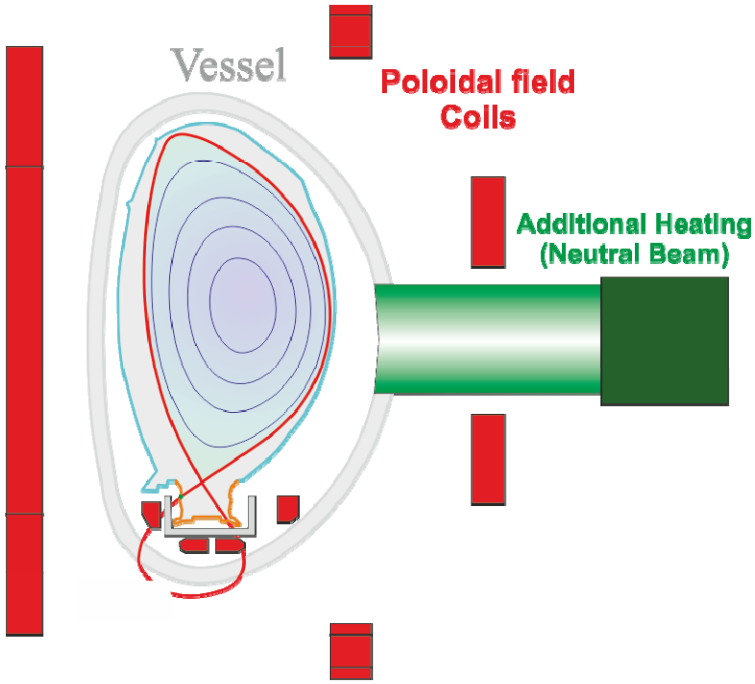
➔Talk FRAAULT04 ”Centralized Coordinated Control to Protect the JET ITER-like Wall.”

➔ Poster MOPMU035 “Shape Controller Upgrades for the JET ITER-like Wall”

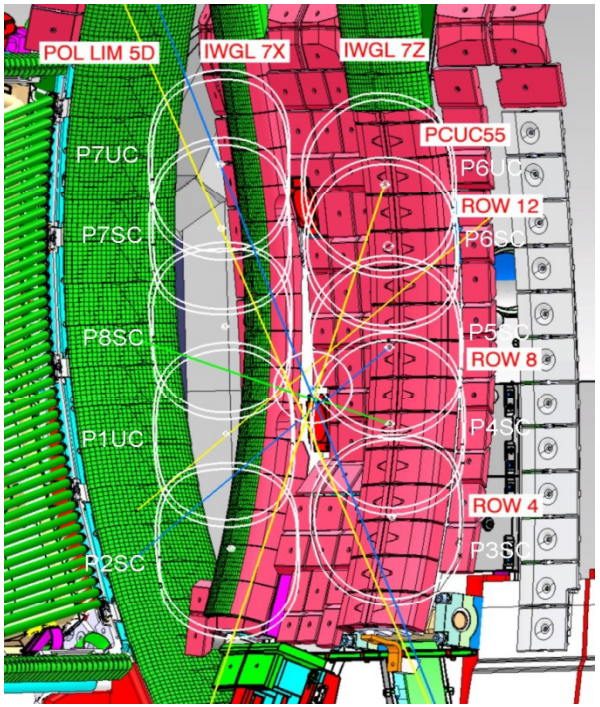
Protection: Shine-Through

Problem

- JET Neutral Beam injects >20MW of high energy neutral Deuterium.



