Wendelstein 7-X

Andreas Werner for the W7-X Team

Max-Planck-Institut für Plasmaphysik, Germany
EURATOM-Association

Max-Planck-
Institut
für Plasmaphysik

Max-Planck Institut für Plasmaphysik

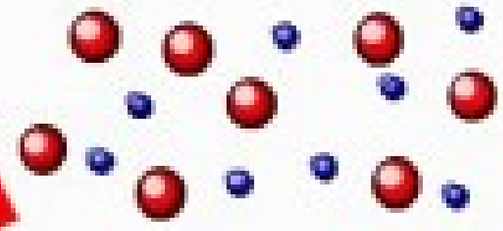
Two sites: Garching & Greifswald

1100 employees, ~450 in Greifswald

The Plasma State

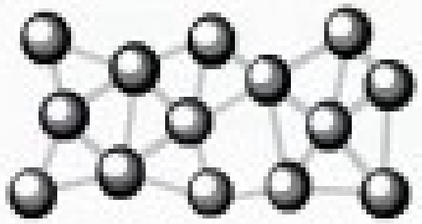
- neutral atoms
- Ions (+)
- electrons (-)

plasma state
quasi neutral

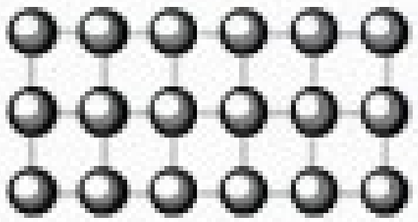


Temperature

gaseous

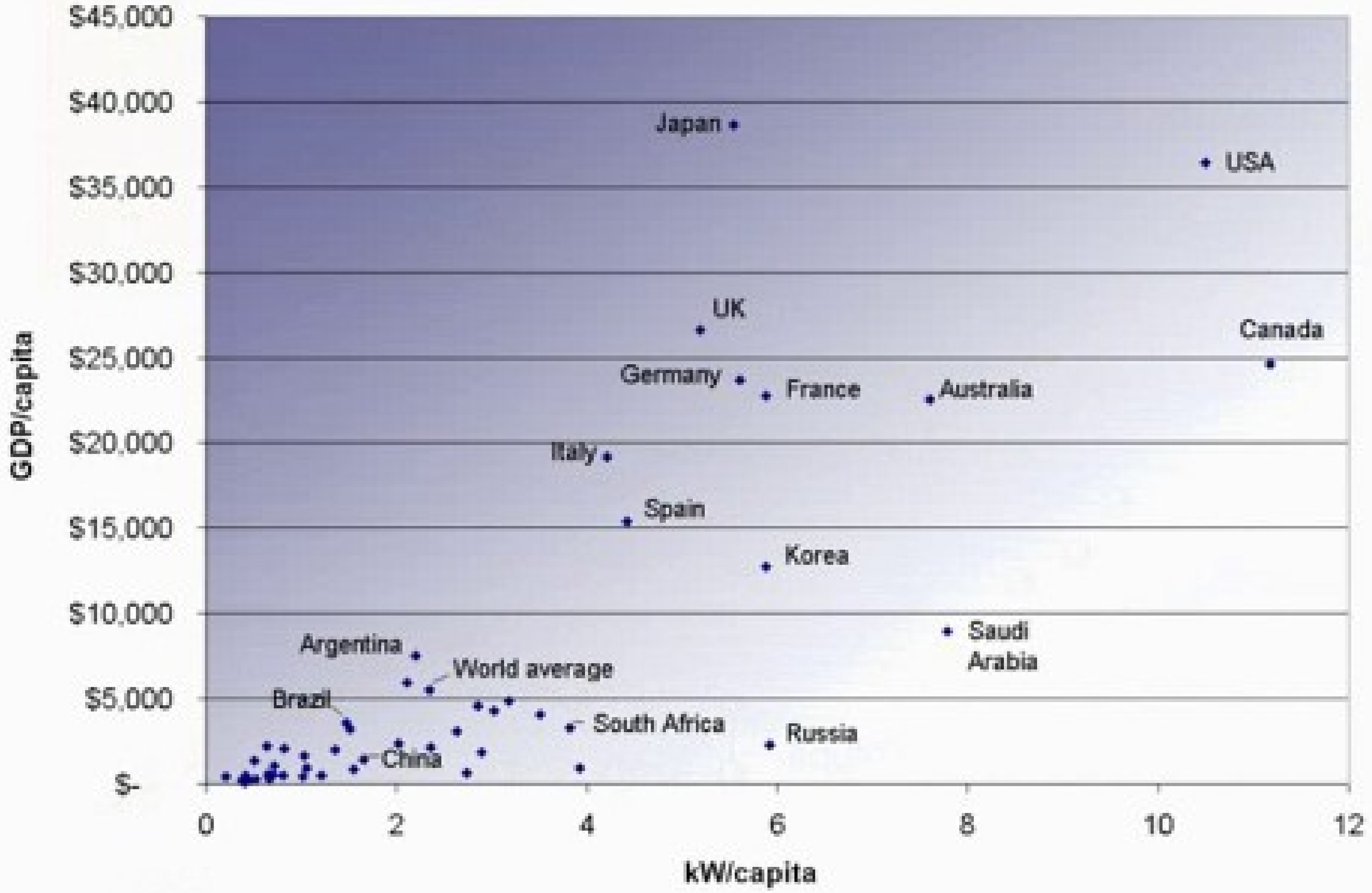


liquid



solid

Power Consumption per Capita



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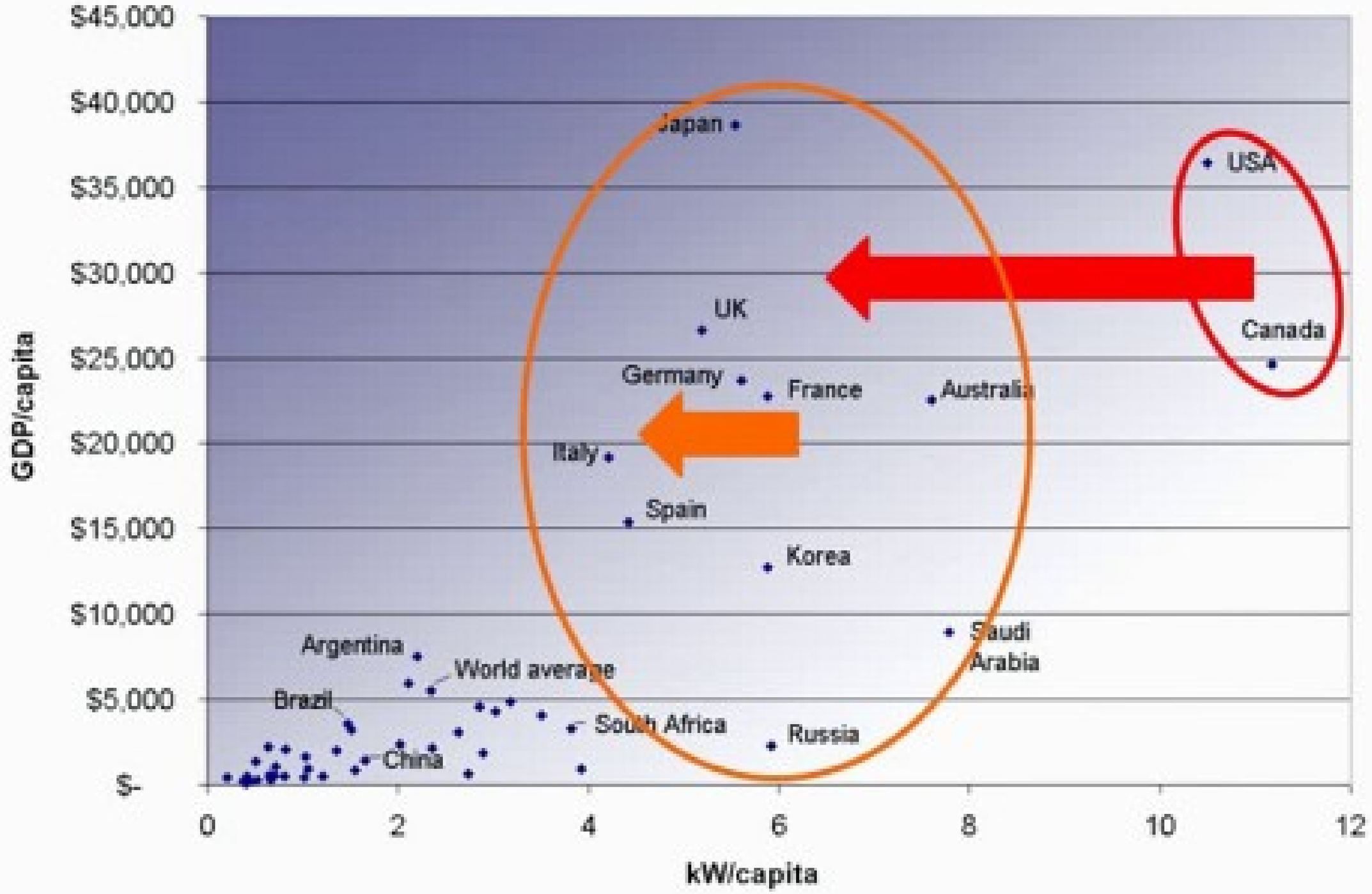

Nuclear Fusion, an Unlimited Energy Source

Can we build a sun on earth?

Hot plasma (ionised gas) inside core
T = 10 Mio K, P = 10 Gbar

Fast protons collide against Coulomb repulsion:
nuclear fusion to Helium + Energy

Gravitation balances radiation pressure

Introduction to nuclear fusion research

The stellarator Wendelstein 7-X

Plasma control and data acquisition for continuous plasma operation

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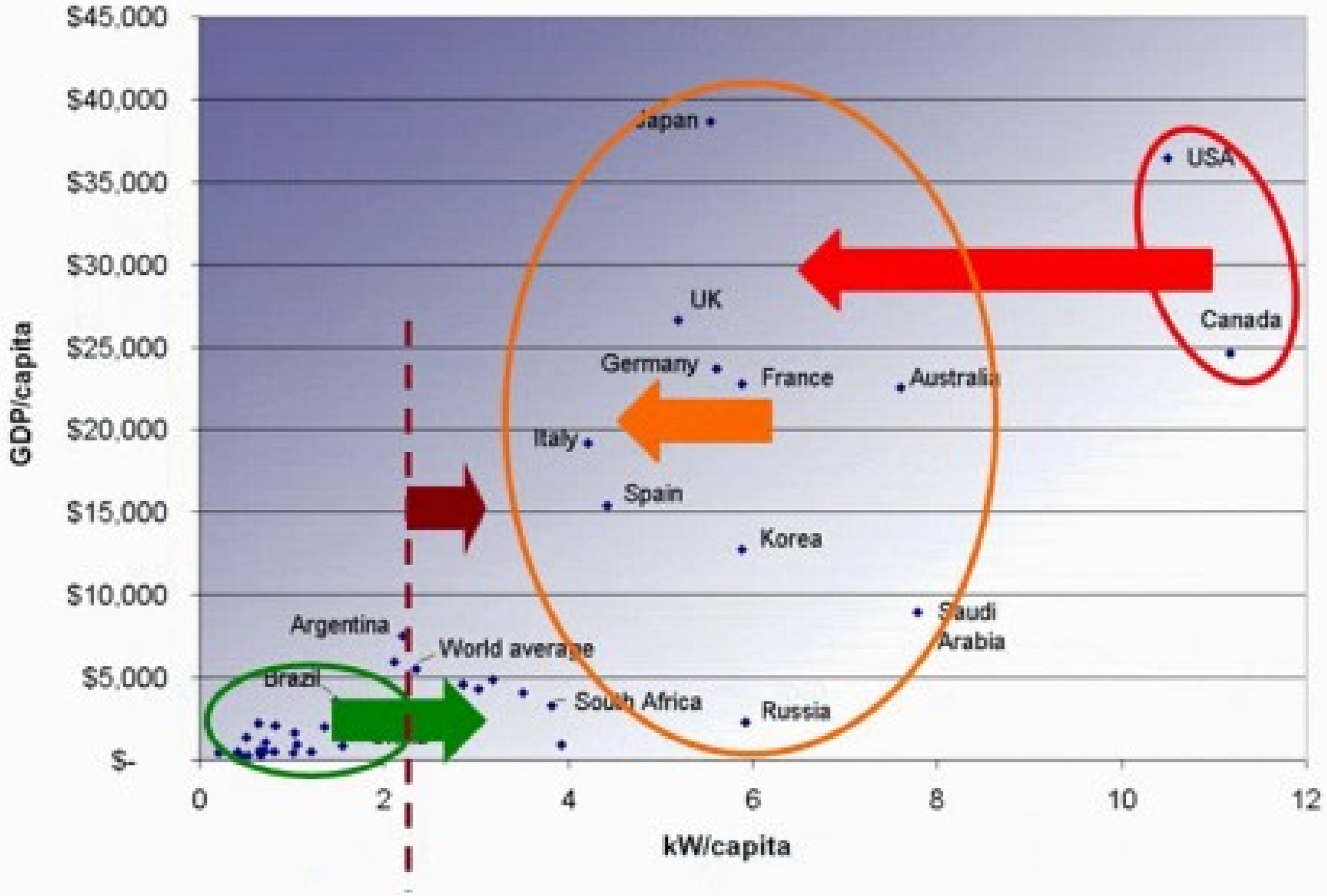
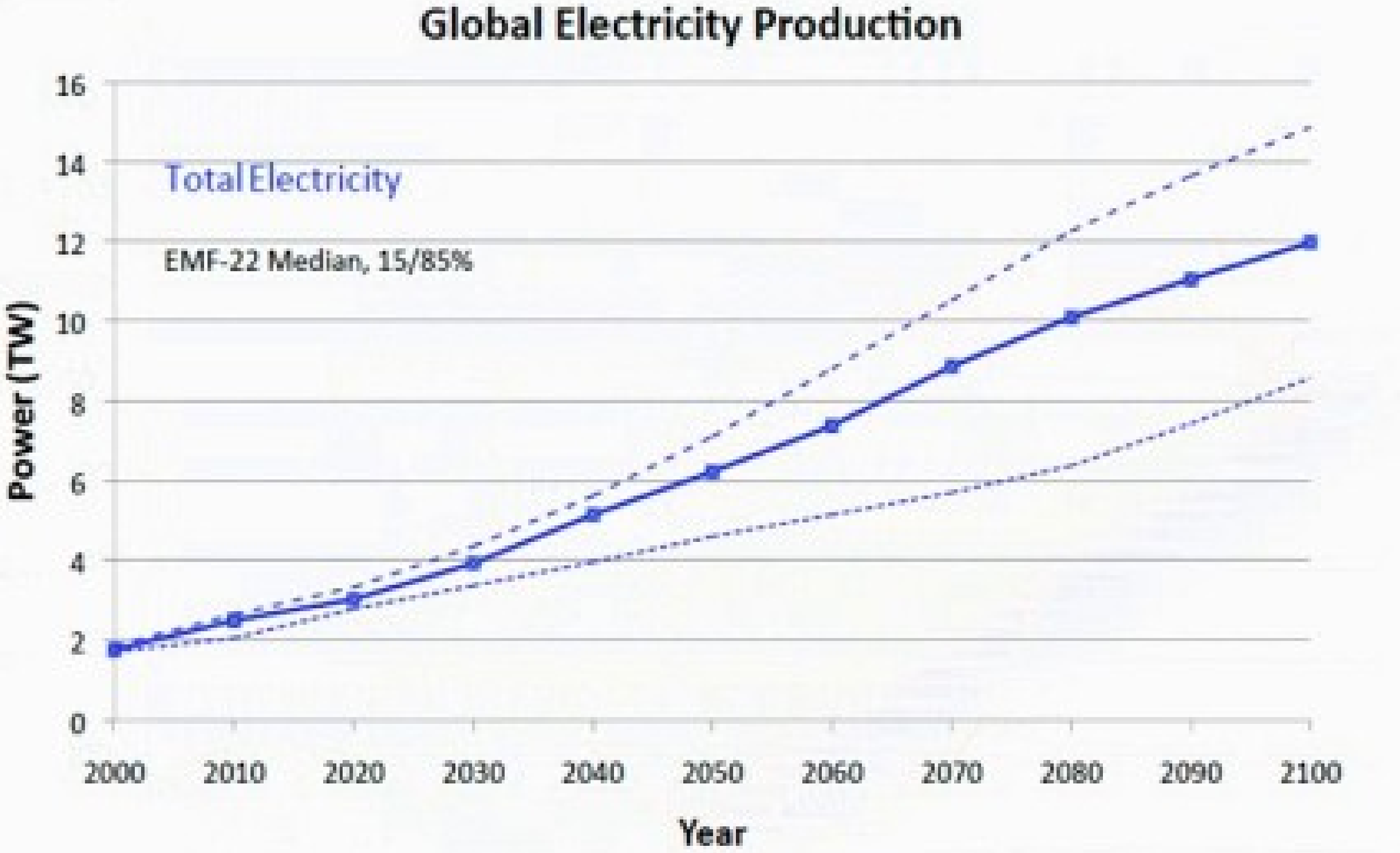


Growing Demand on Electricity



⇒ **Power production should comprise all (renewable) energy sources**

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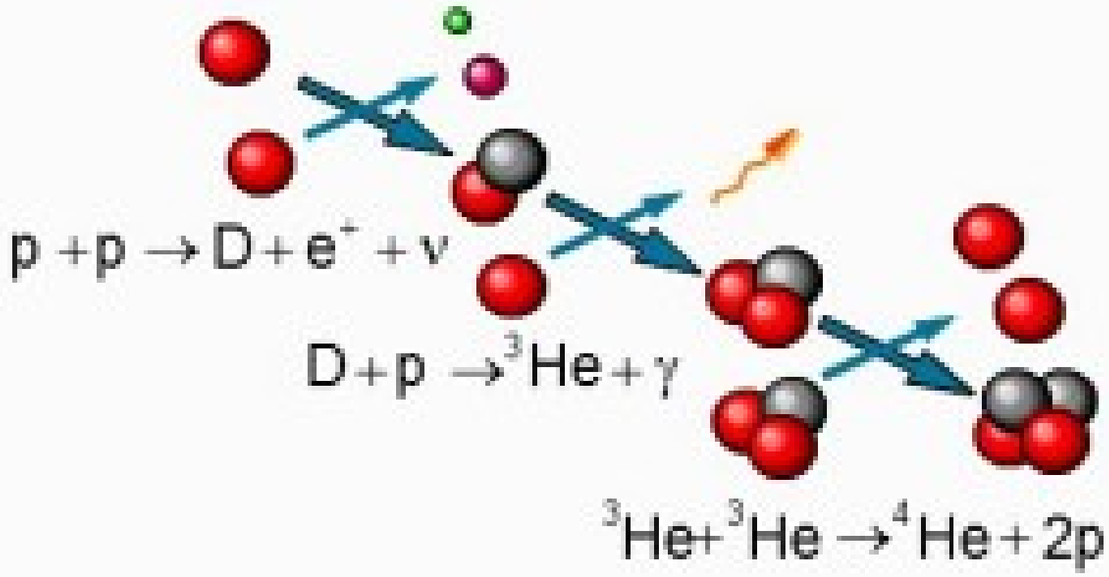

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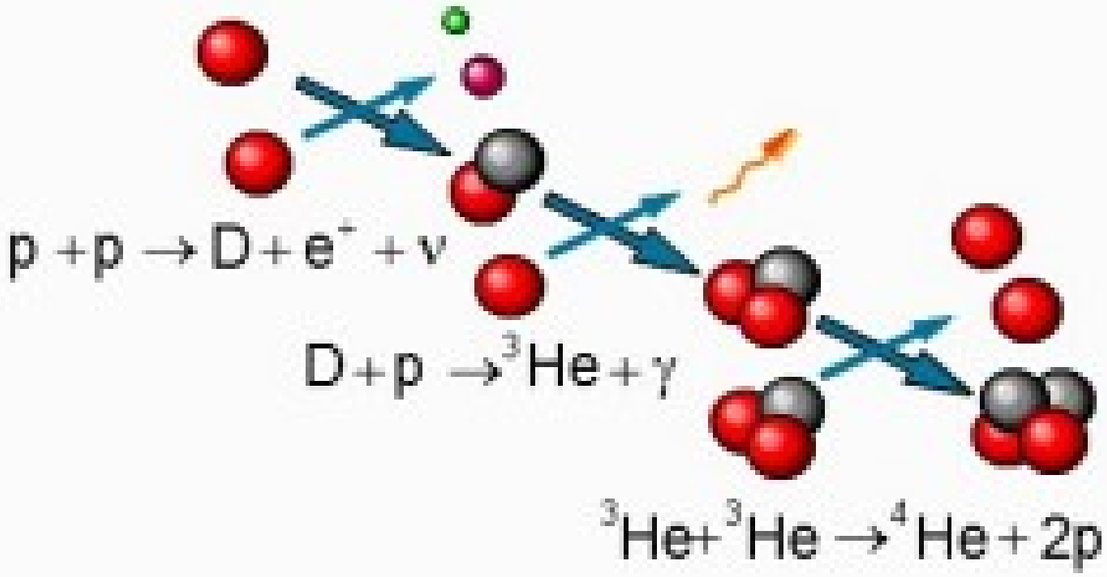
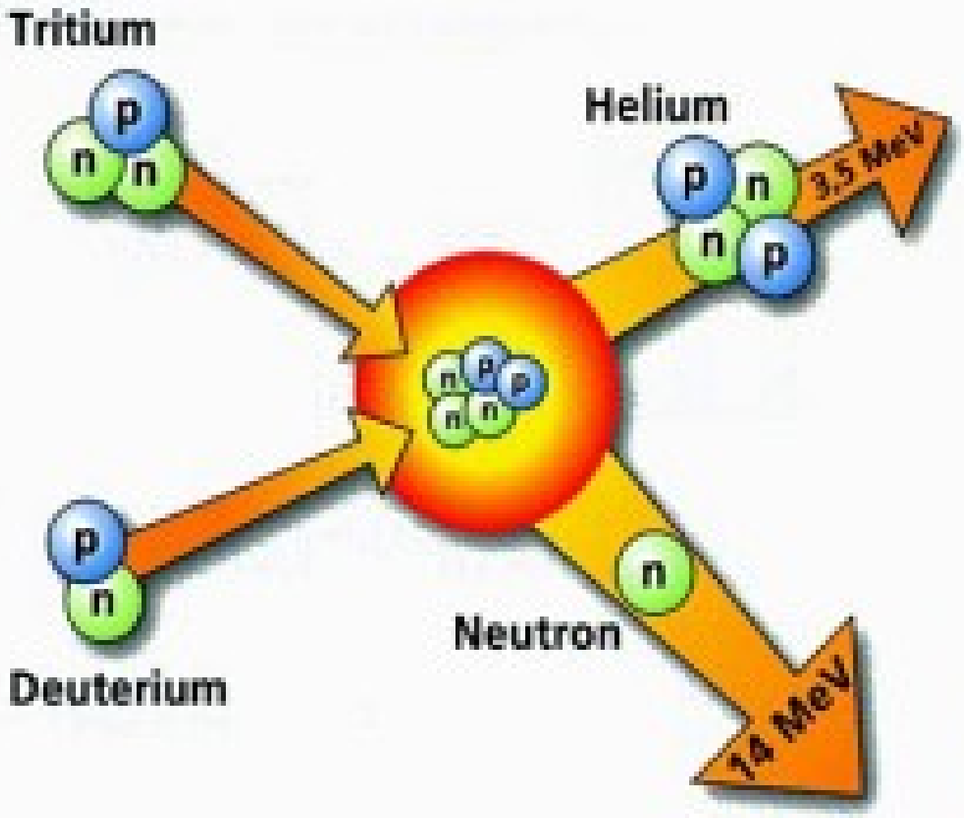
At least we could try!