Beam Line View into Torus



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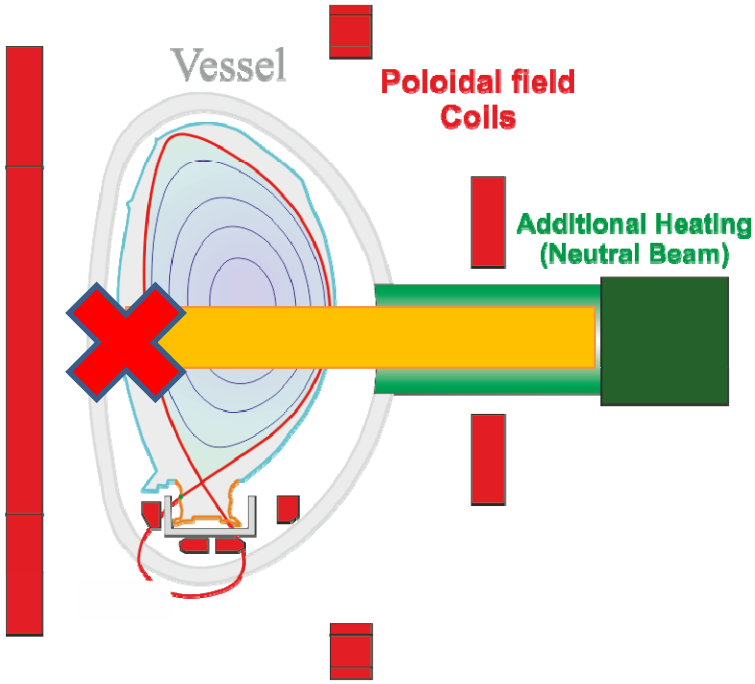
- Plasma density too low ➔ beam passes the plasma and damages the wall



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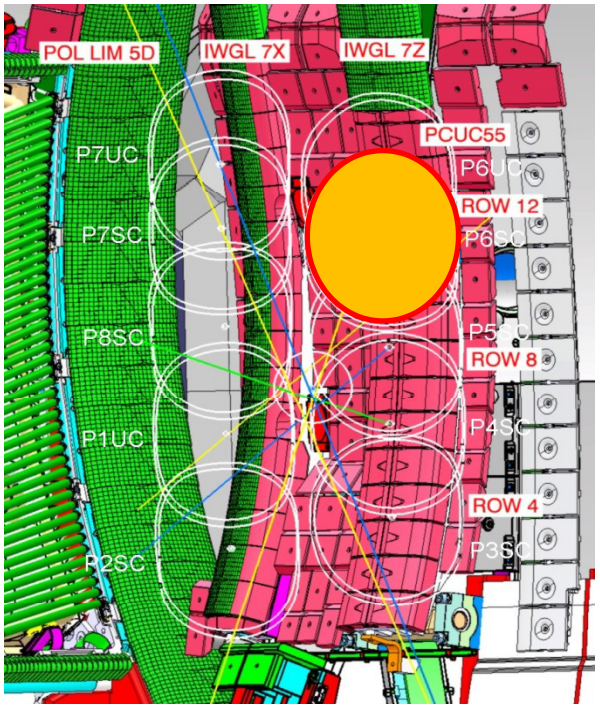

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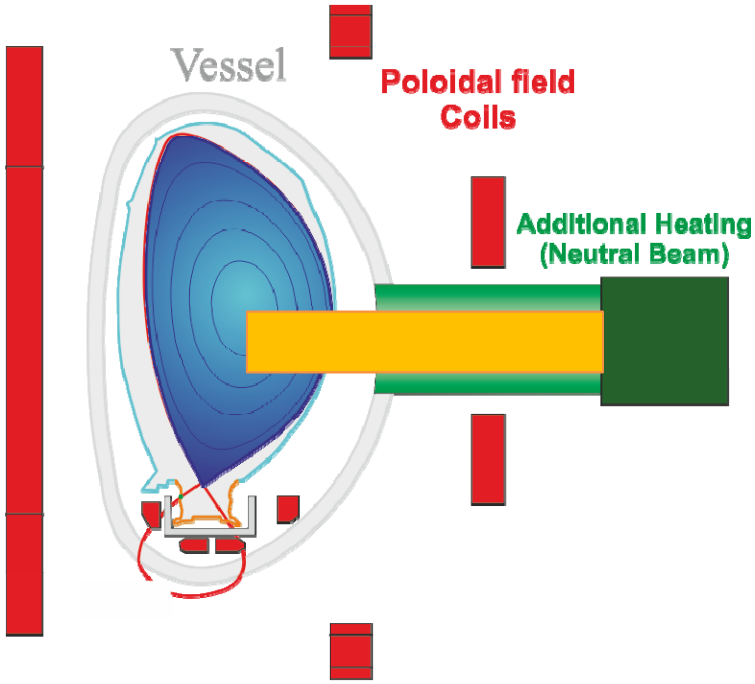

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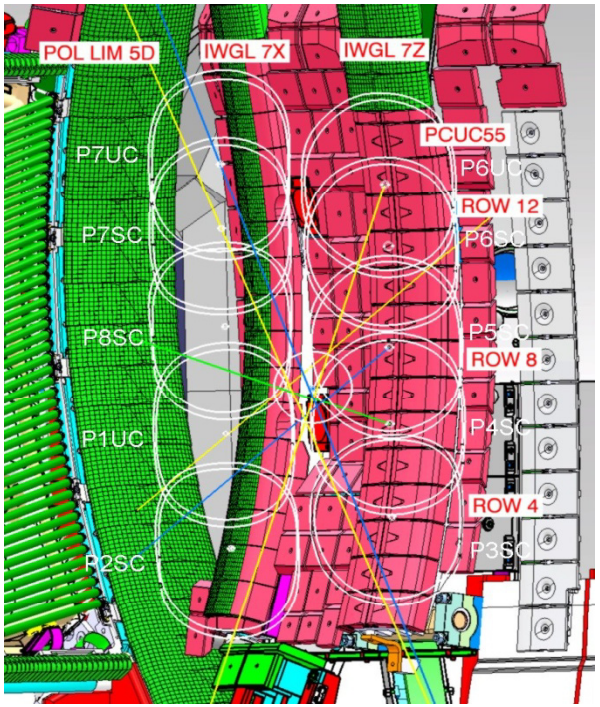

Shine-Through protection

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- Plasma density too low ➔ beam passes the plasma and damages the wall
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- **Active protection needed! ➔ Beam not fired if density too low!**

Diagnostic & Protection

- **Dedicated** density diagnostic for this protection.
  Robust but not precise (measures radiation ~density)
  ➔ *Last line of defence against damage to the vessel.*

- Routine protection of the vessel components:
  - Density from interferometer (precise but not robust → affected by ELMs)
  - Correction system to handle fringe jumps (uses other diagnostics)
  - Neutral Beam injection **enabled** only if density is good.

JET integrated approach

Main challenge = implement protection functions!

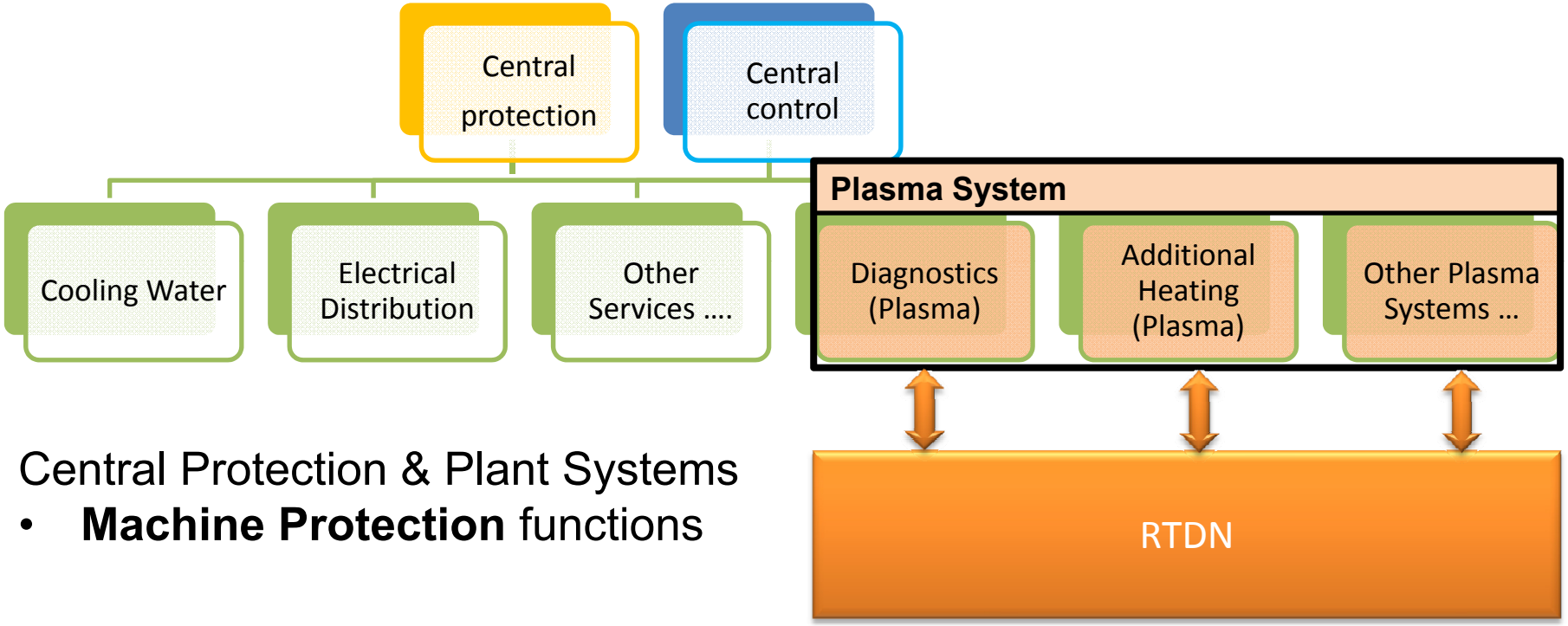
JET appr: many protection layers.