With magnetic confinement instead of gravity



Fusion Process on Earth



Ash, keeps a plasma burning

To be converted to heat

Fusion process by collisions

Particles must be fast enough to overcome Coulomb repulsion

DT most at lowest possible particle velocities / temperatures

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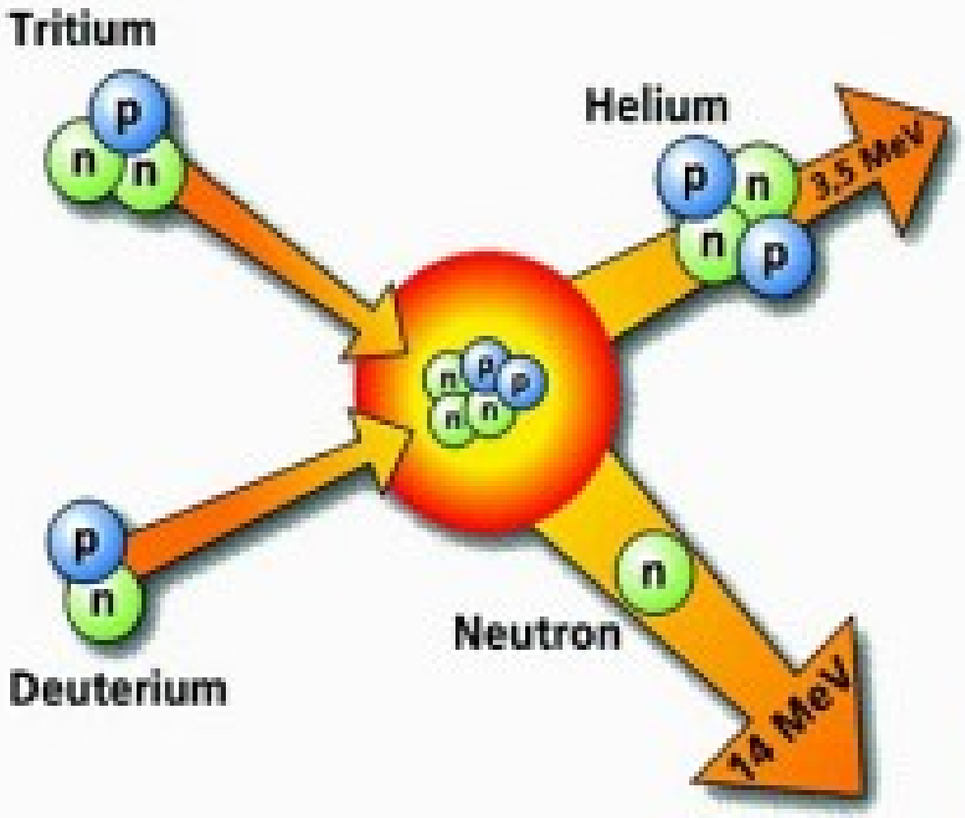

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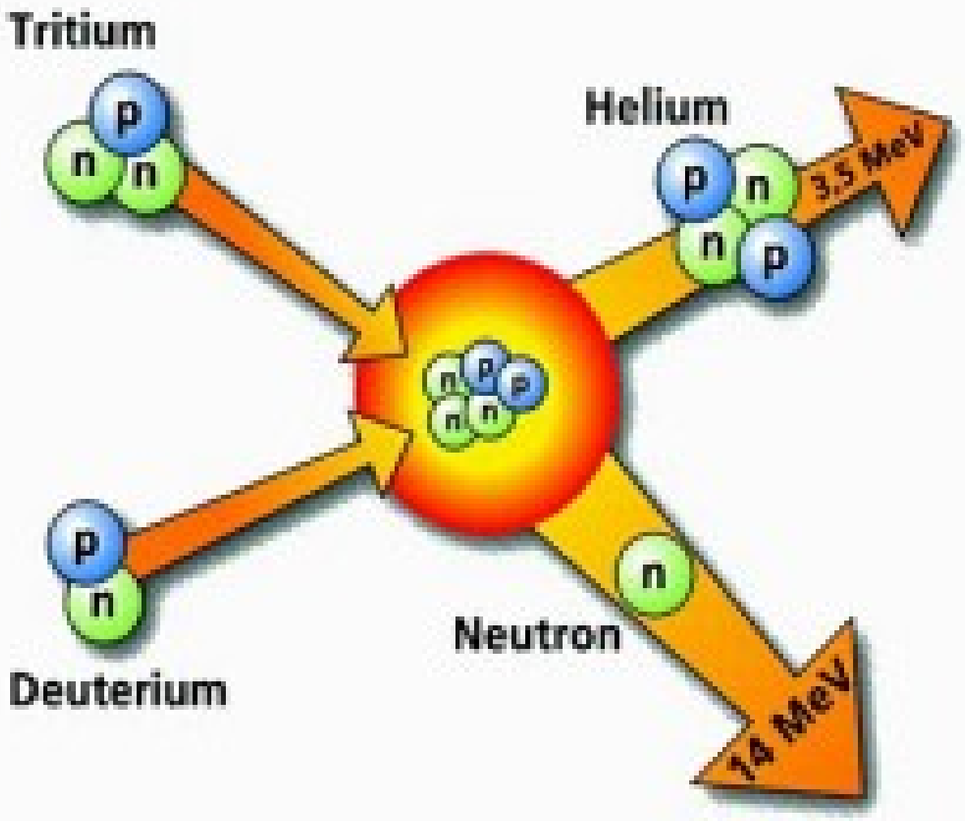
Temperature of 100 Mio K required!

Where to get Tritium from?



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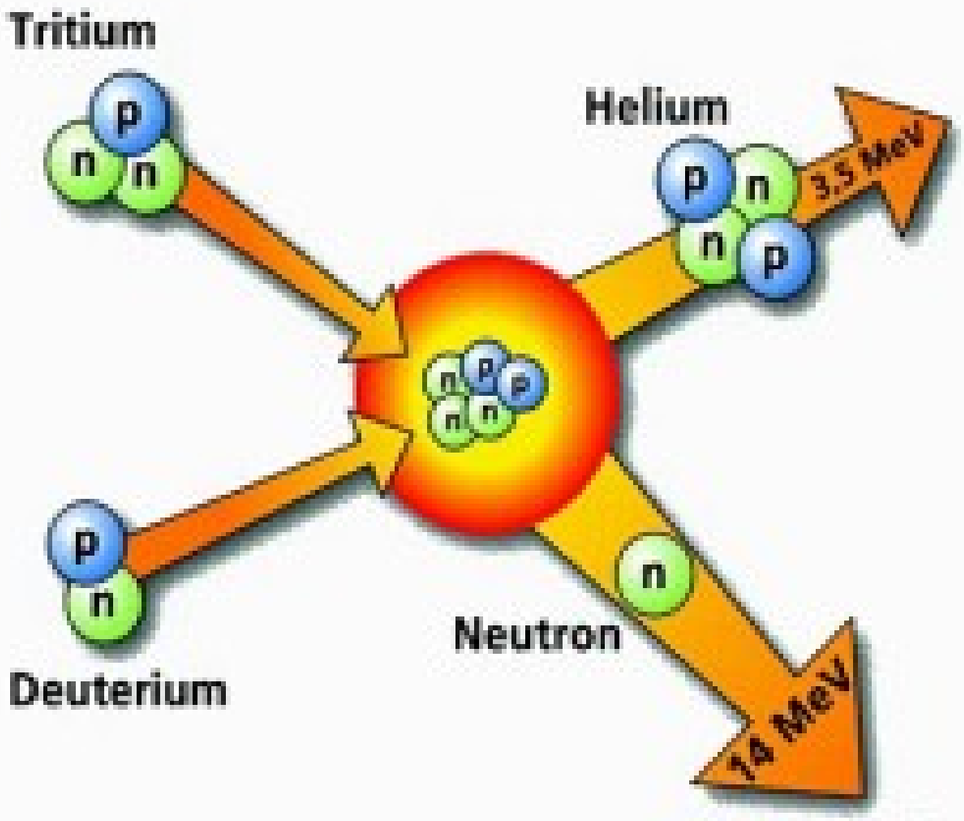
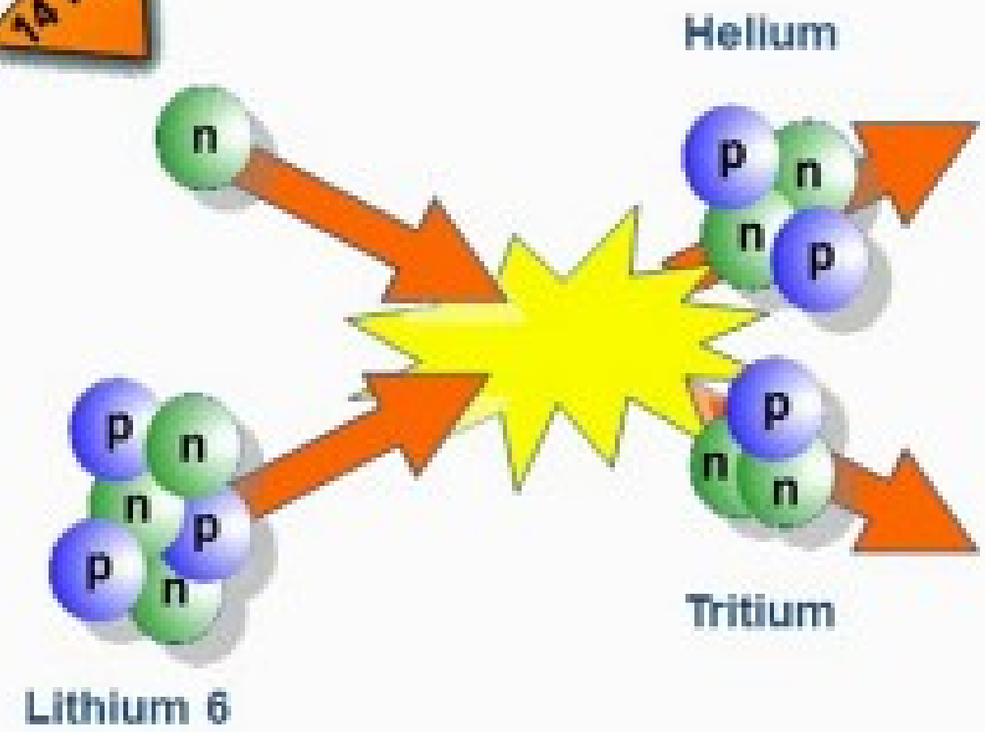


Breading of Tritium



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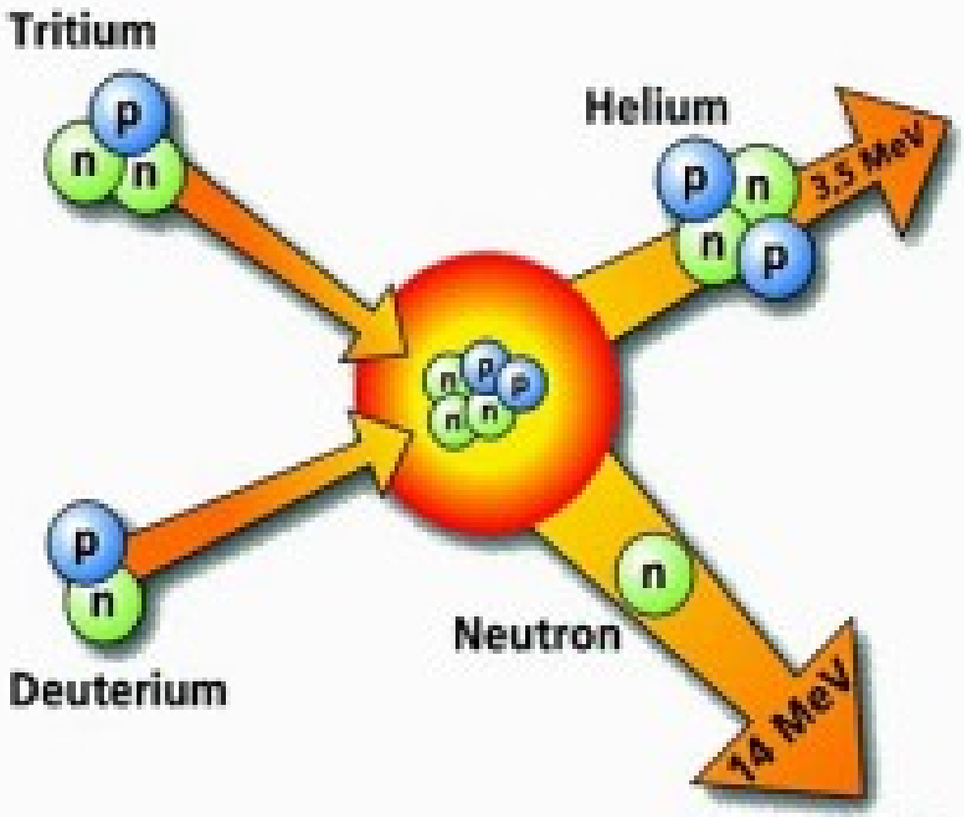
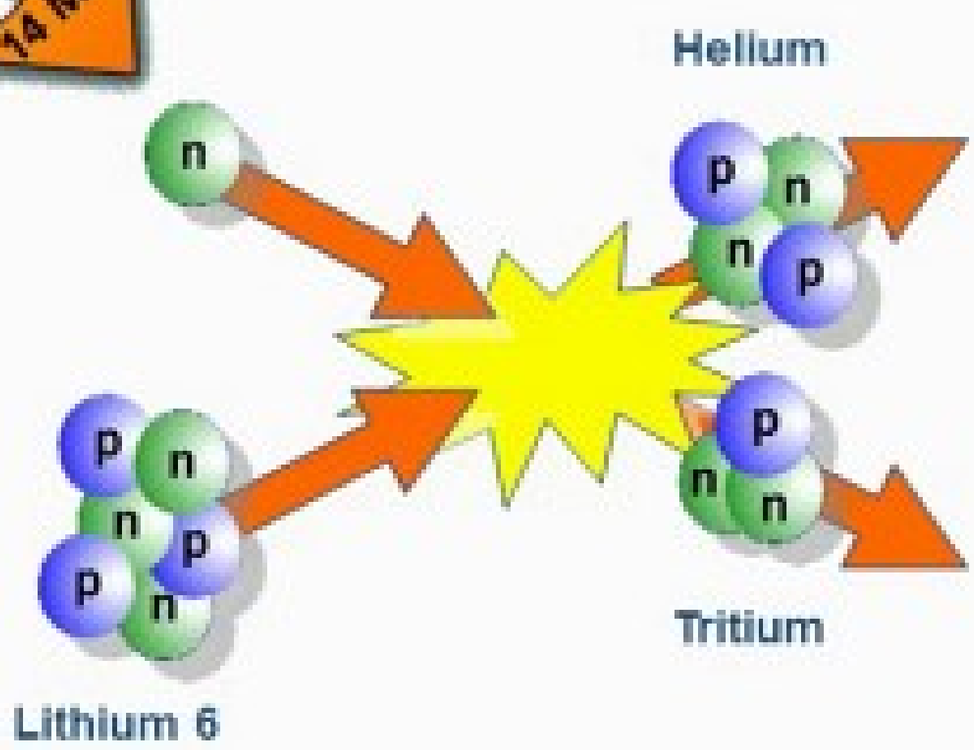


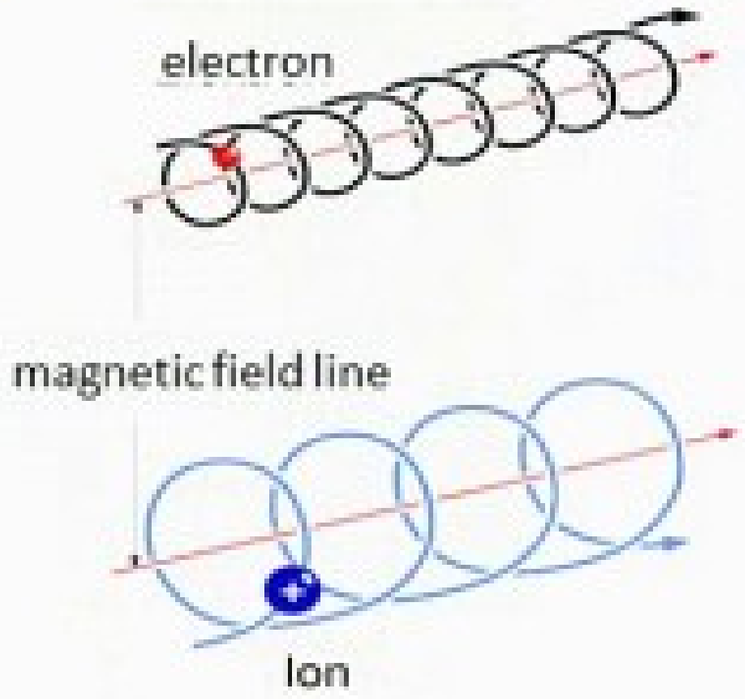
1 year energy for 1 family

Breading of Tritium



Building an Isolating Container (Thermos Jug)

Charged particles (plasma) bound to field lines



Particle loss at the ends => torus topology

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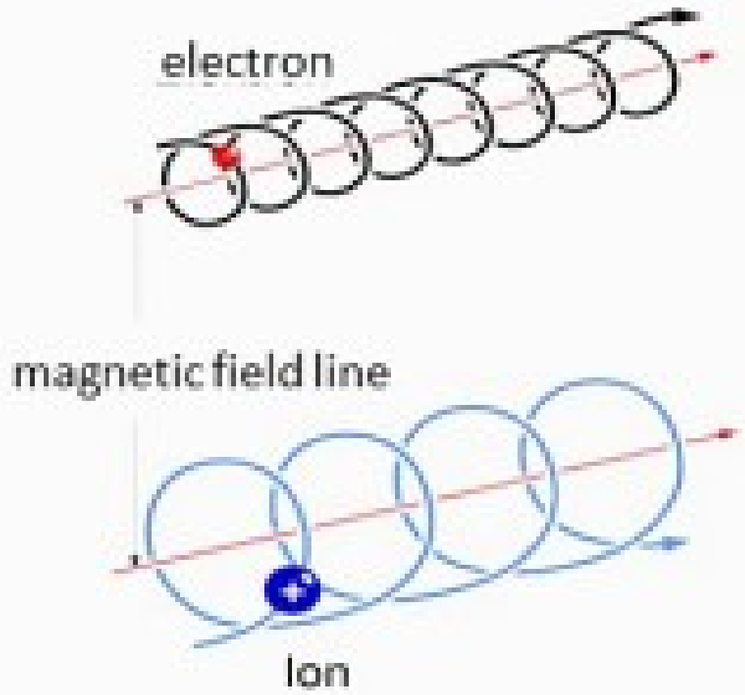

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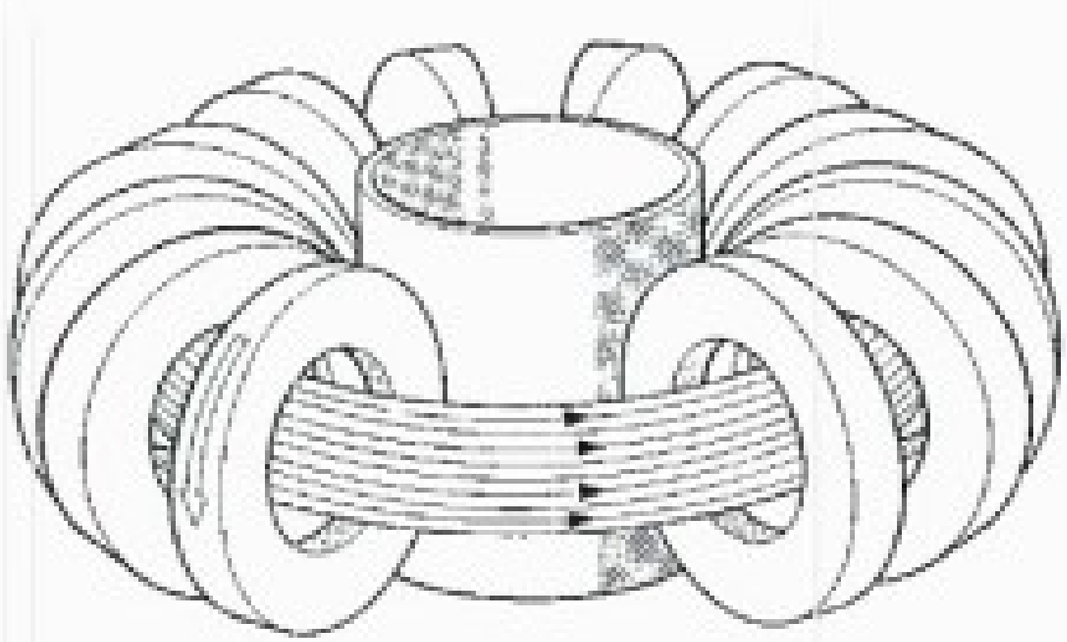

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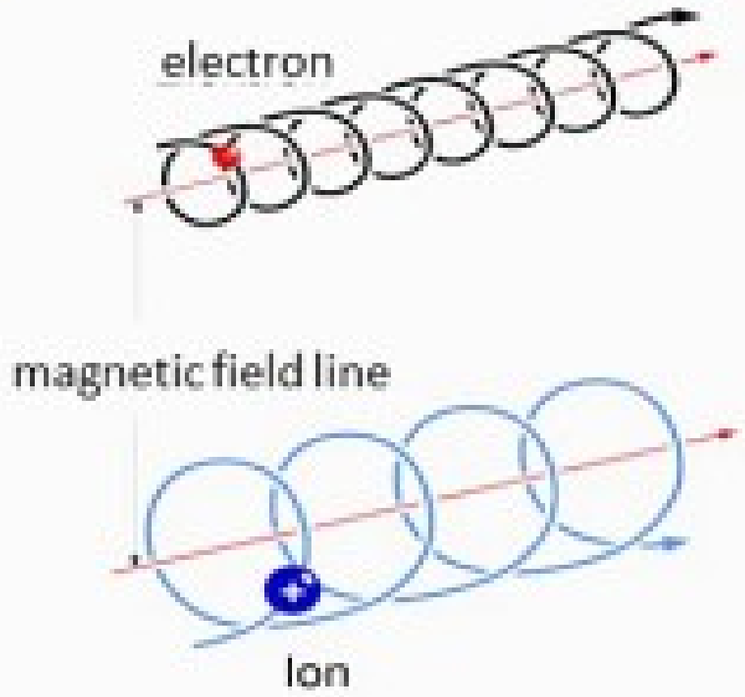

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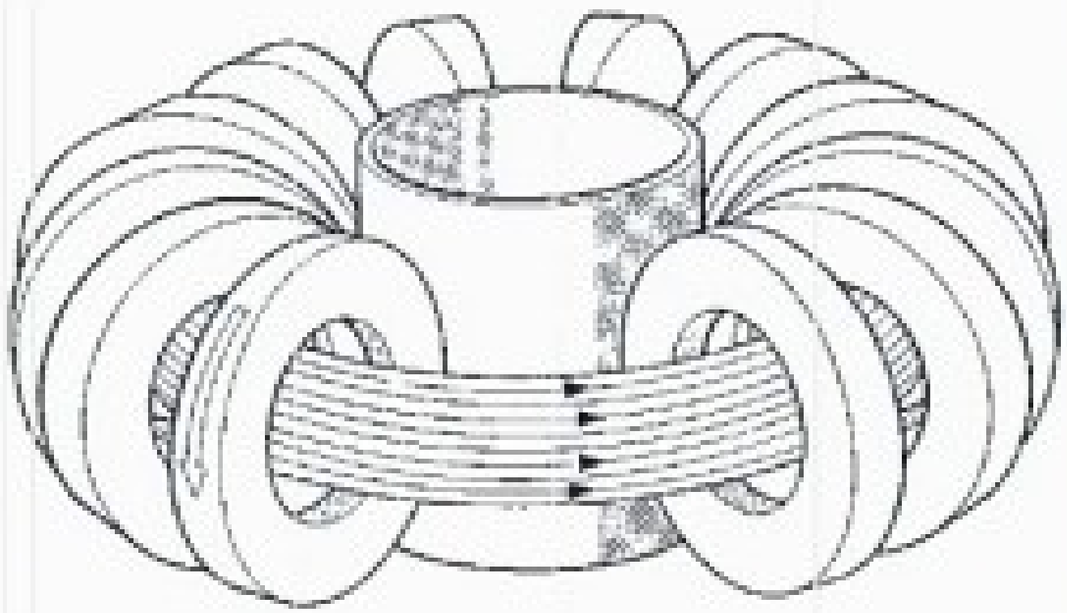

Directions: **toroidal**, poloidal, helical

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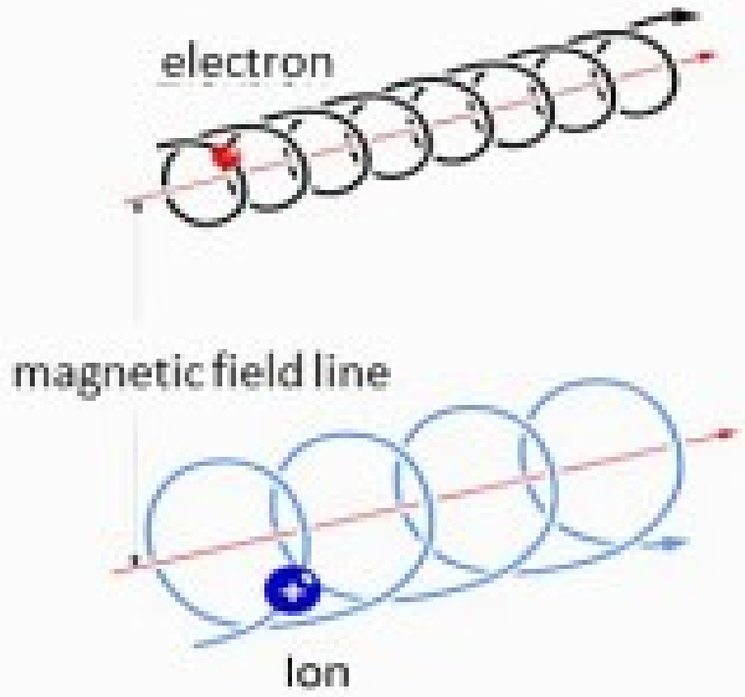
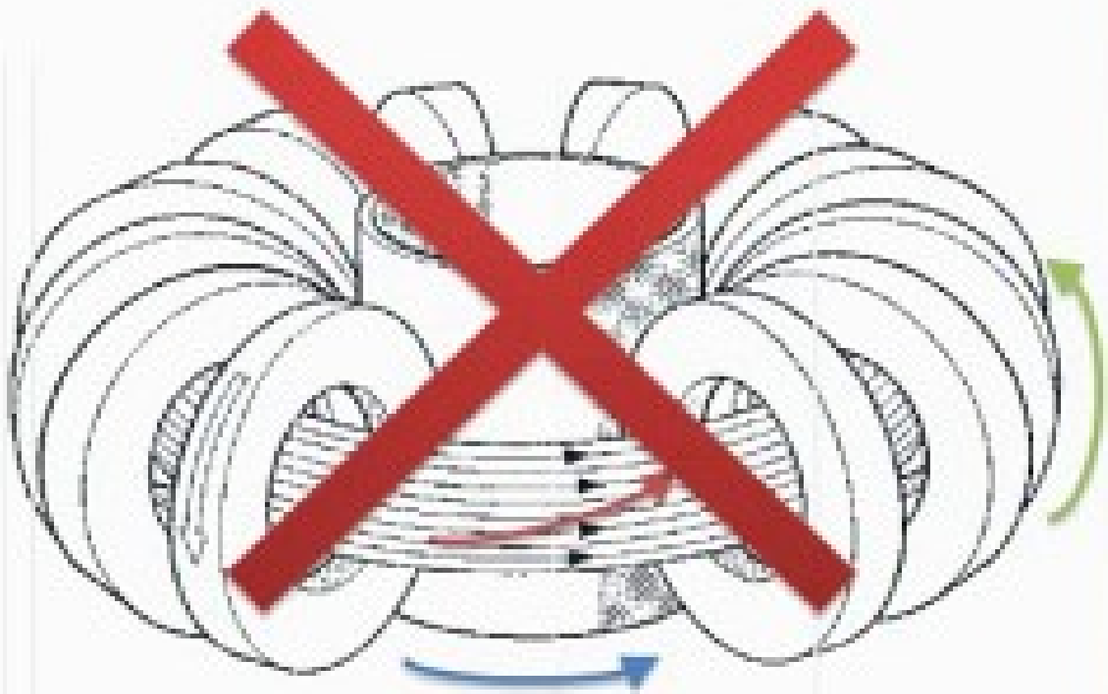


Particle loss at the ends => torus topology

This doesn't work!

Particle drift by inhomogeneous fields

Ions move upwards
Electrons move downwards
After 50 us loss of particles!



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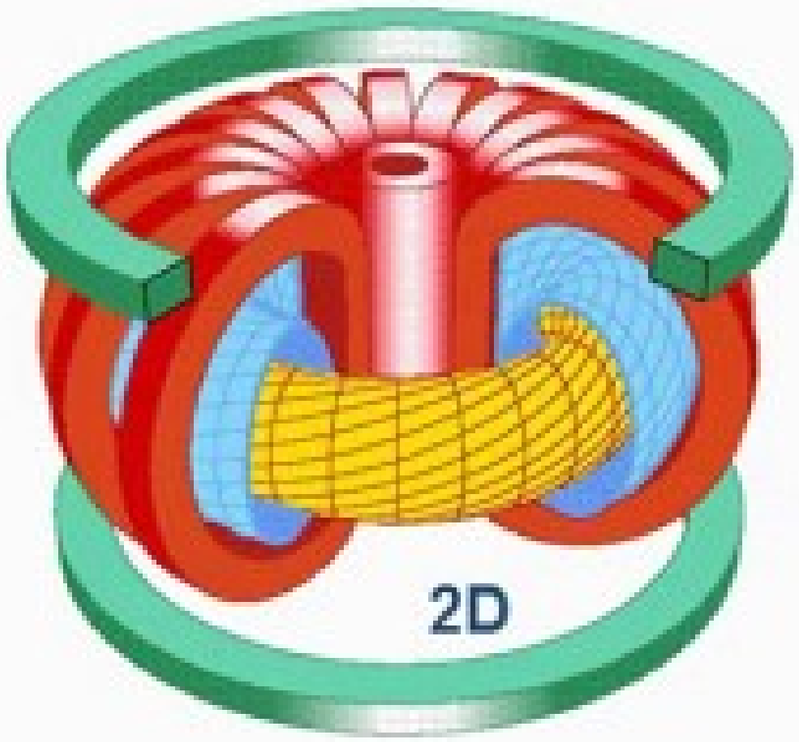
Two Concepts for Helical Magnetic Fields

Tokamak



Poloidal (minor circumference) part of the magnetic field generated by plasma current (transformer principle)

+ Theory is simpler (2D problem)

+ Best confinement

- No continuous operation (induction)

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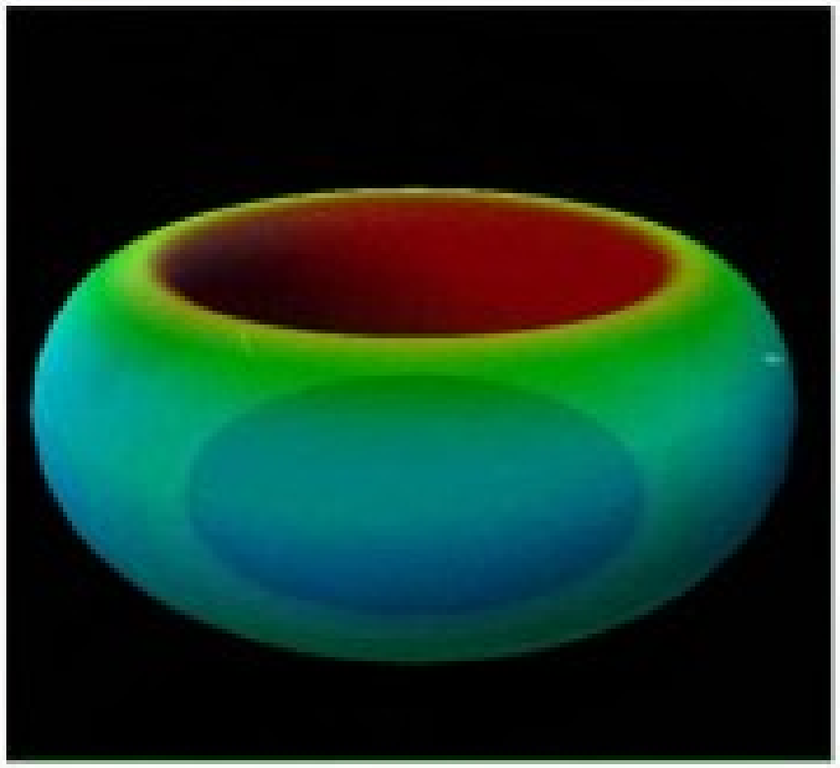

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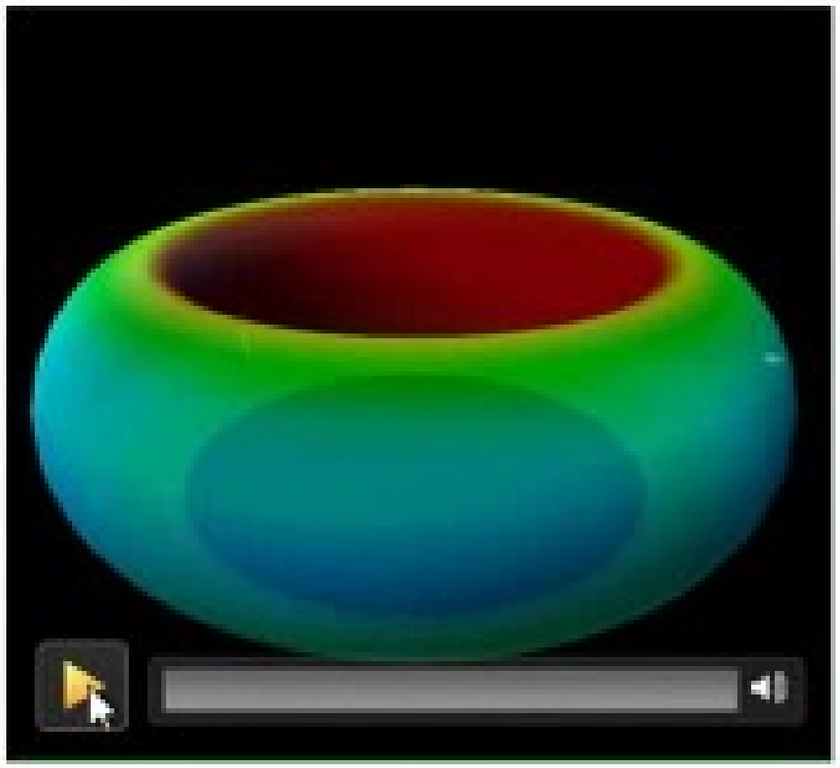

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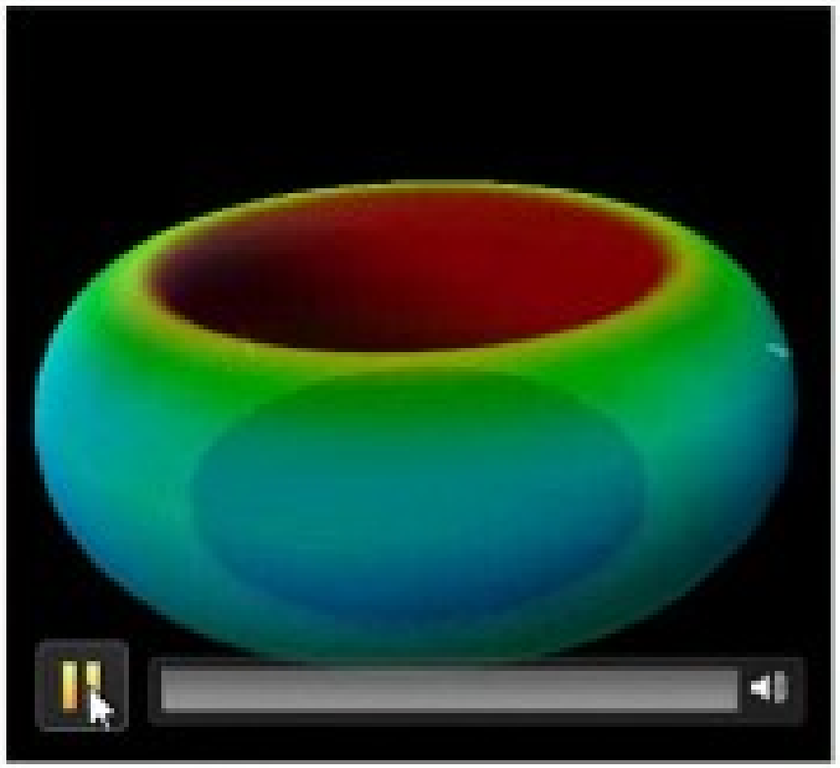

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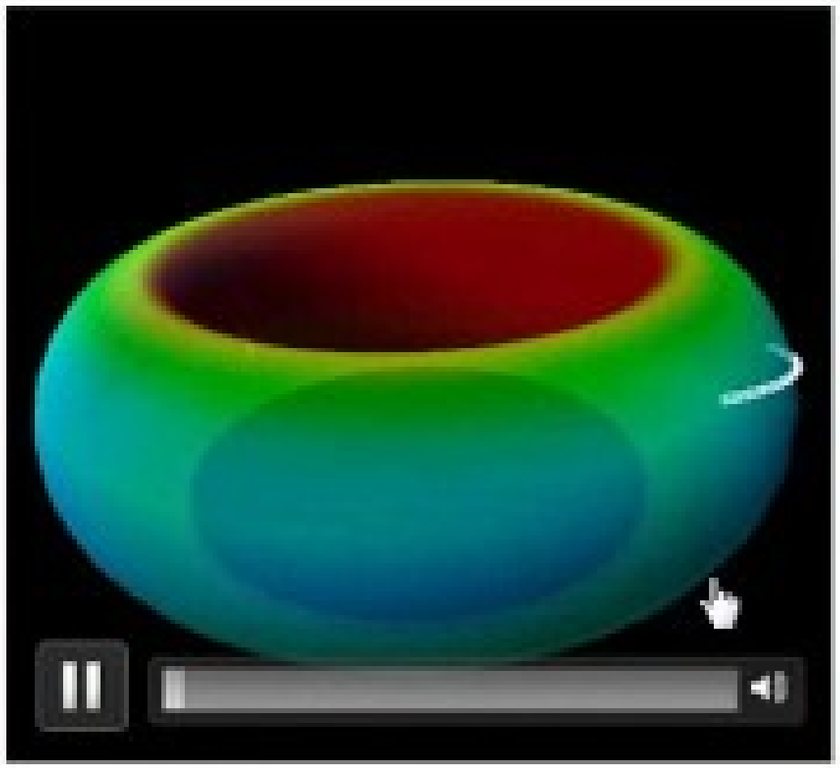

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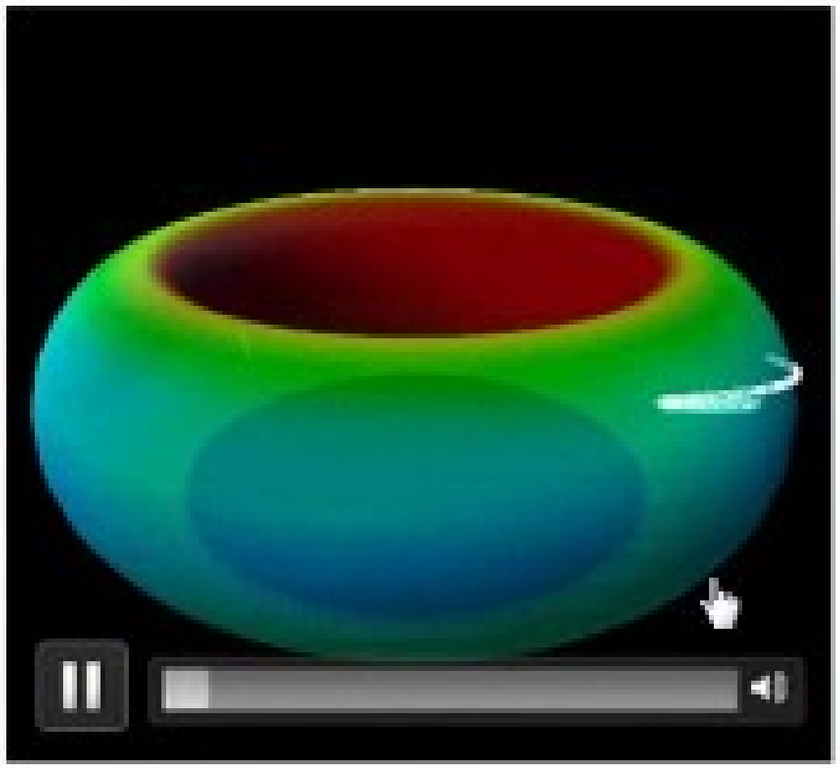

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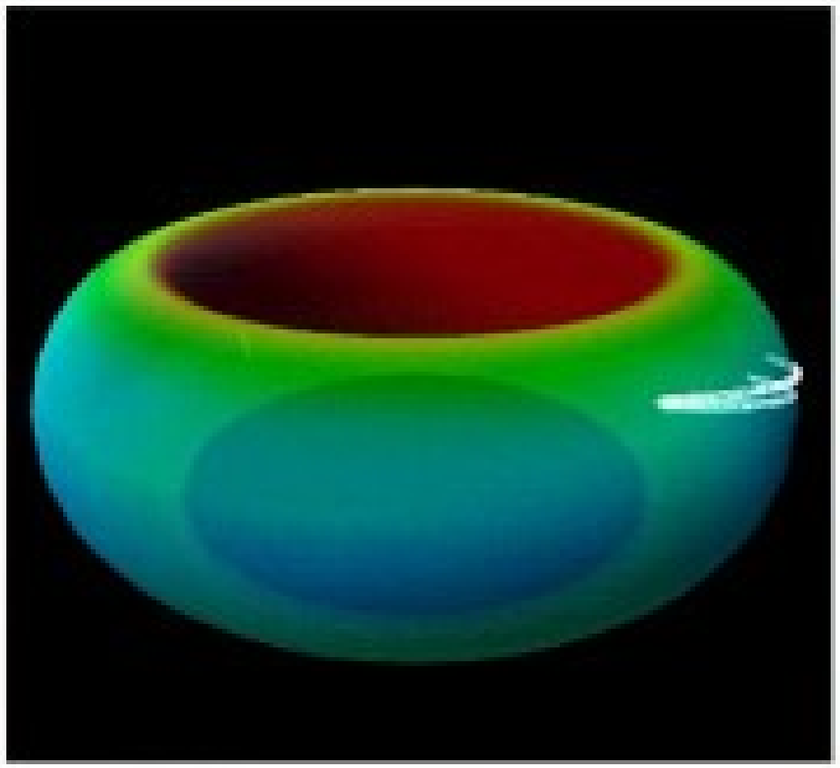

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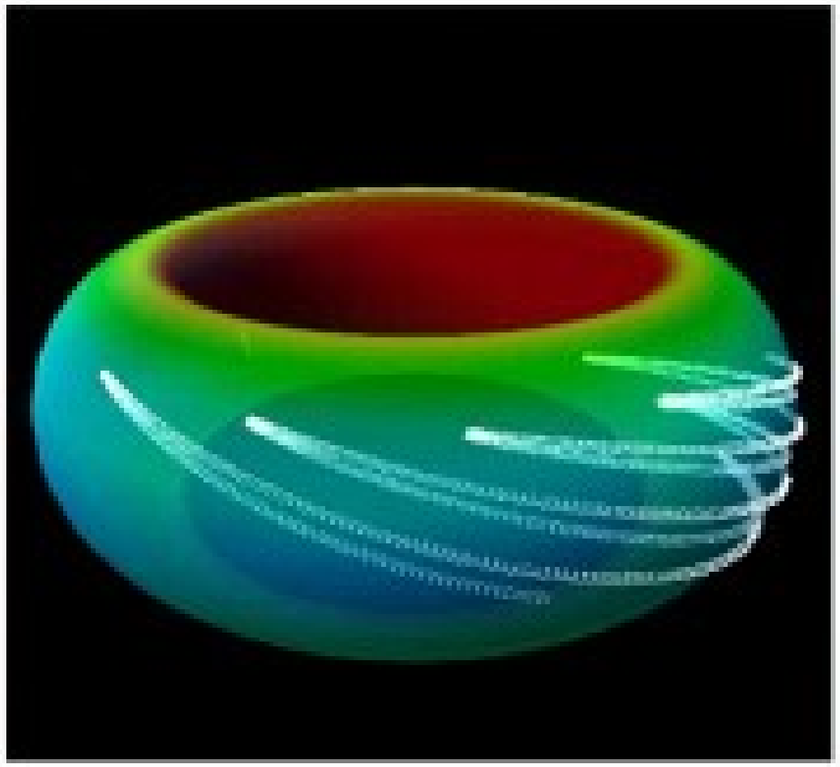