- Risk Management ➔ **operating instructions**
  - Limit dangerous operation ➔ require special permit.
  - Manage progressive exploration of operational space.
- Machine Protection: Highly Reliable / Very Simple
  - Avoid cases where major damage on a single event
- Intelligent Protection: Less Reliable / Complex and Intelligent
  - Handle situations that could result in loss in machine life
  - Verify **operating instructions**
- Limit Avoidance
  - Control Systems know and avoid limits
- Intelligent User Interface
  - Impose **operating instructions**
  - Minimize human errors.

JET architecture

Central Control (coordinates, monitors)

- **Intelligent user interface**



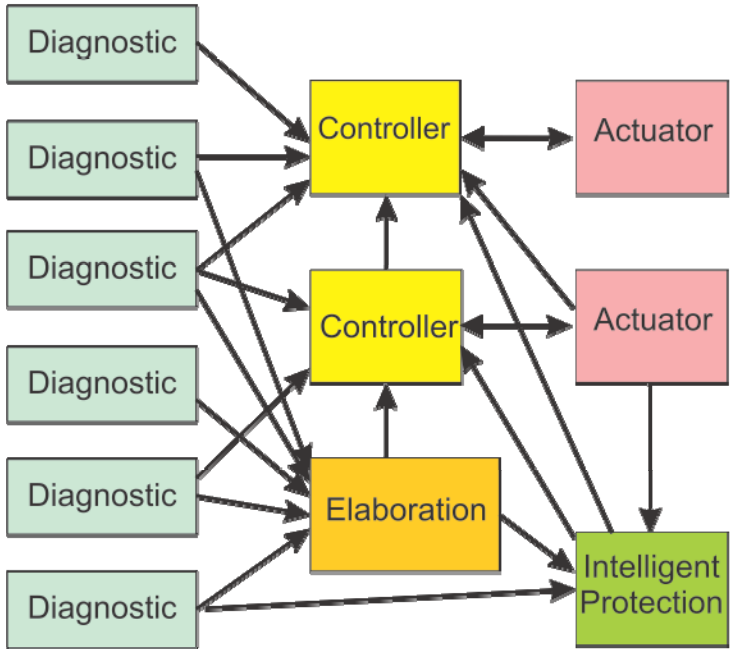
Central Protection & Plant Systems

- **Machine Protection** functions

New system: RTDN Real Time Data Network

- Control Systems: Regulation, Stabilisation, **Limit Avoidance**
- **Intelligent Protection** Systems