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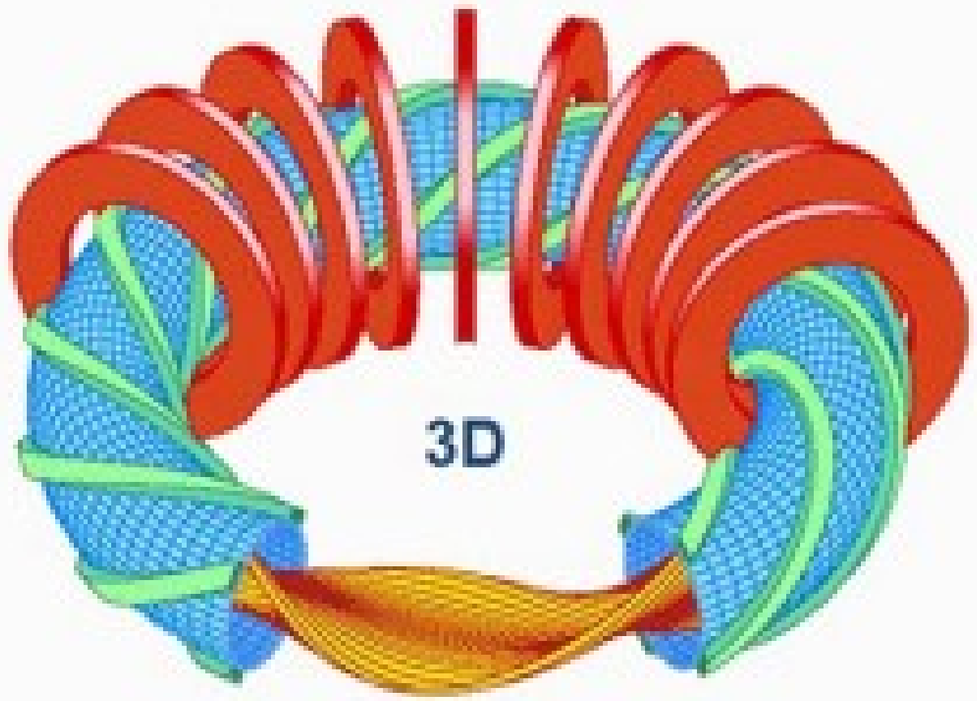
Stellarator



Magnetic field essentially generated by external coils

- Theory complex (3D problem)

- Somewhat worse confinement

+ Continuous operation

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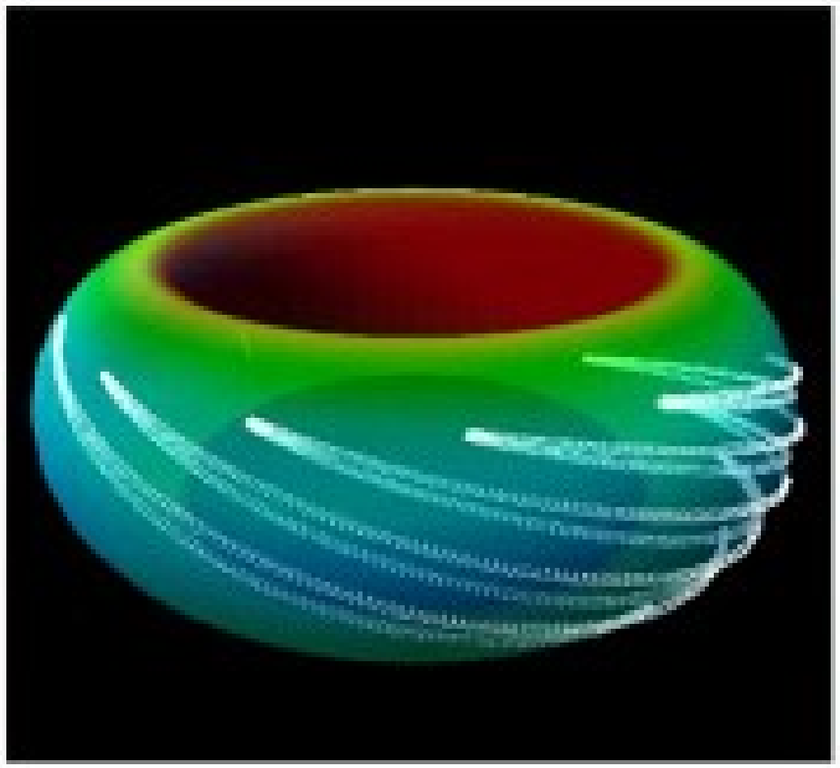

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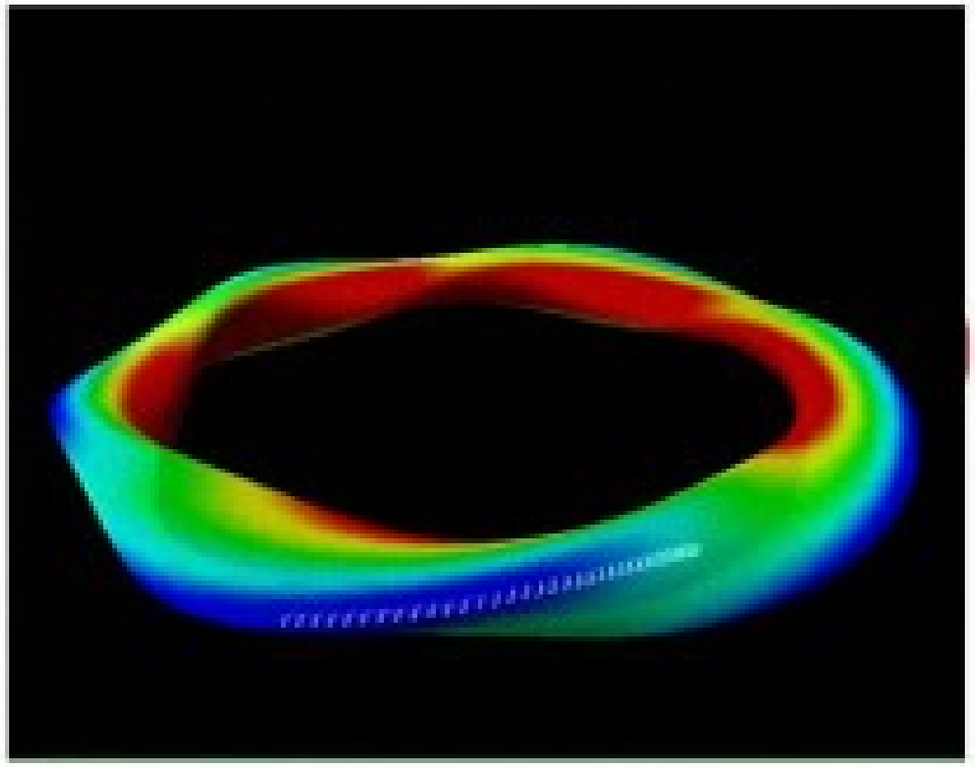

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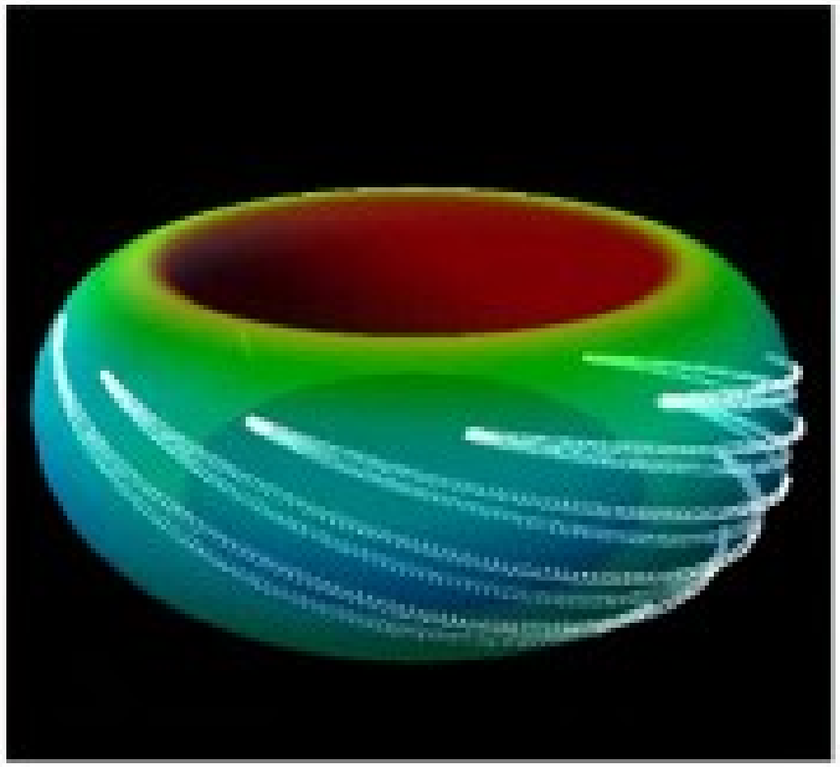

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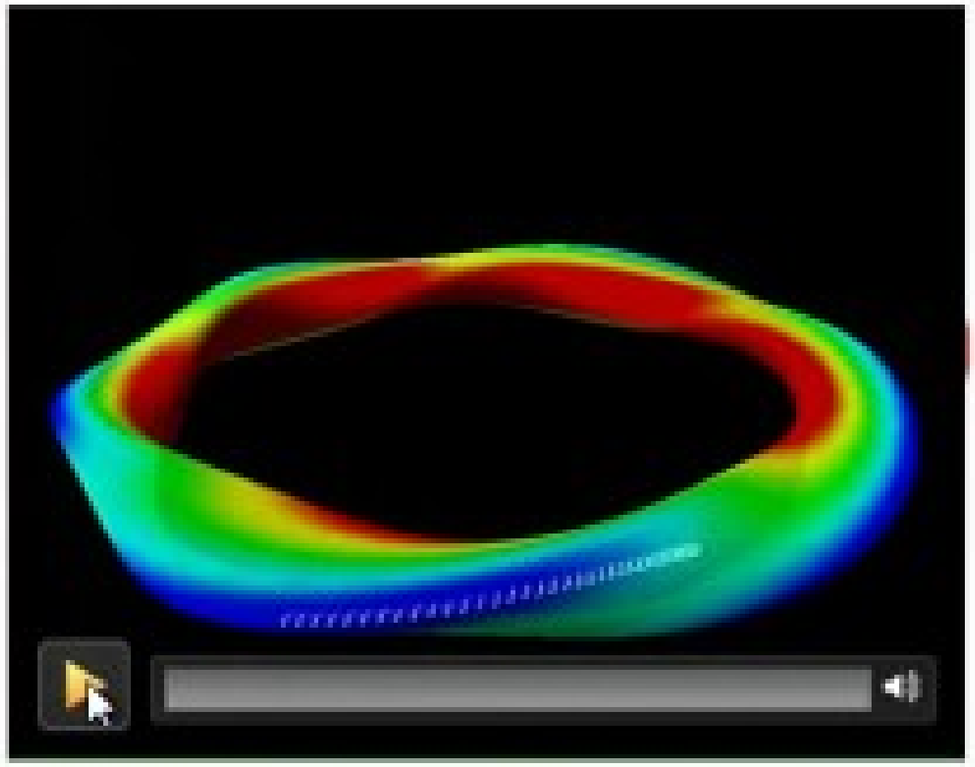

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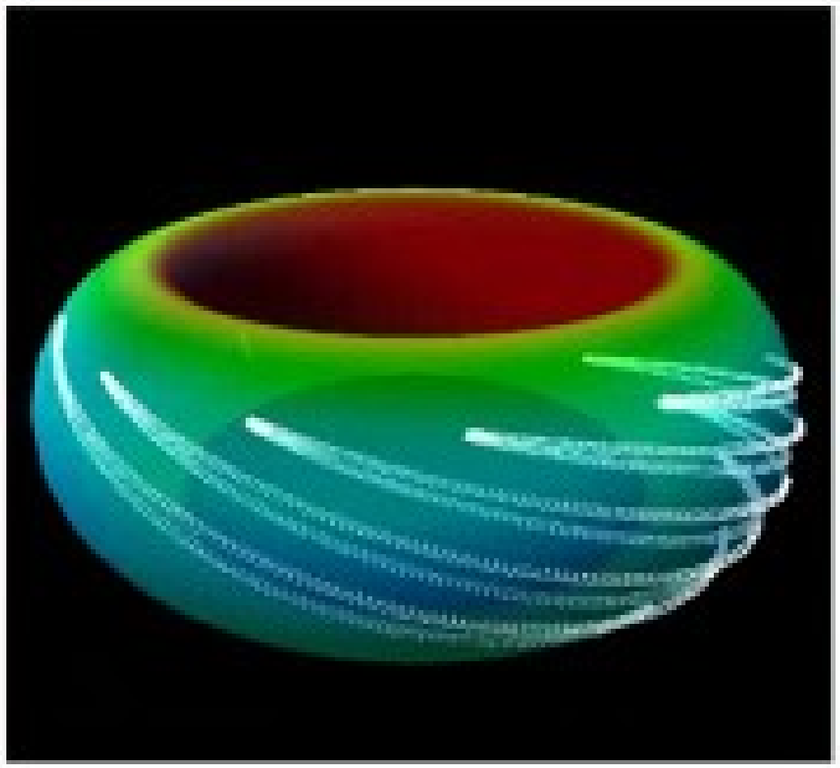

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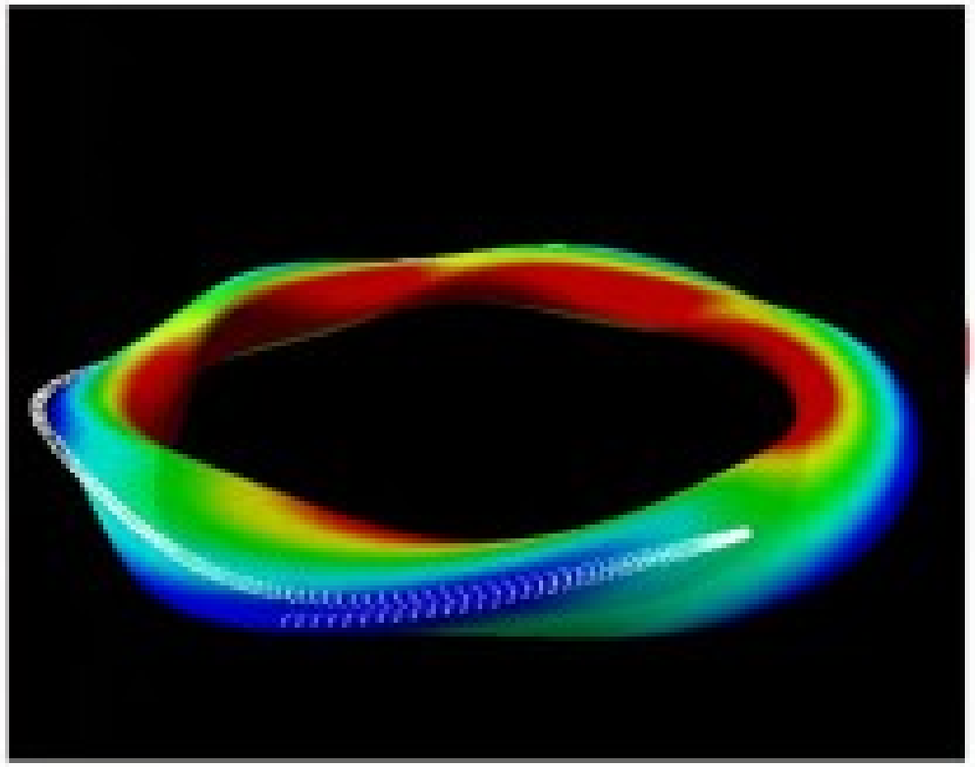

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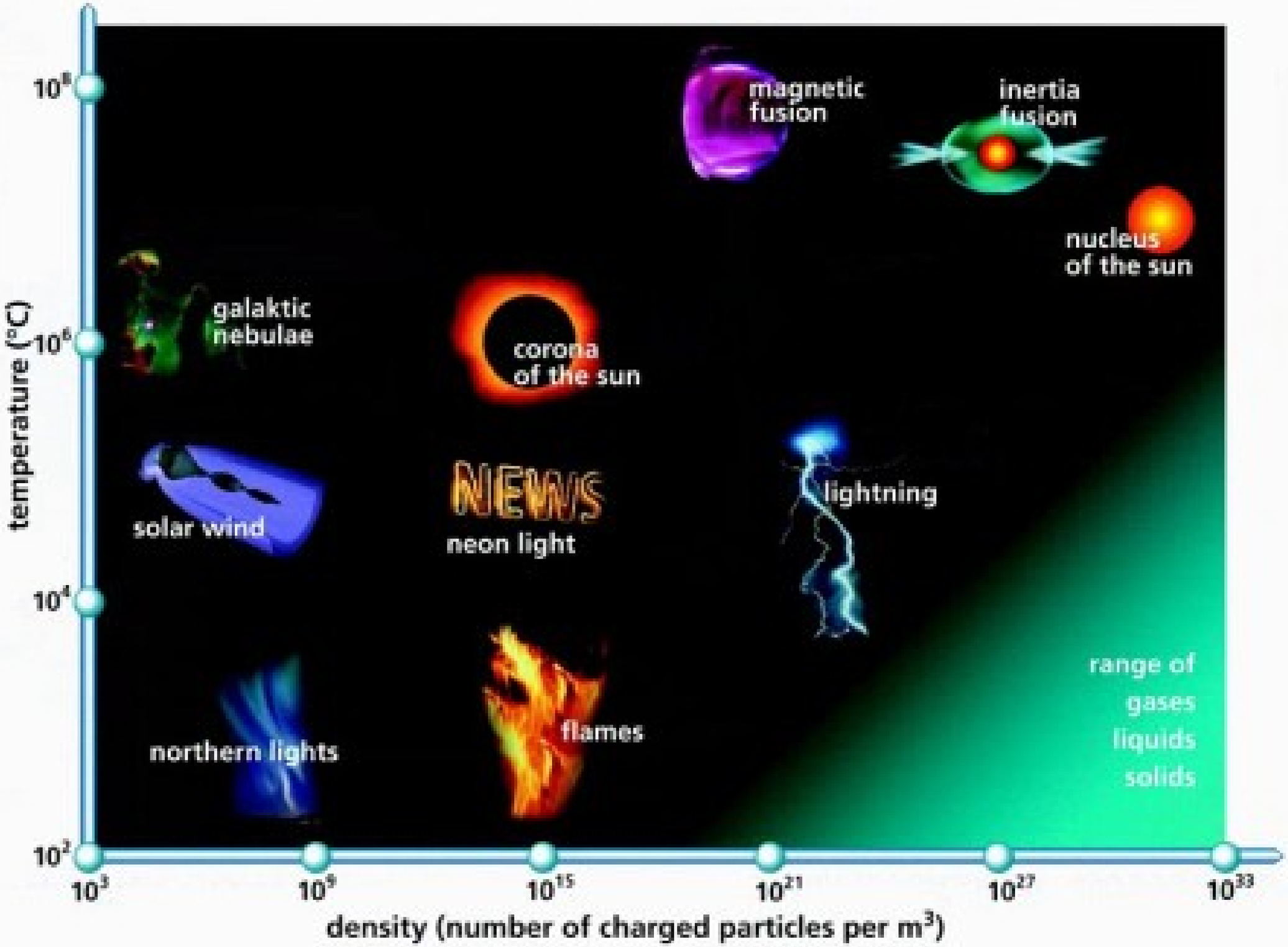
Plasma Types



A Fusion Power Plant

Optimisation of triple product: density, temperature and confinement

T = 100 Mio K

$n = 10^{20}\ m^{-3}$

P = 2 bar

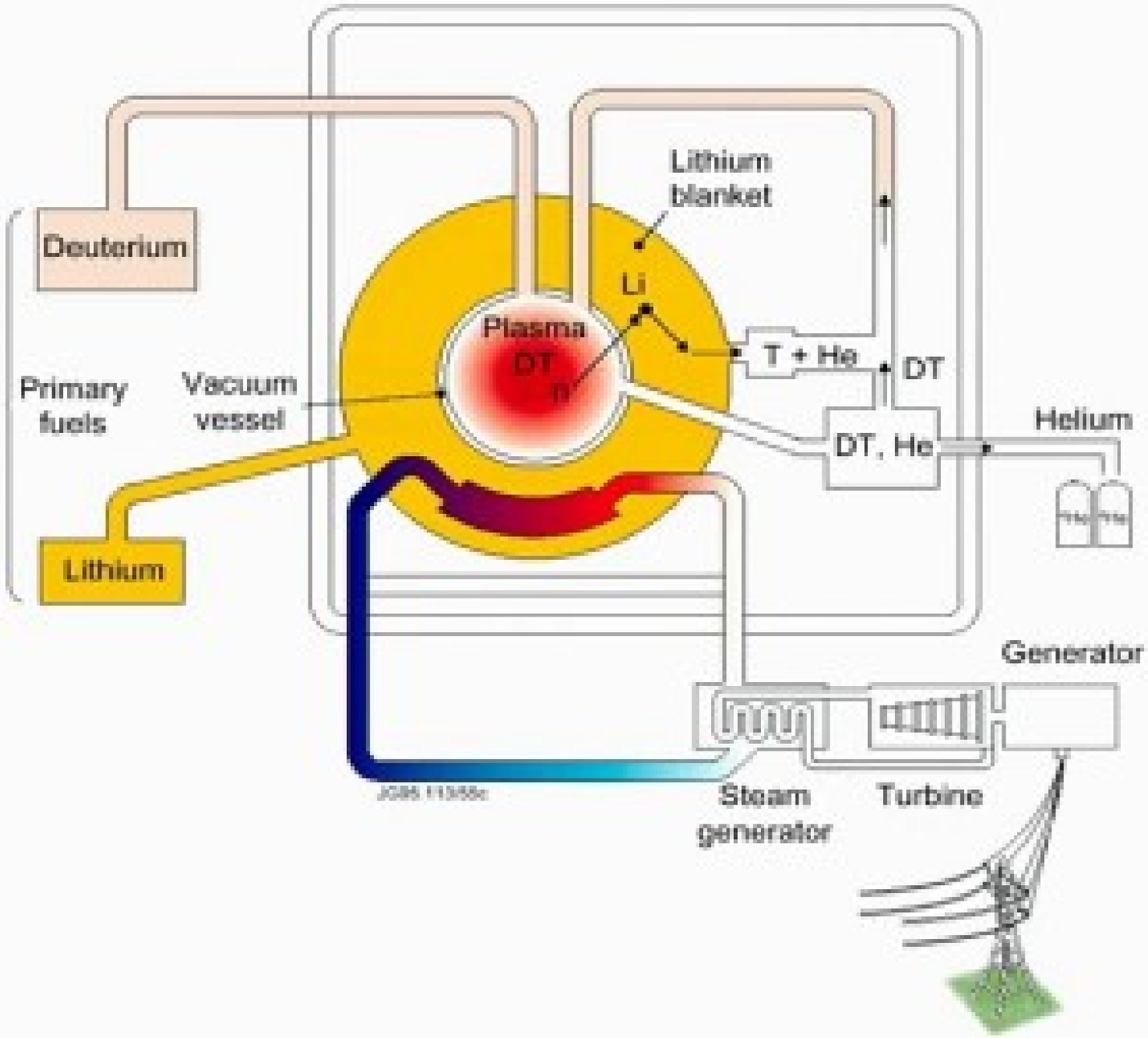
Optimisation of triple product: density, temperature and confinement

T = 100 Mio K
n = 10^{20} m^{-3}
P = 2 bar

Power plant

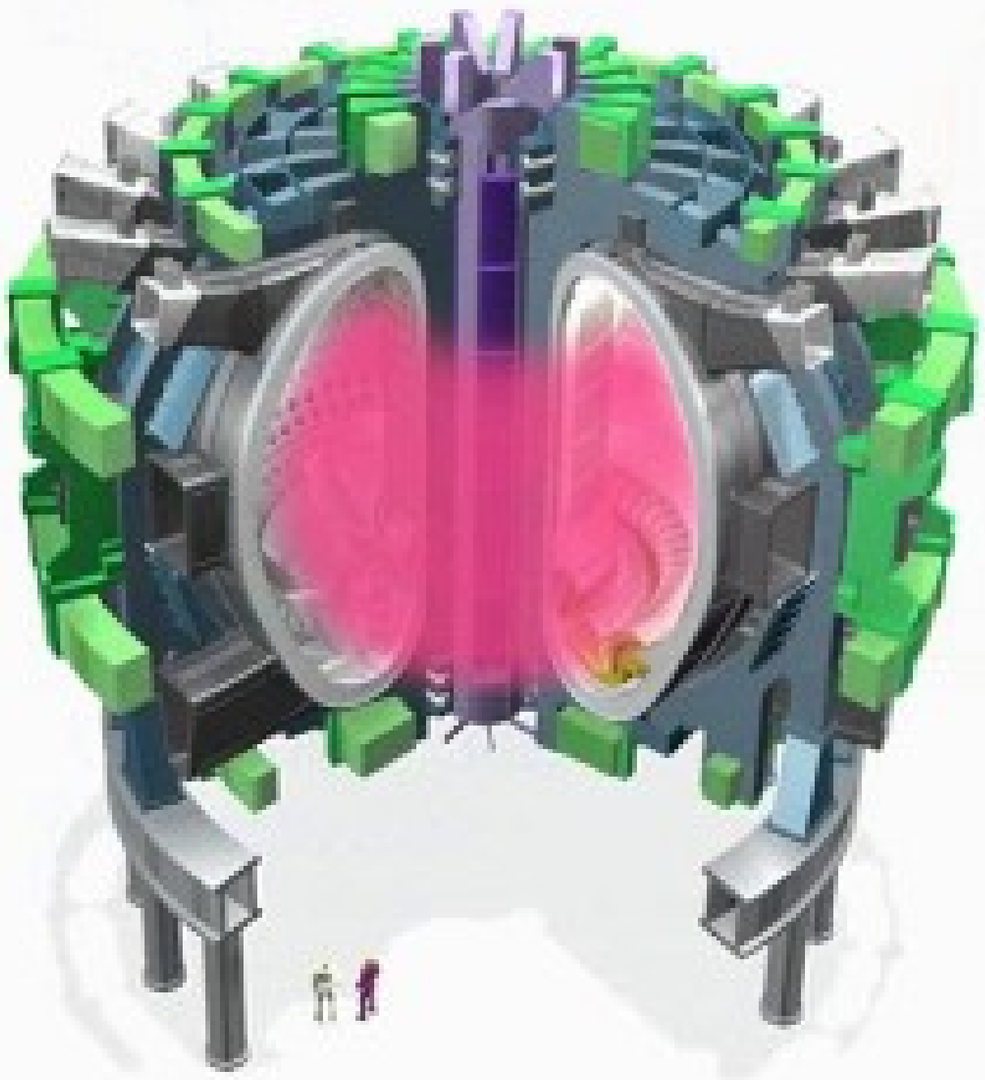
Basically heat production as existing reactors

No chain reactions (inherently safe)

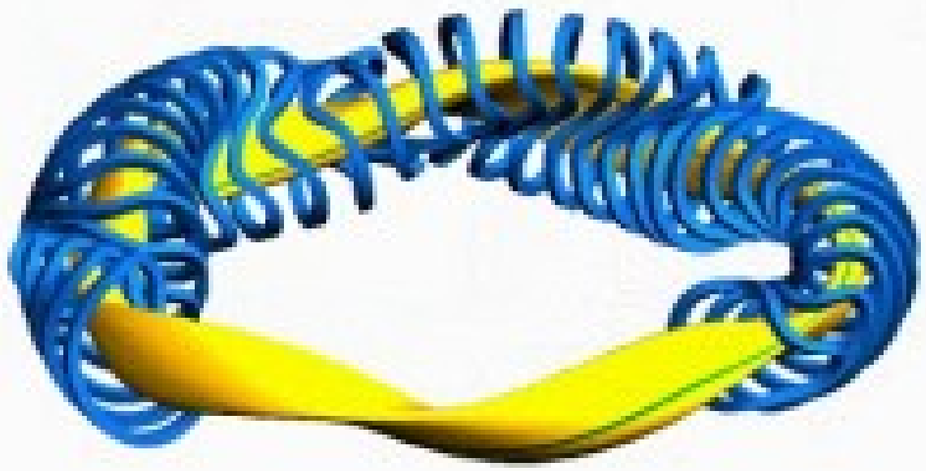


Largest Tokamak and Stellarator (under construction)

Tokamak (ITER) – first burning plasma, non-steady operation
Stellarator (W7-X) – continuous operation, better economic efficiency
IPP does research on both concepts!



ITER



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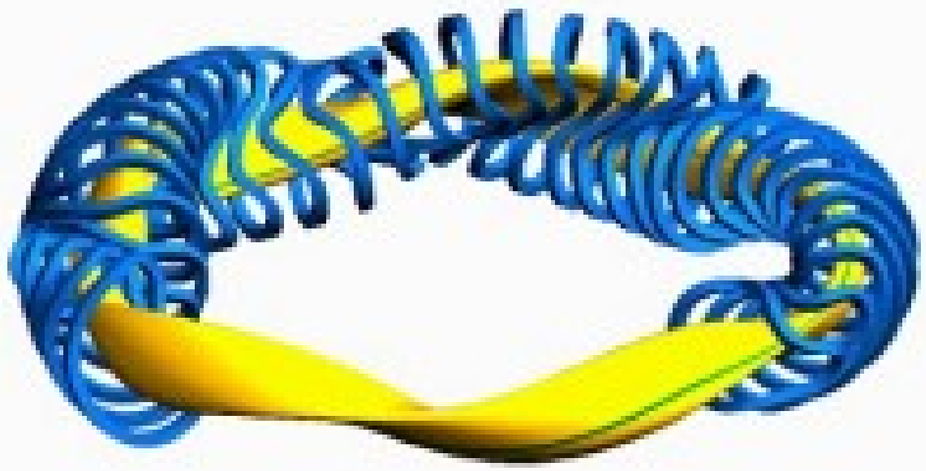
Helical B-field, B = 3 ... 5 Tesla
Strength limited by mechanical forces



ITER **Wendelstein 7-X**

IPP History: From classical Stellarators ...

1970 1980 1990 2000 2010

Greifswald

W7-X

Garching

WEGA

W7-AS

R=2m, m=5, modular advanced Stellarator partially optimized island divertor

R=5.5m, superconducting optimized Helias integraed test of reactor capability

hybrid operation

W7-A

OH

R=0.5m
Ba-heating

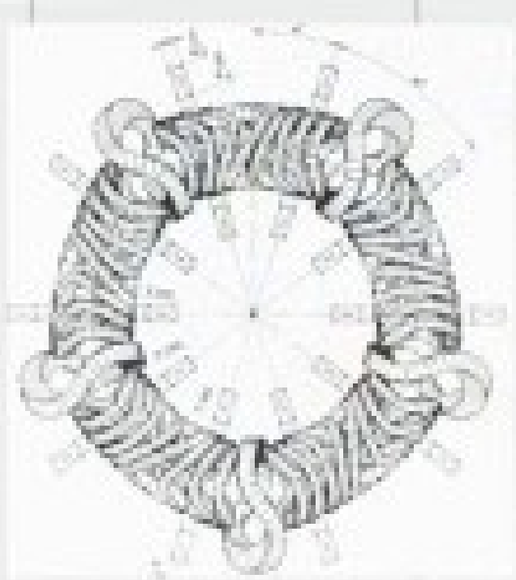
W2-B

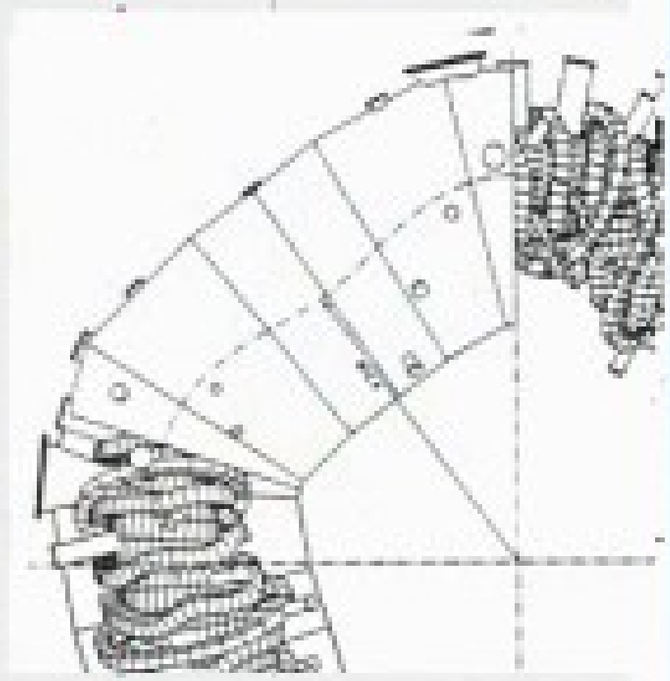
R=2m, m=5
NBI, ECRH: Itor->0
role of Er on conf.

W2-A

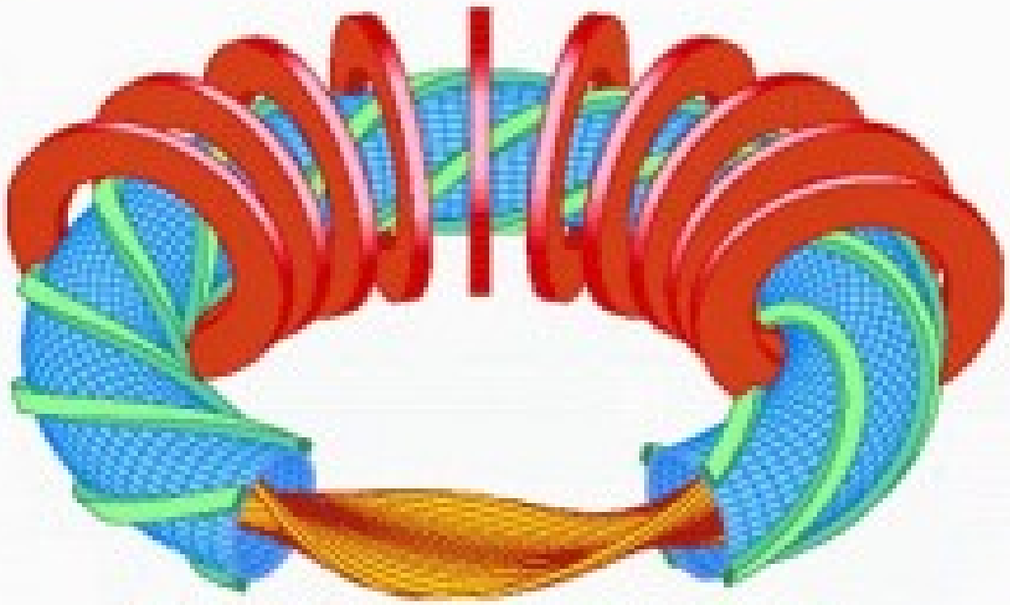
W1-B

W1-A



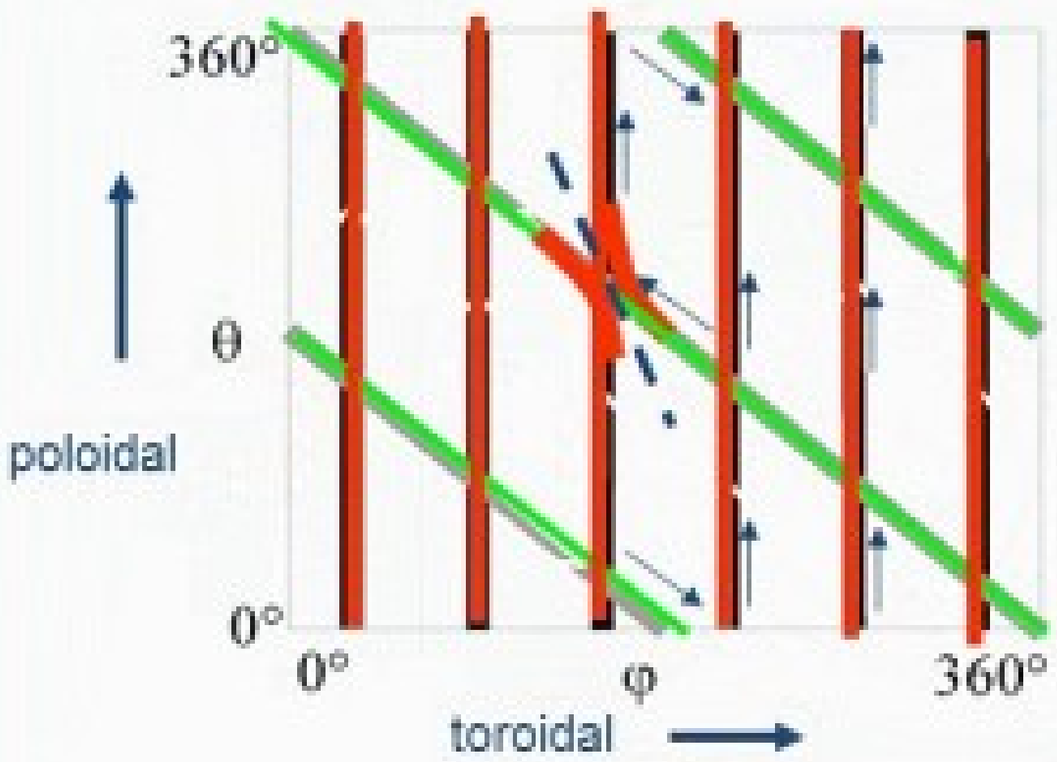


... to optimised, advanced, modular ones



toroidal field coils

helical field coils



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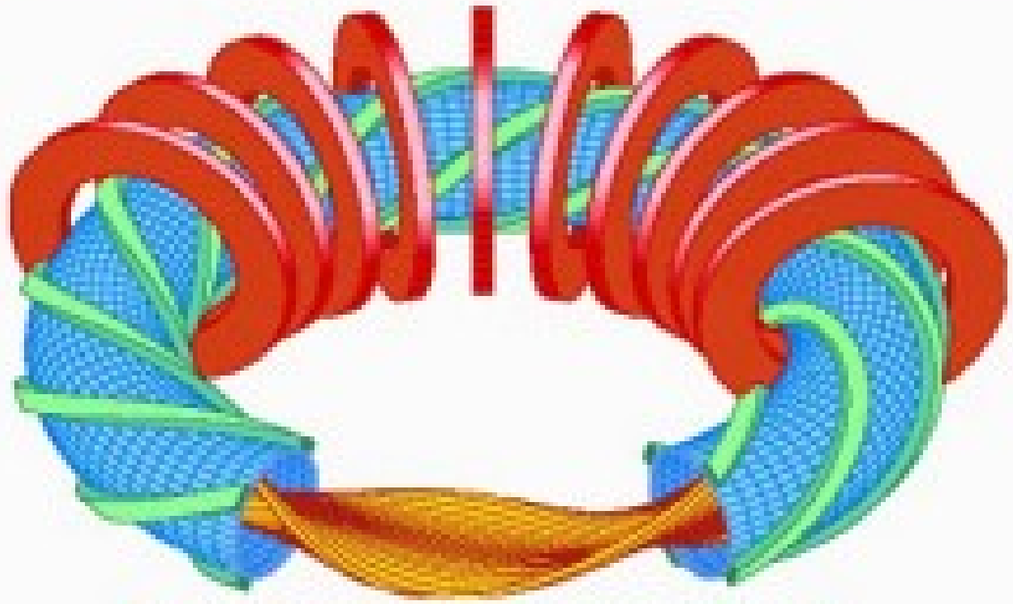
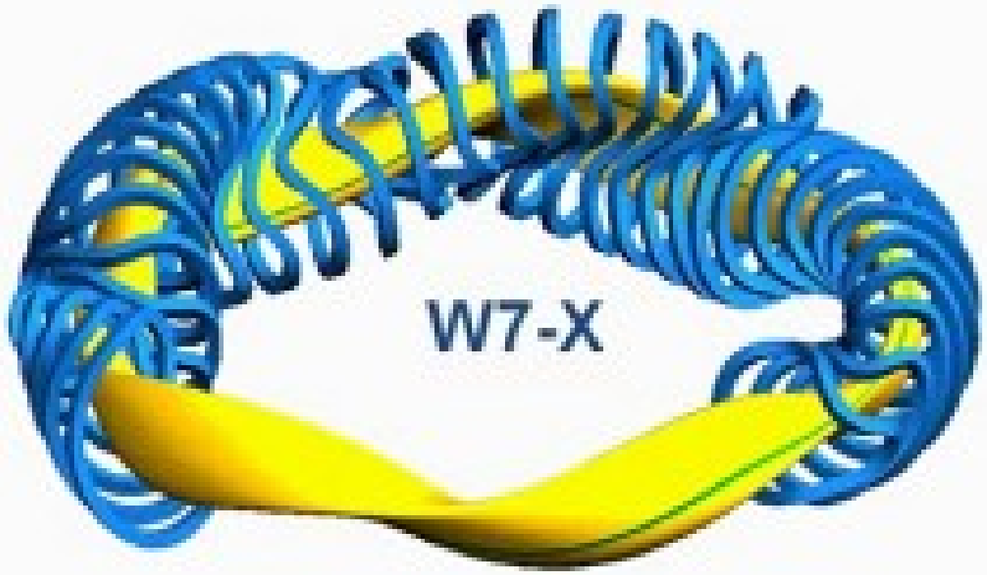
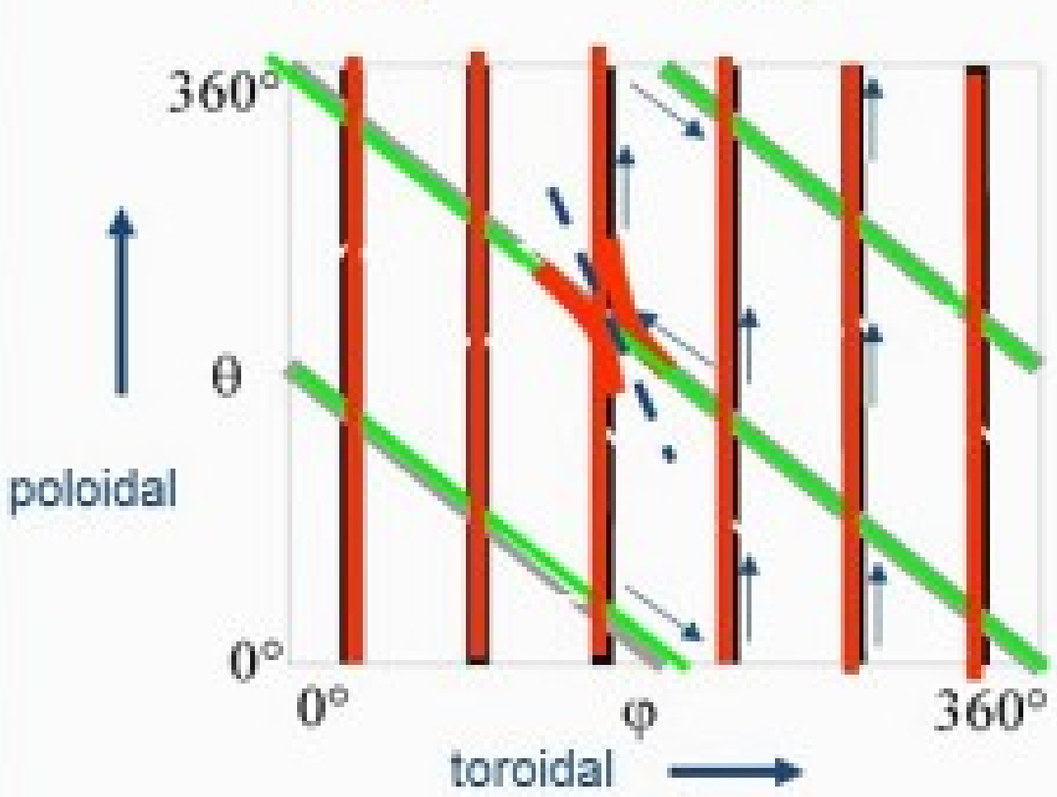