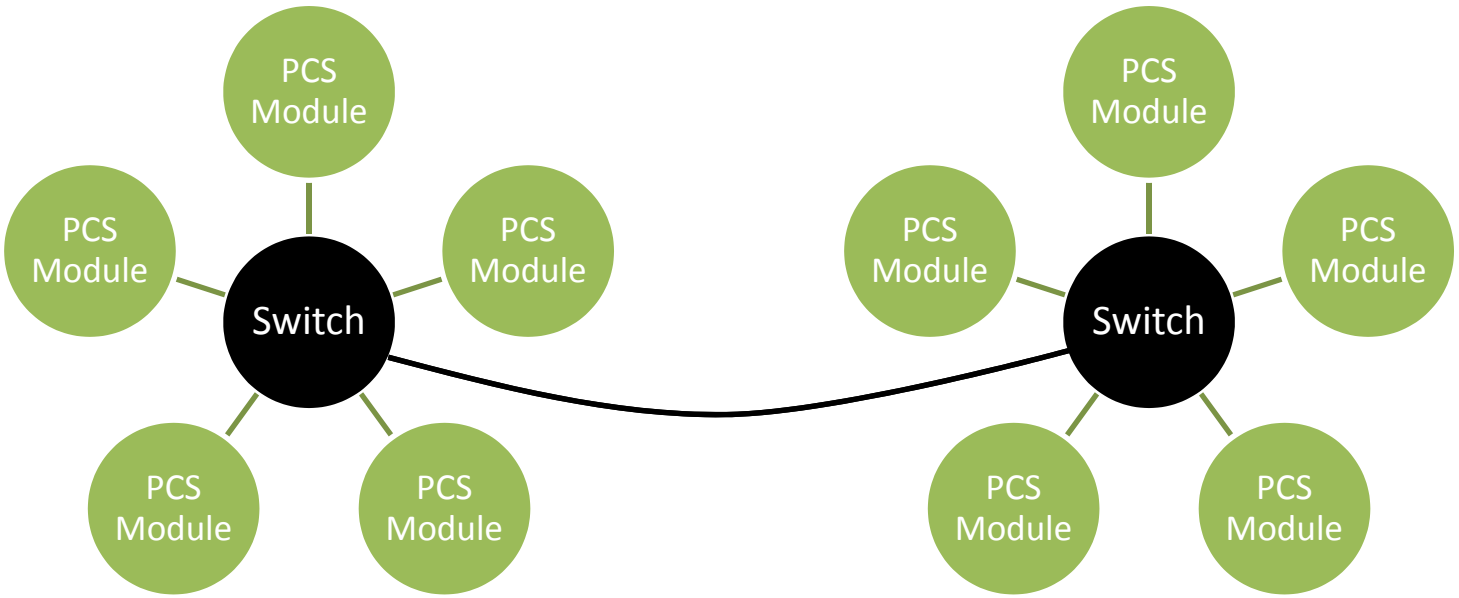
JET architecture



- RTDN Control and Protection functions ➔ Grouped into modules
  - Similar reliability requirements
  - Same schedule requirements ➔ evolving system
  - …
- Complex functional diagram ➔ Simple network topology
  - Flexible and expandable to support evolution
  - Very High availability to support Protection Functions

RTDN Network

- Based on **ATM switches,** currently uses a **Dual Star** topology.
  - 155Mbit link to nodes 620Mbit backbone
  - Easy to add new nodes
  - Resilient against single node failure (compared to ring topologies)
  - Uses highly available switches (COTS).



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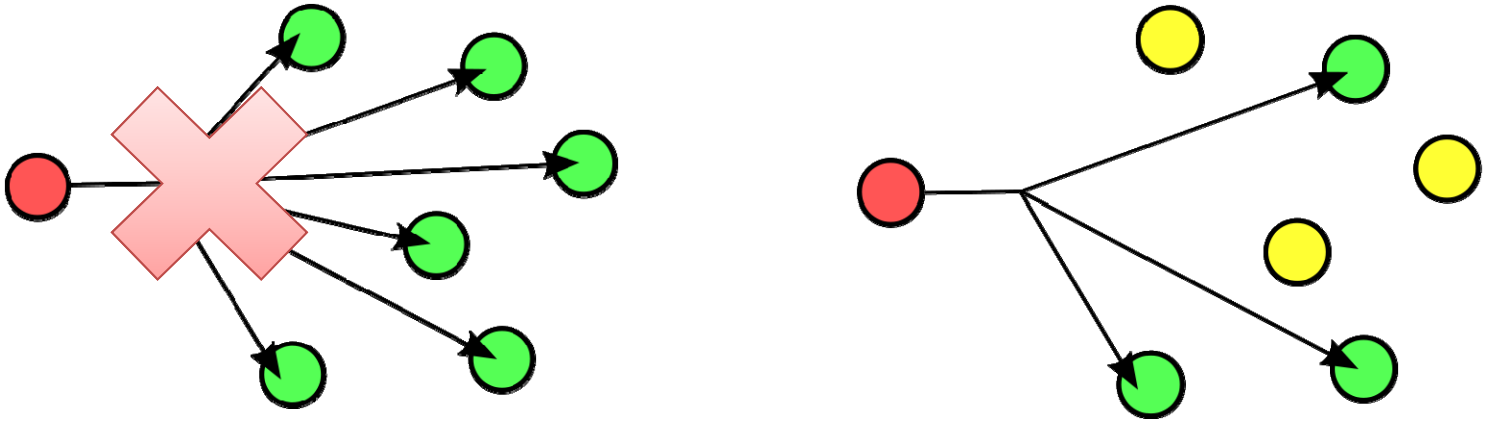
  - Traffic only to actual users → reduced traffic at branches.



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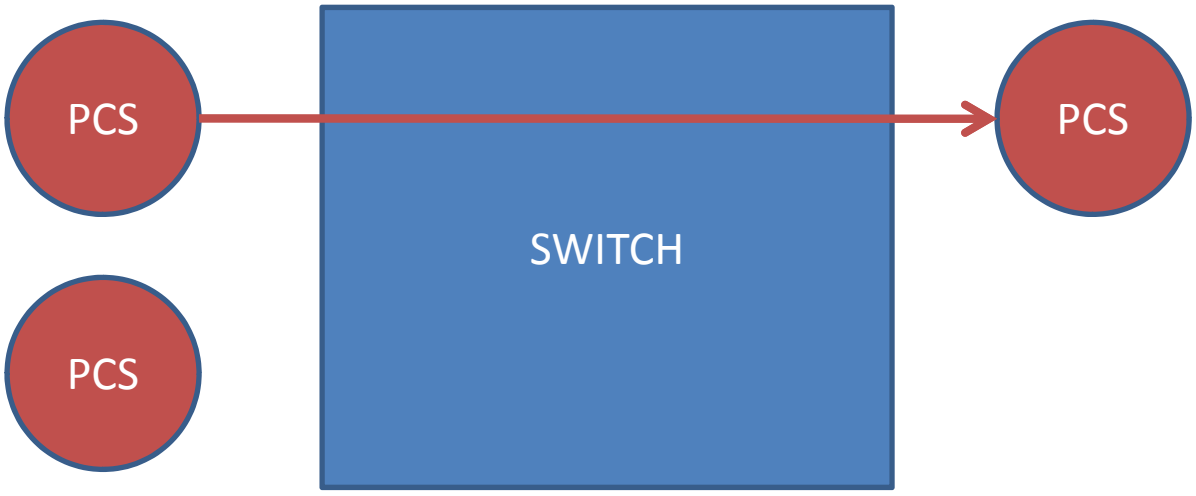
  - allows introduction of a new PCS Module: until tested isolate output.
  - It also allows seamless replacement of a PCS Module with another