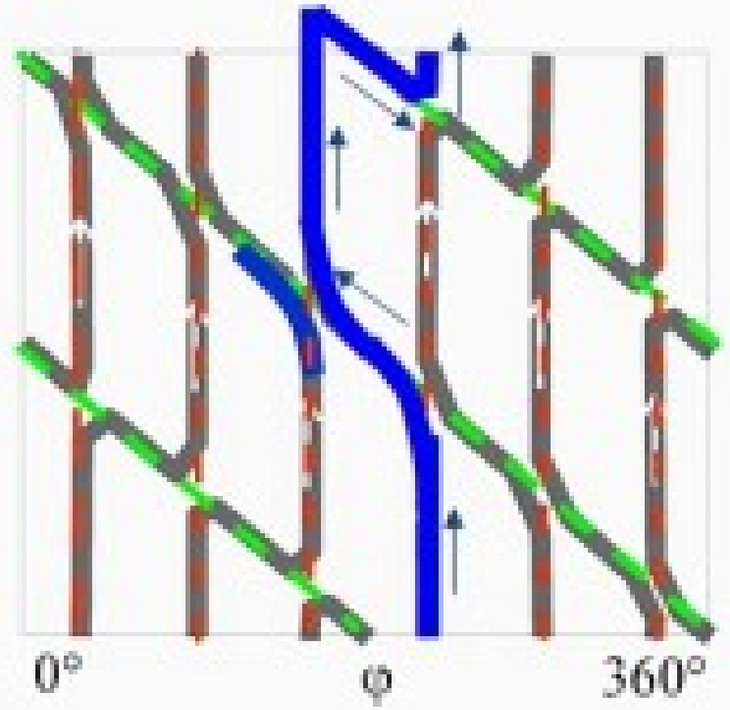
toroidal field coils

helical field coils



modular coils





Wendelstein 7-X in Detail

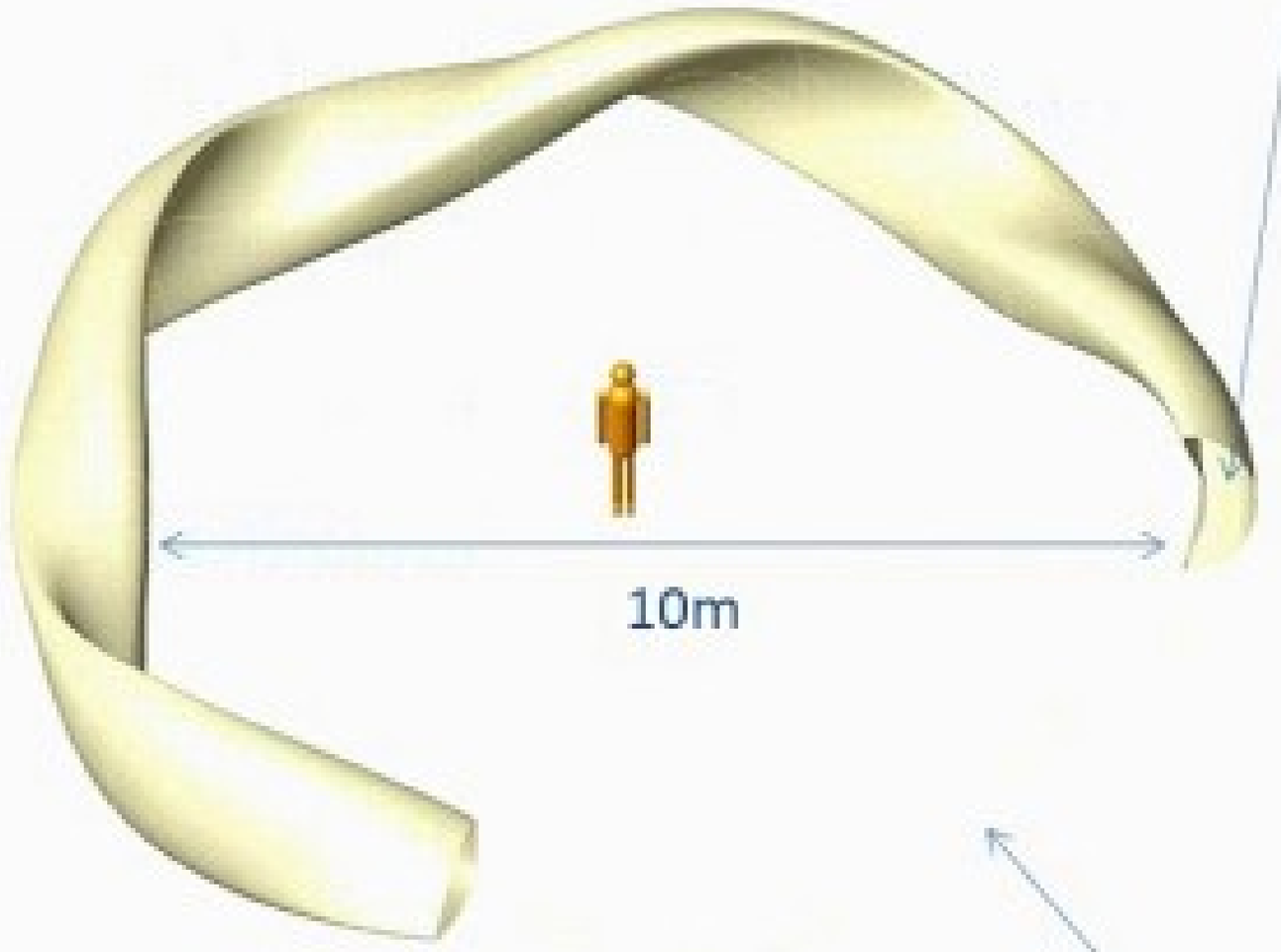
Key Features:

- Exploration of stellarators as potential reactors
- Superconducting modular magnets
- Plasma operation up to 30 mins
- Optimised confinement

Plasma

High temperature, but low density

T = 100 Mio. K
$n = 10^{20}\ m^{-3}$
P = 1 ... 5 bar

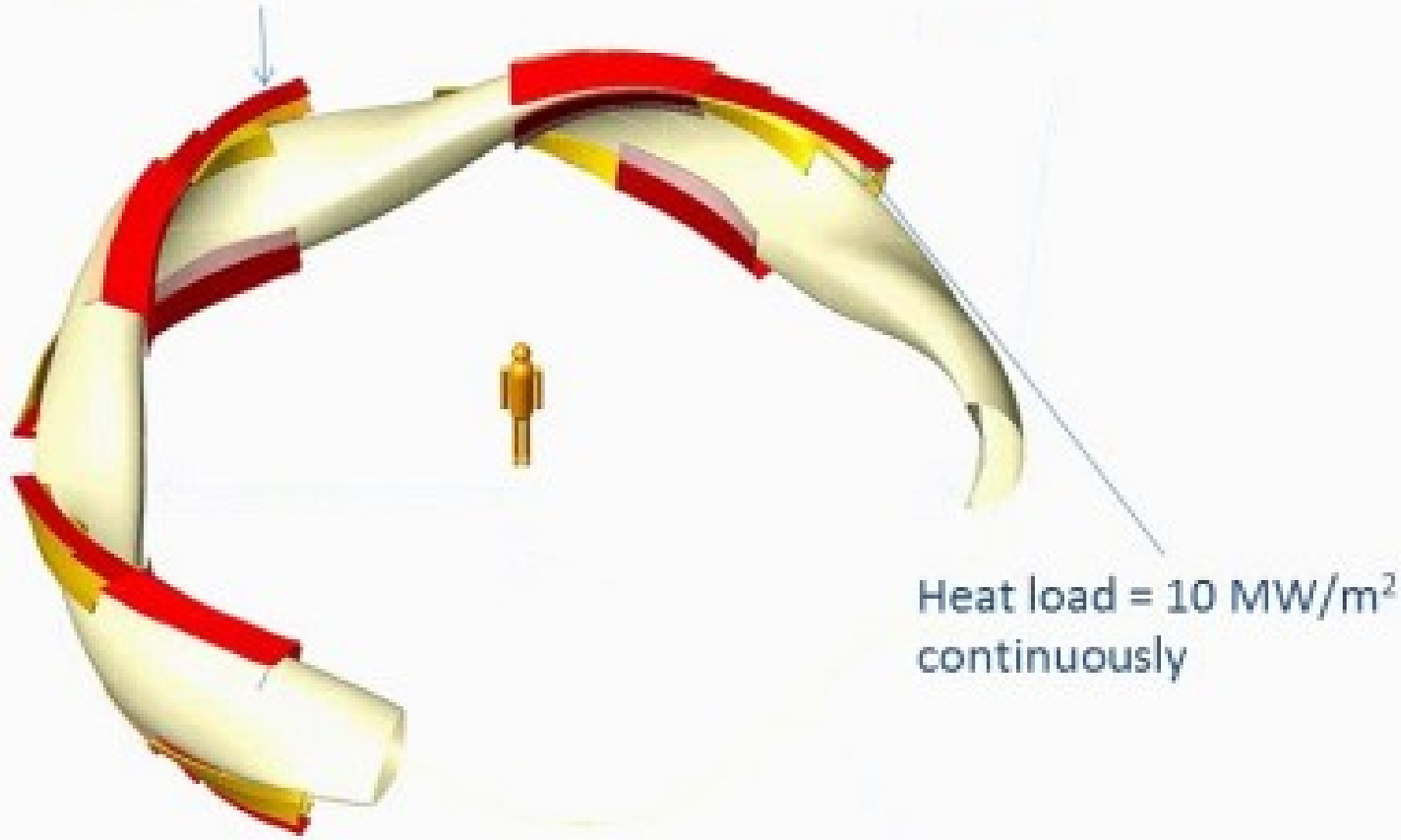


Sensors
Spectrometers
Cameras
Pickup coils
Microwave probing
....

B = 3 T
E = 8 MJ

Plasma+Divertor

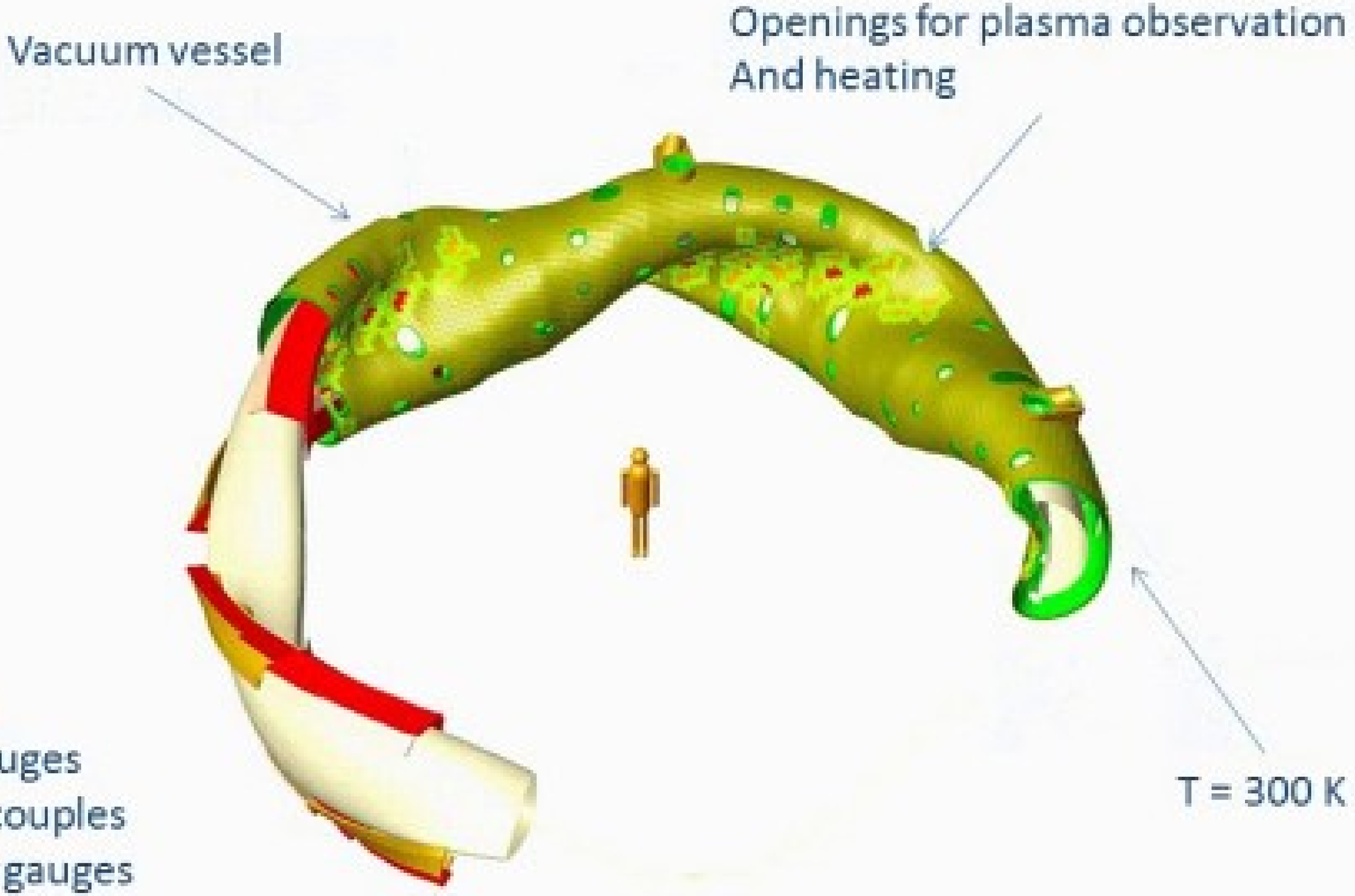
Plasma <-> wall contact at divertors (graphite tiles)
for Helium ash exhaust



Heat load = 10 MW/m^2
continuously

Sensors
Flow meters
Thermocouples
IR cameras

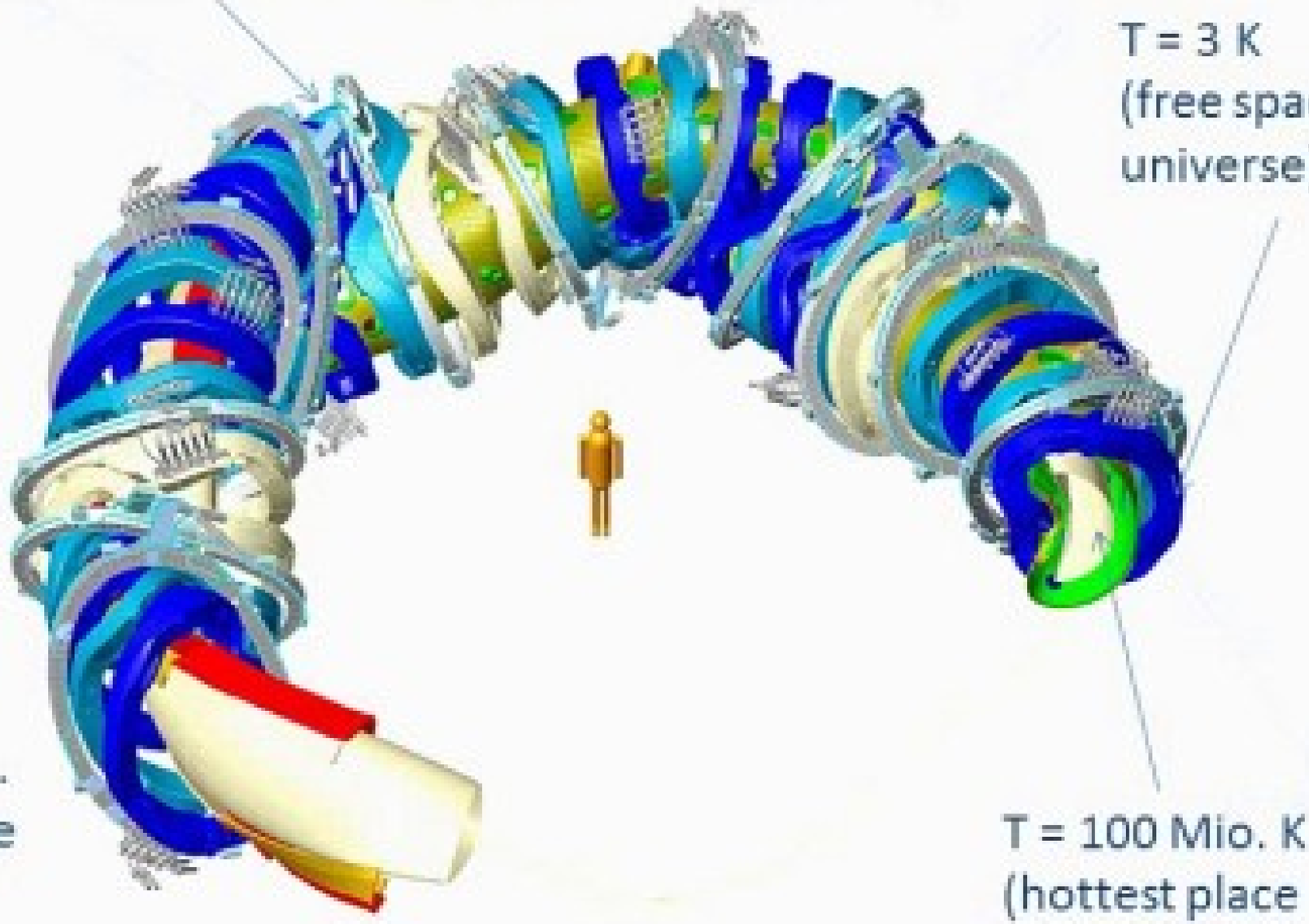
Plasma+Divertor+Vessel



Sensors
Strain gauges
Thermocouples
Pressure gauges

Superconducting Coil System

70 Helium cooled superconducting coils

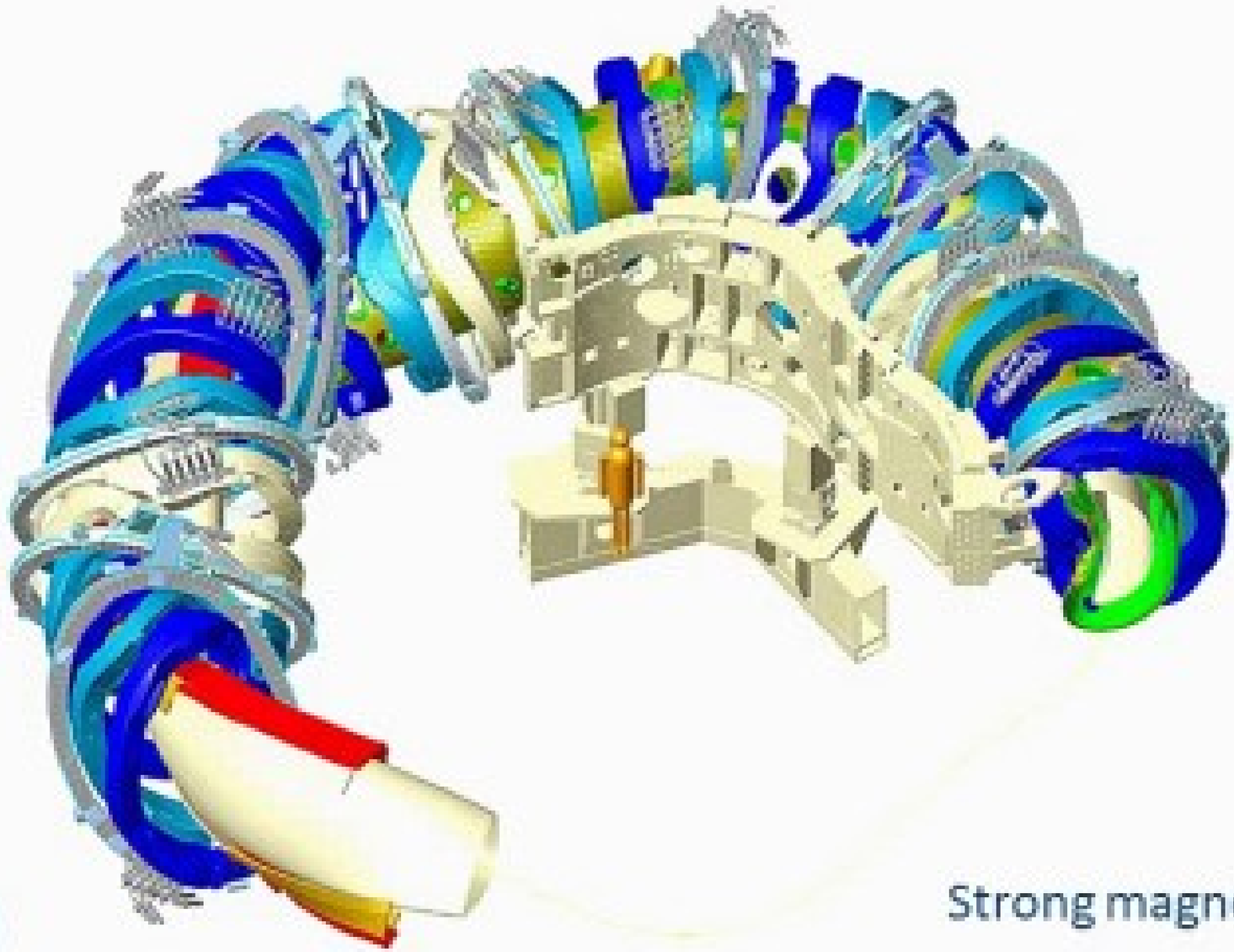


T = 3 K
(free space in universe)

T = 100 Mio. K
(hottest place in universe)

Sensors
Cryogenic sens.
Quench voltage

Support Structure

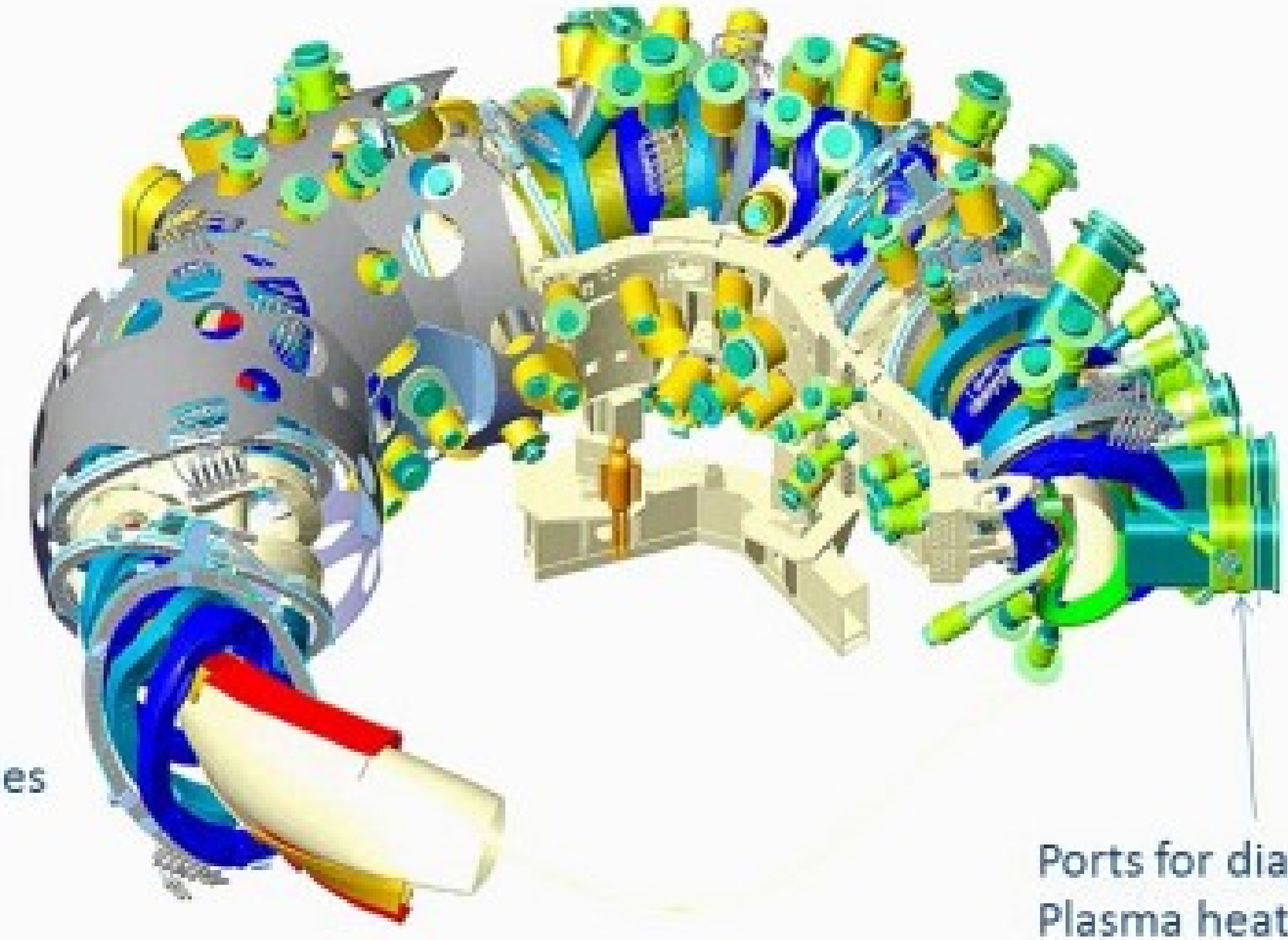


Sensors
Strain gauges
(Audio)
(Laser scanner)
...