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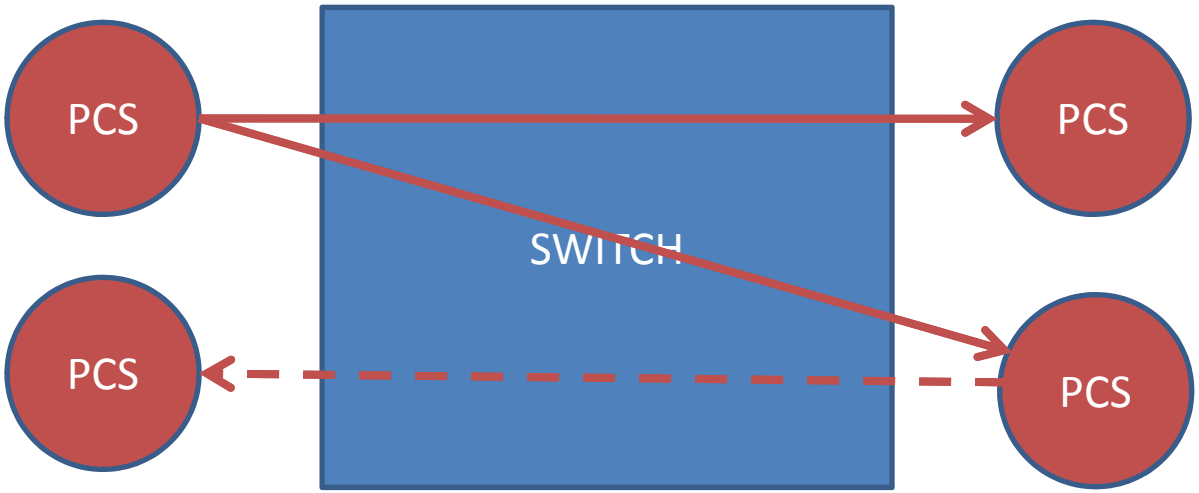

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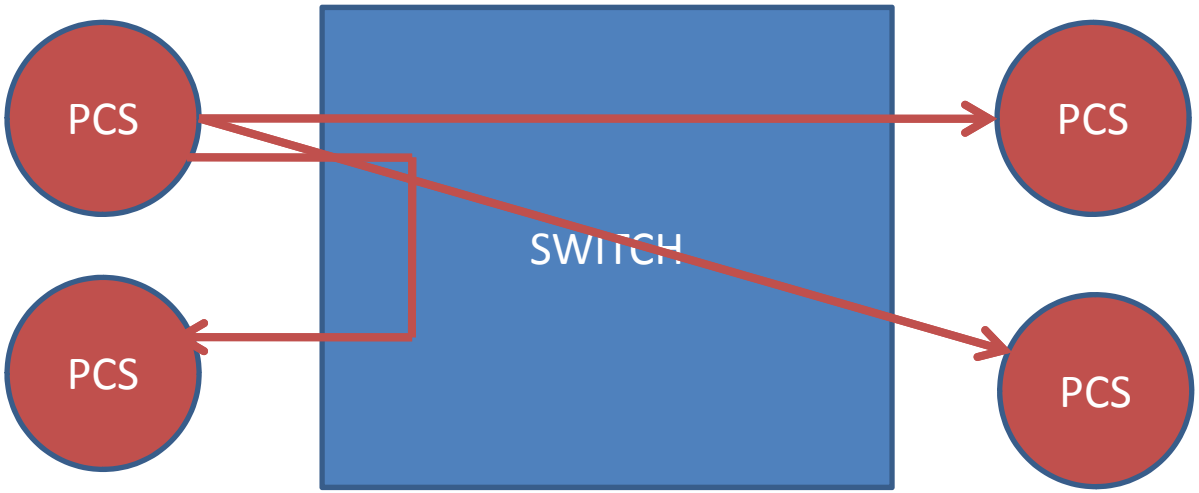

RTDN Software

Recent implementation of RTDN modules is being standardized around MARTe framework:

- ➔ Talk: THDAULT06 ”MARTe Framework: a Middleware for Real-time Applications Development”
- ➔ Poster: WEPMN014: “The Software and Hardware Architectural Design of the Vessel Thermal Map Real-Time System in JET”
- ➔ Poster: WEPMN036 “Qualitative Comparison of EPICS IOC and MARTe for the Development of a Hard Real-Time Control Application ”

Conclusions

JET has been a great scientific and technical success, with a long track record of efficient operation.

One of the contributing elements was certainly its approach to the “Plasma System”:

- Layered Protection functions
- Strong integration between Plasma Control and Protection functions

Now it is the turn of ITER to take the lead and to bring fusion one step closer to the final goal.

And to do this once again the challenges of the highly integrated and evolving “Plasma System” will have to be addressed.