Strong magnetic forces

Sliding bearings with mechanical loads of 300t @ T = 20 K

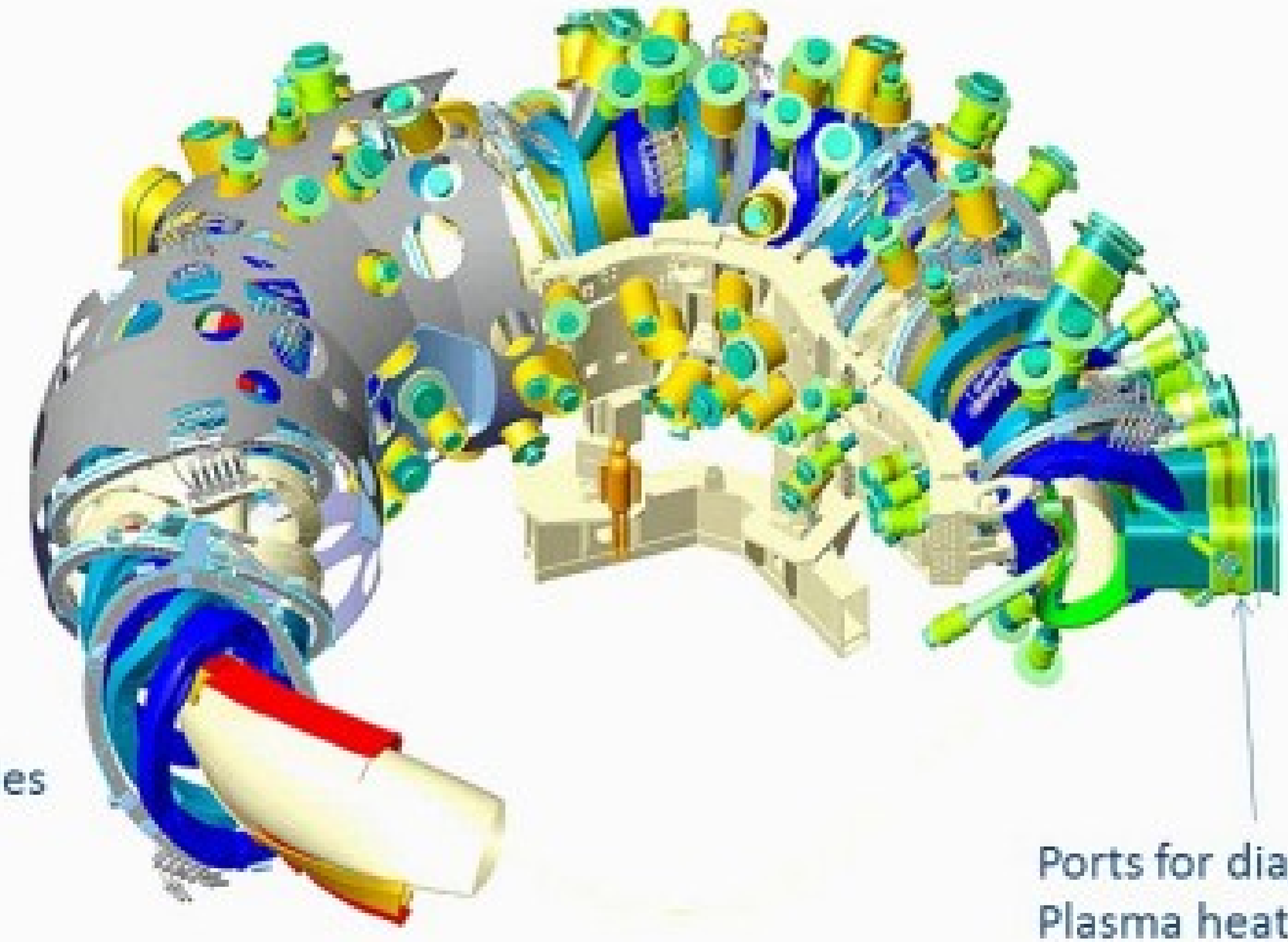
Cryostat and Access Ports



Sensors
Thermocouples

Ports for diagnostics,
Plasma heating,
cooling

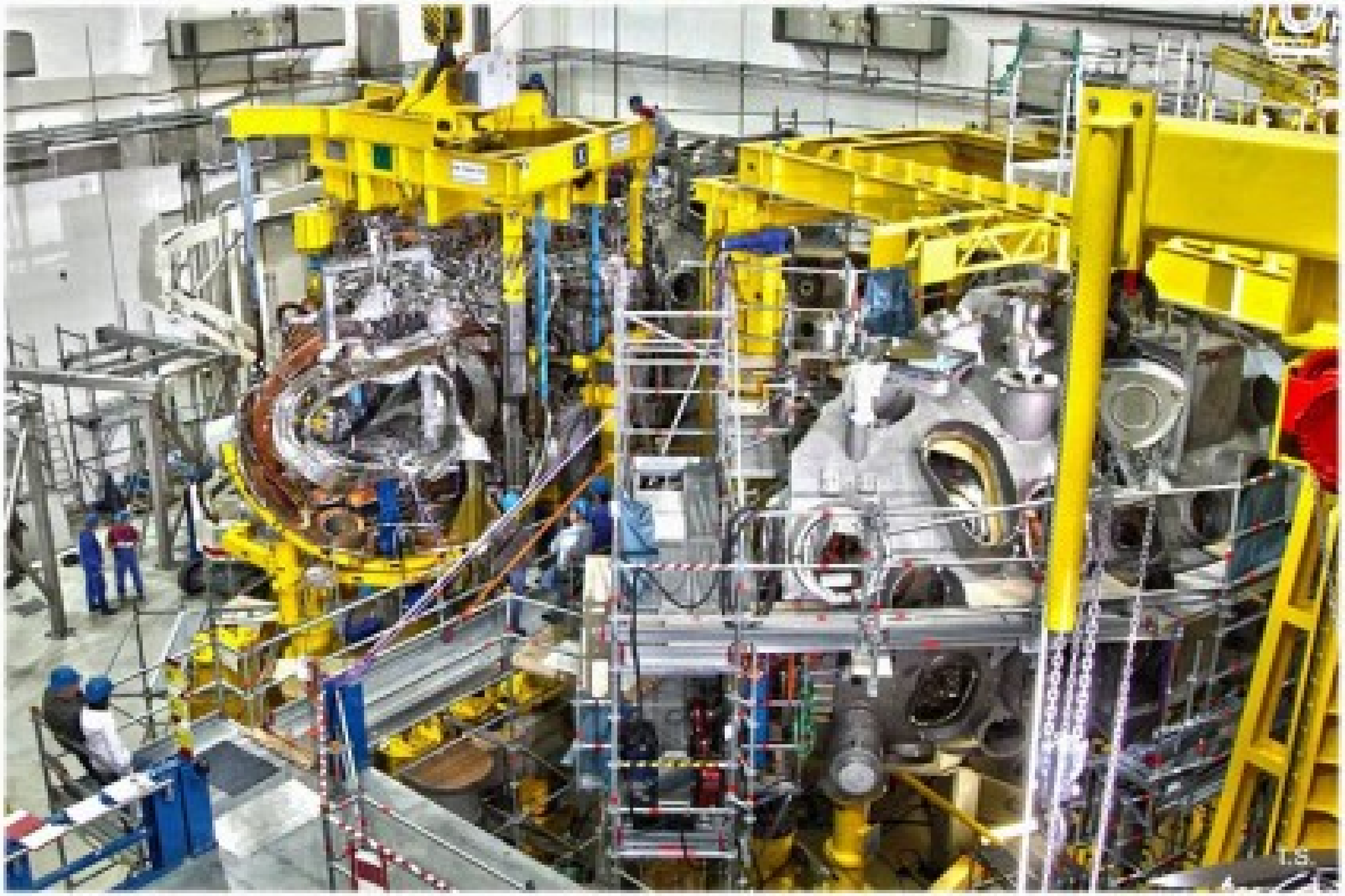
Cryostat and Access Ports



Sensors
Thermocouples

Ports for diagnostics,
Plasma heating,
cooling

Assembly of W7-X: View into the experiment hall before closing the torus
Scheduled for operation in late 2014



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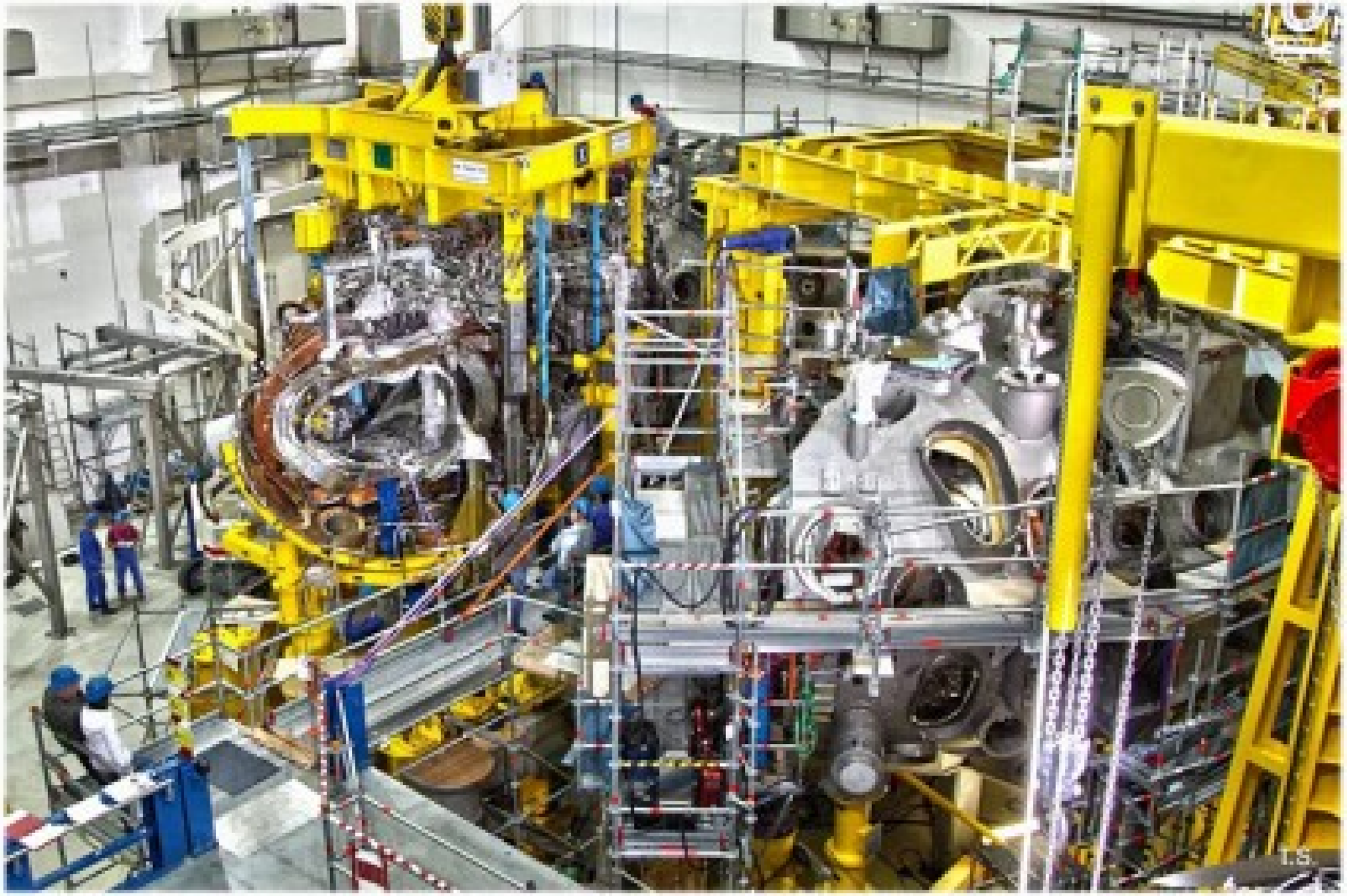
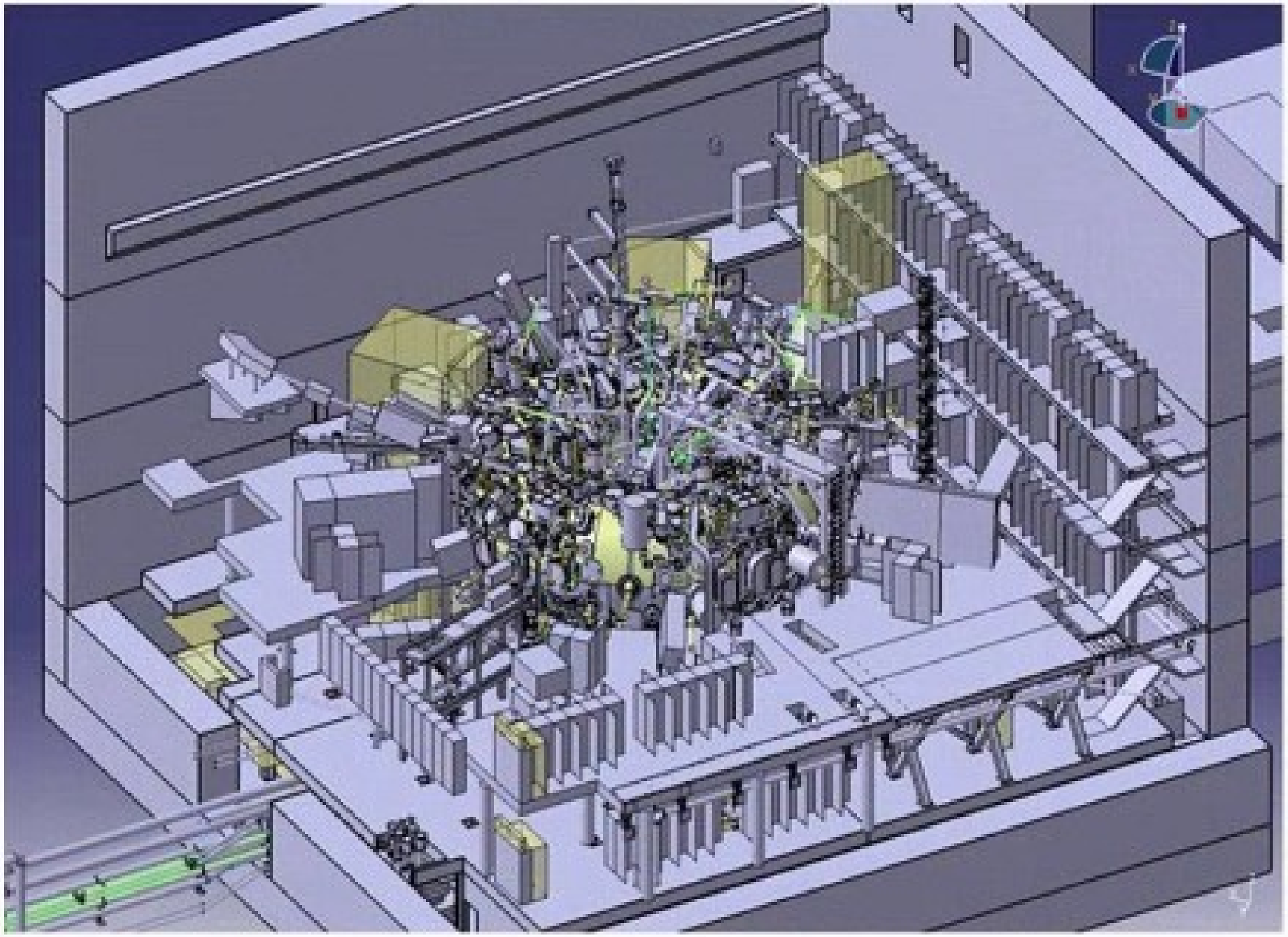
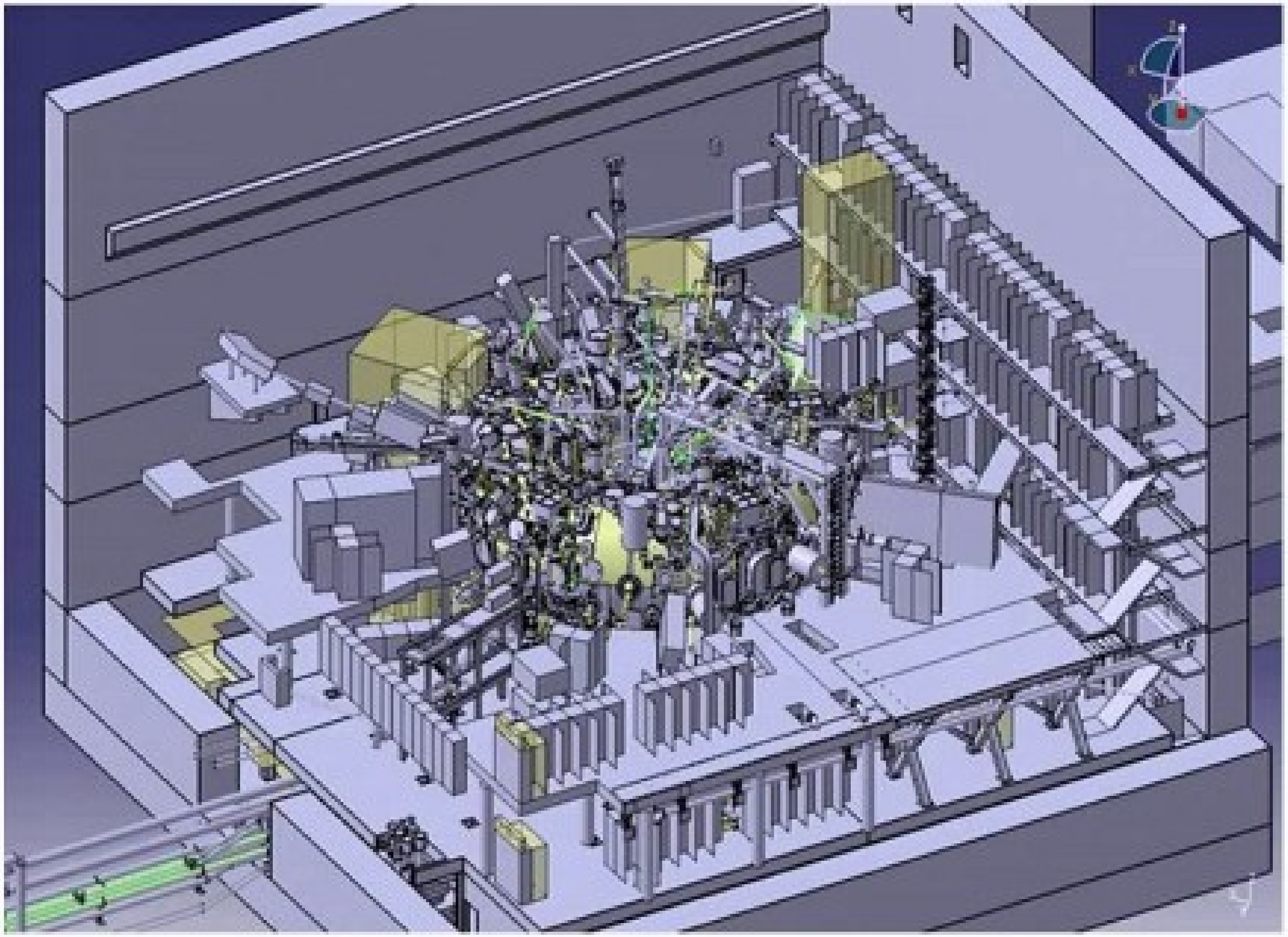


Torus Hall



Torus Hall

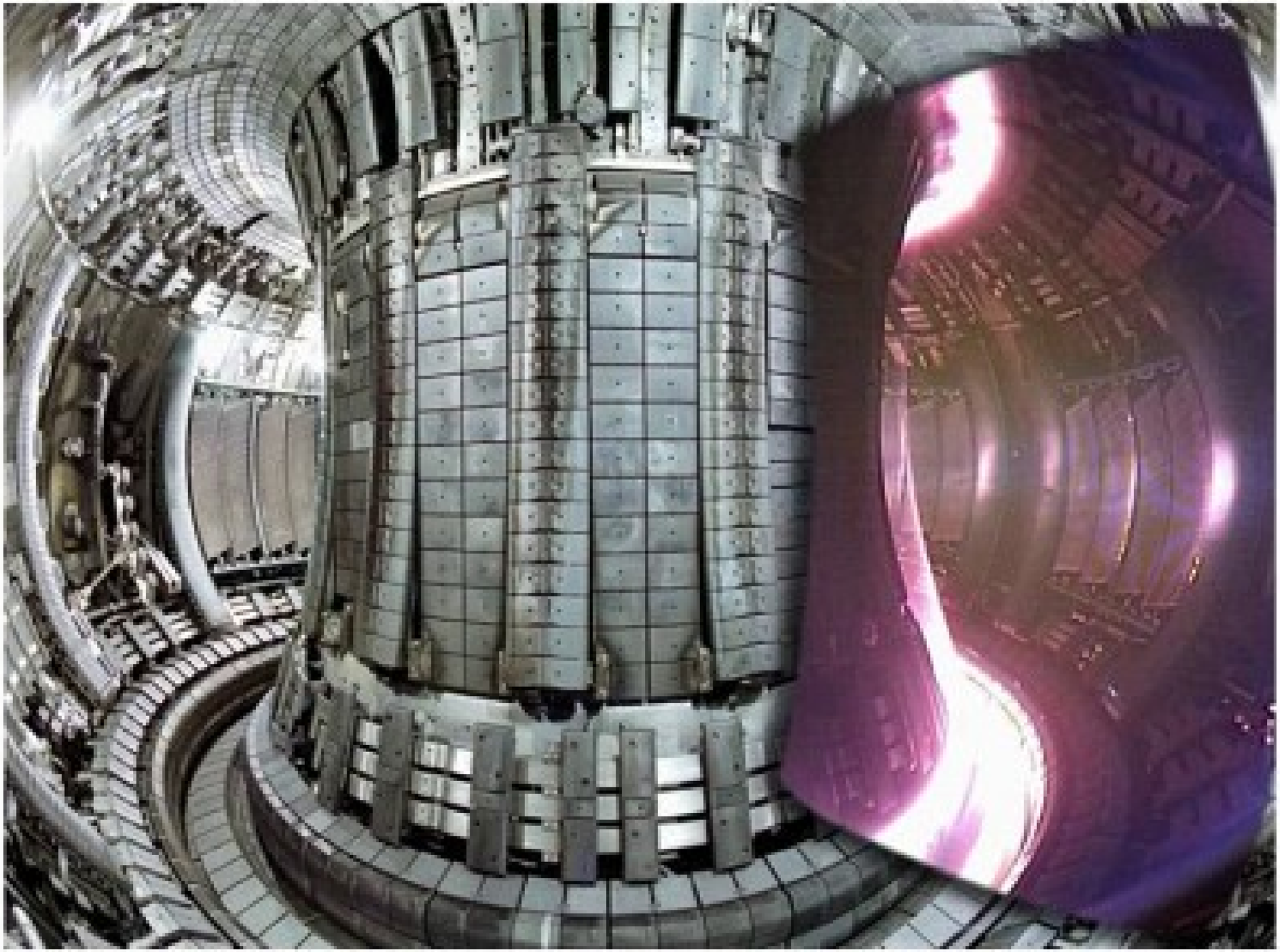


Control and Data Acquisition

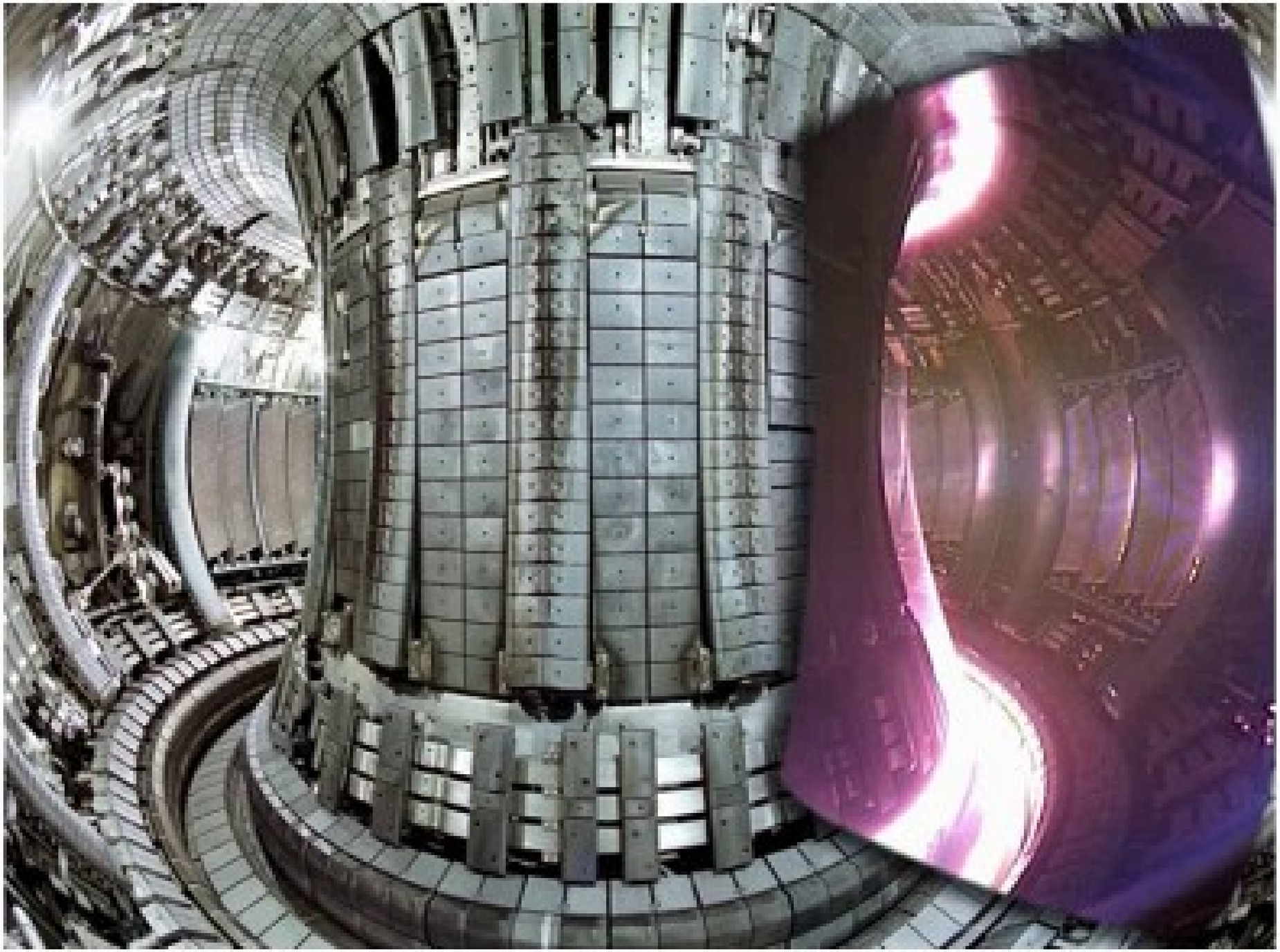
New challenges due to continuous operation:

- Automated (complex) data analyses
- Intelligent plasma control
  stabilisation of favored plasma states
- Continuous high performance data rates
- High quality software products

Example JET (Joint European Torus)



Example JET (Joint European Torus)



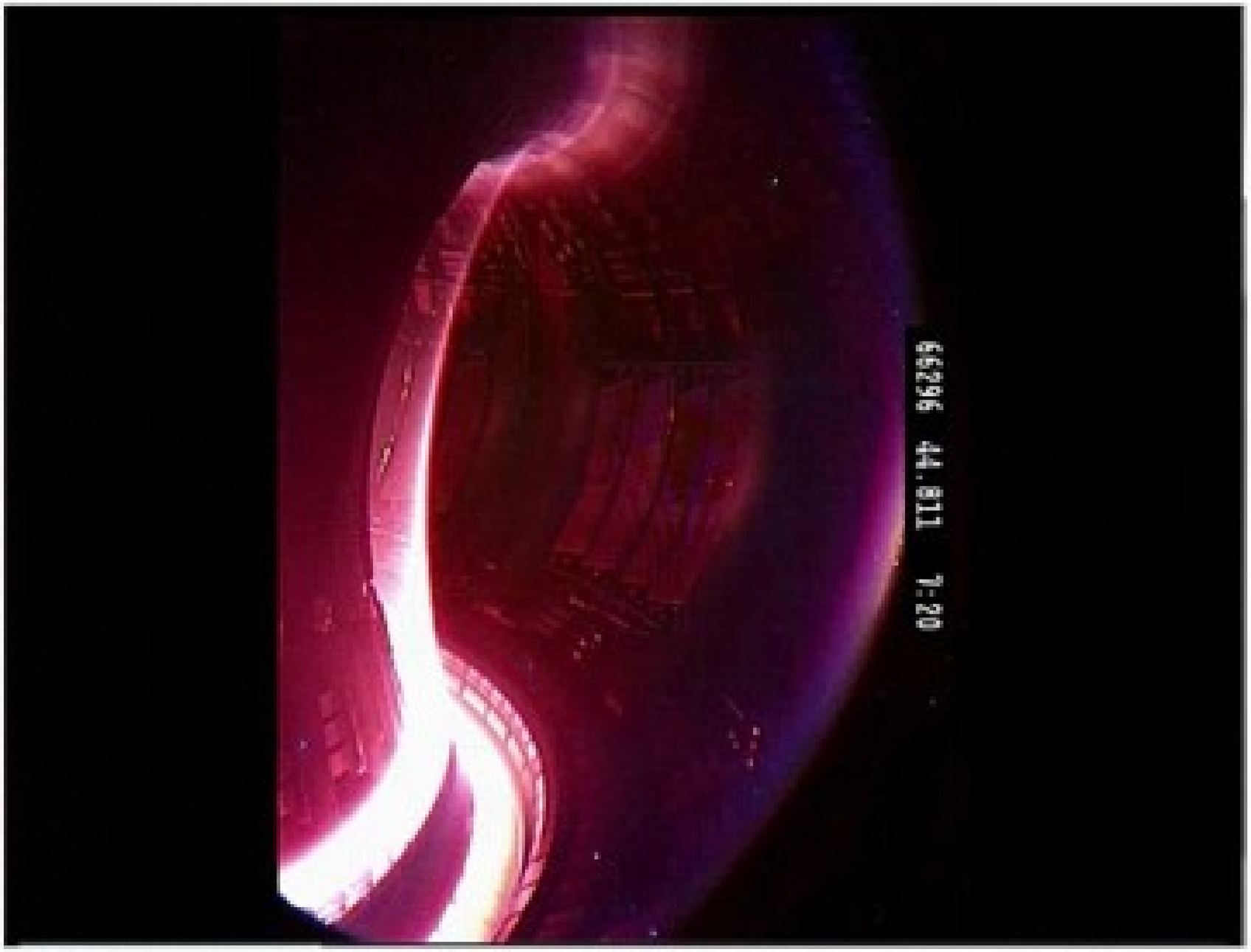
Plasma in Operation (JET Tokamak)

Magneto-Hydrodynamics

Magnetic field
Is frozen into
Plasma

Active control
for stabilisation

10 seconds
only!



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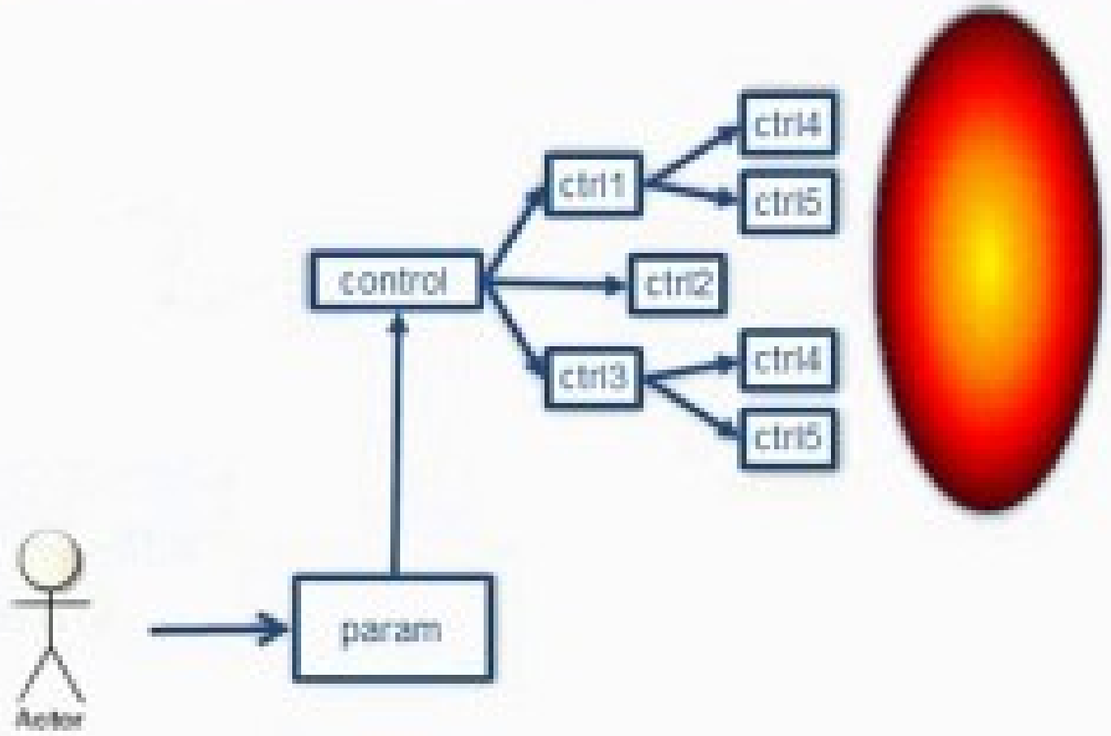
The Control "Business"



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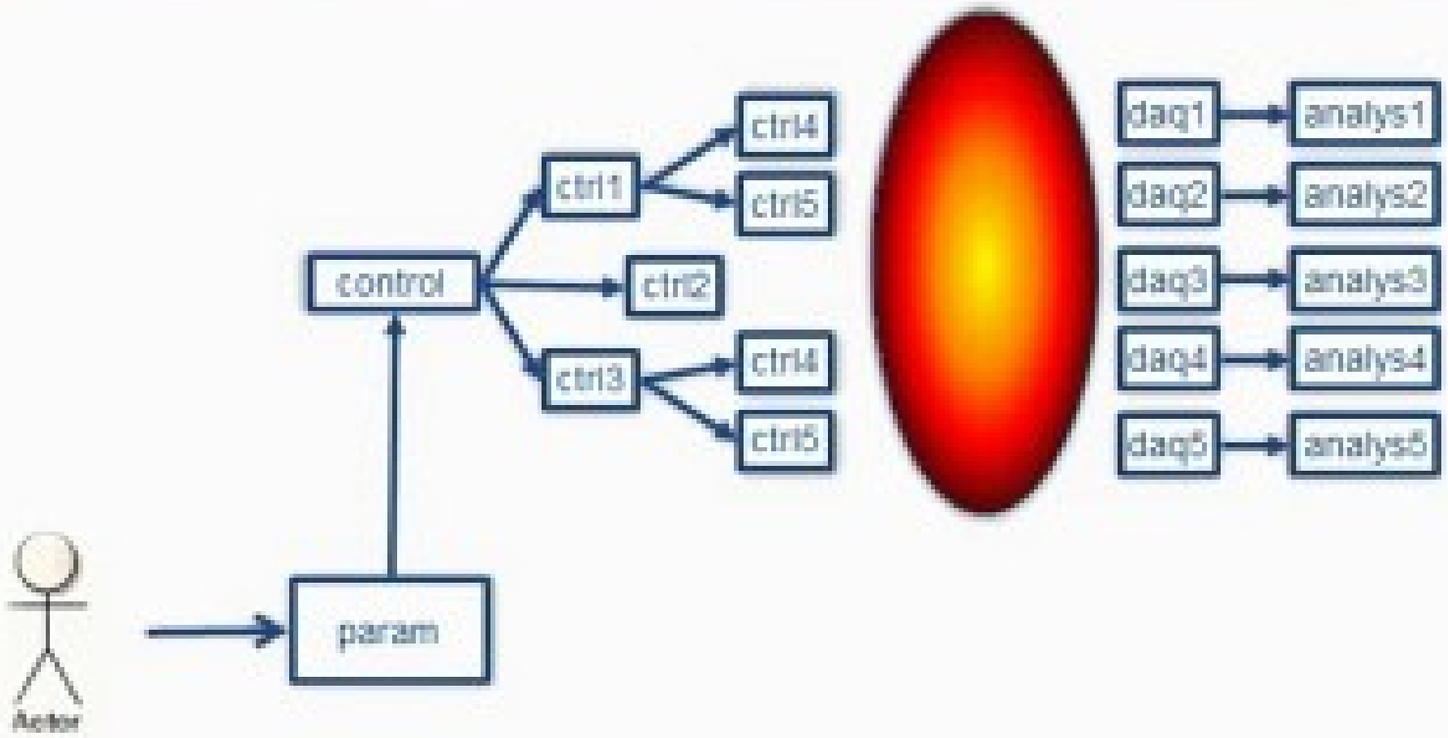

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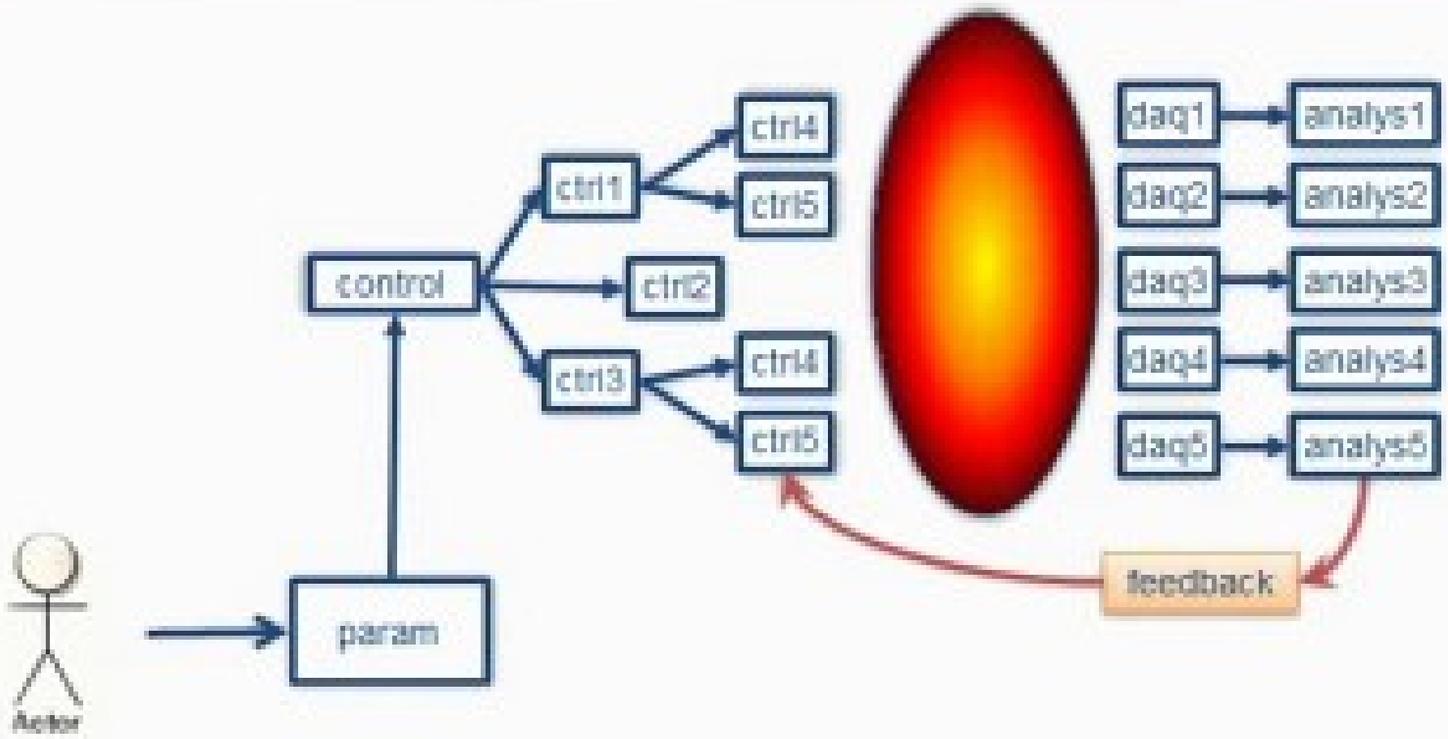

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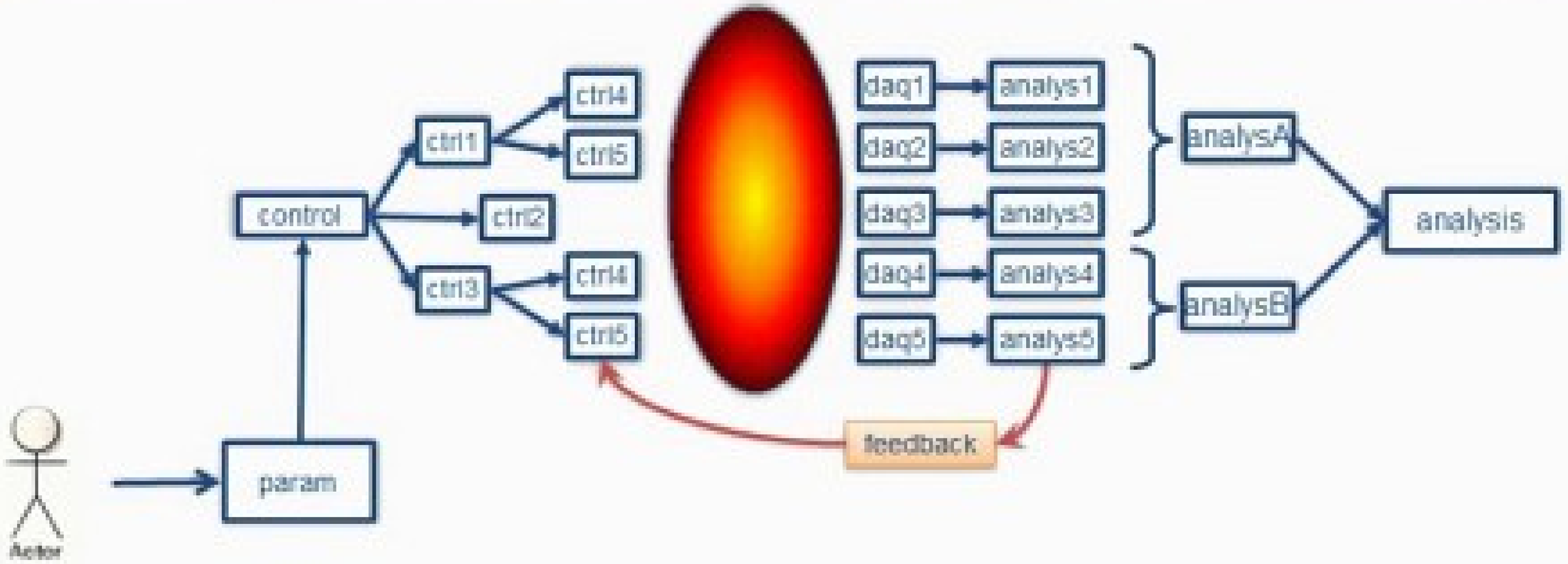

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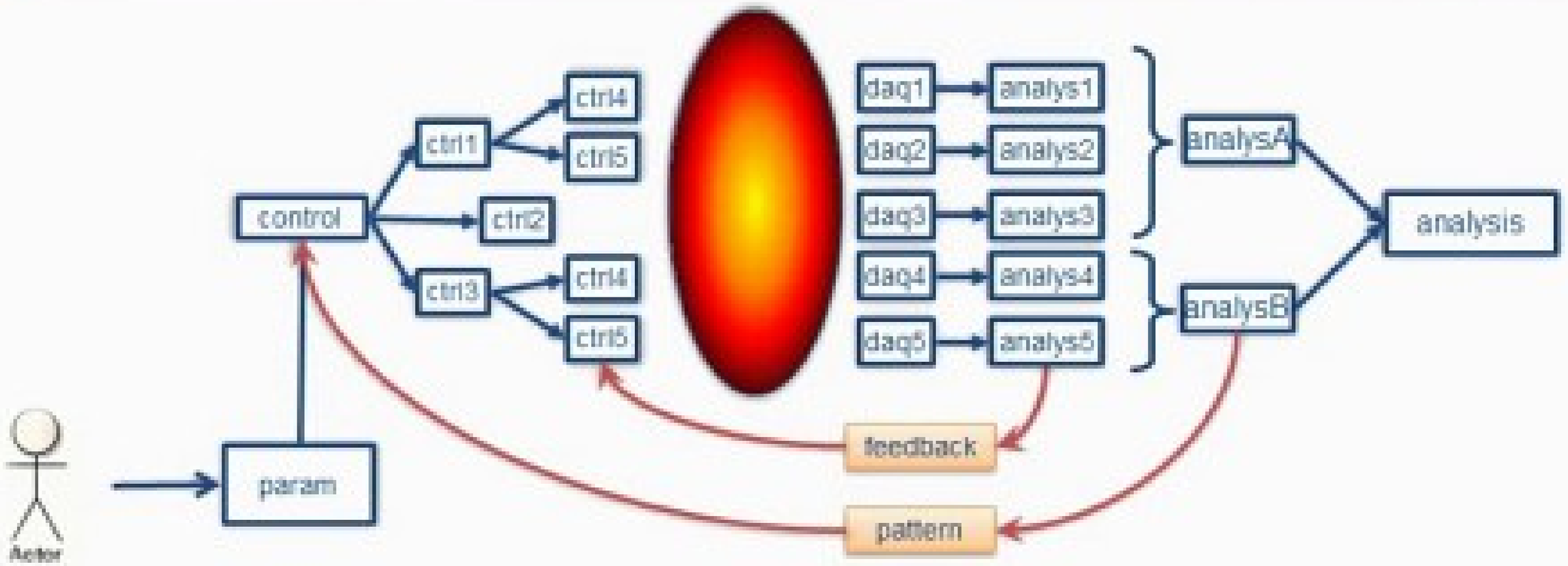

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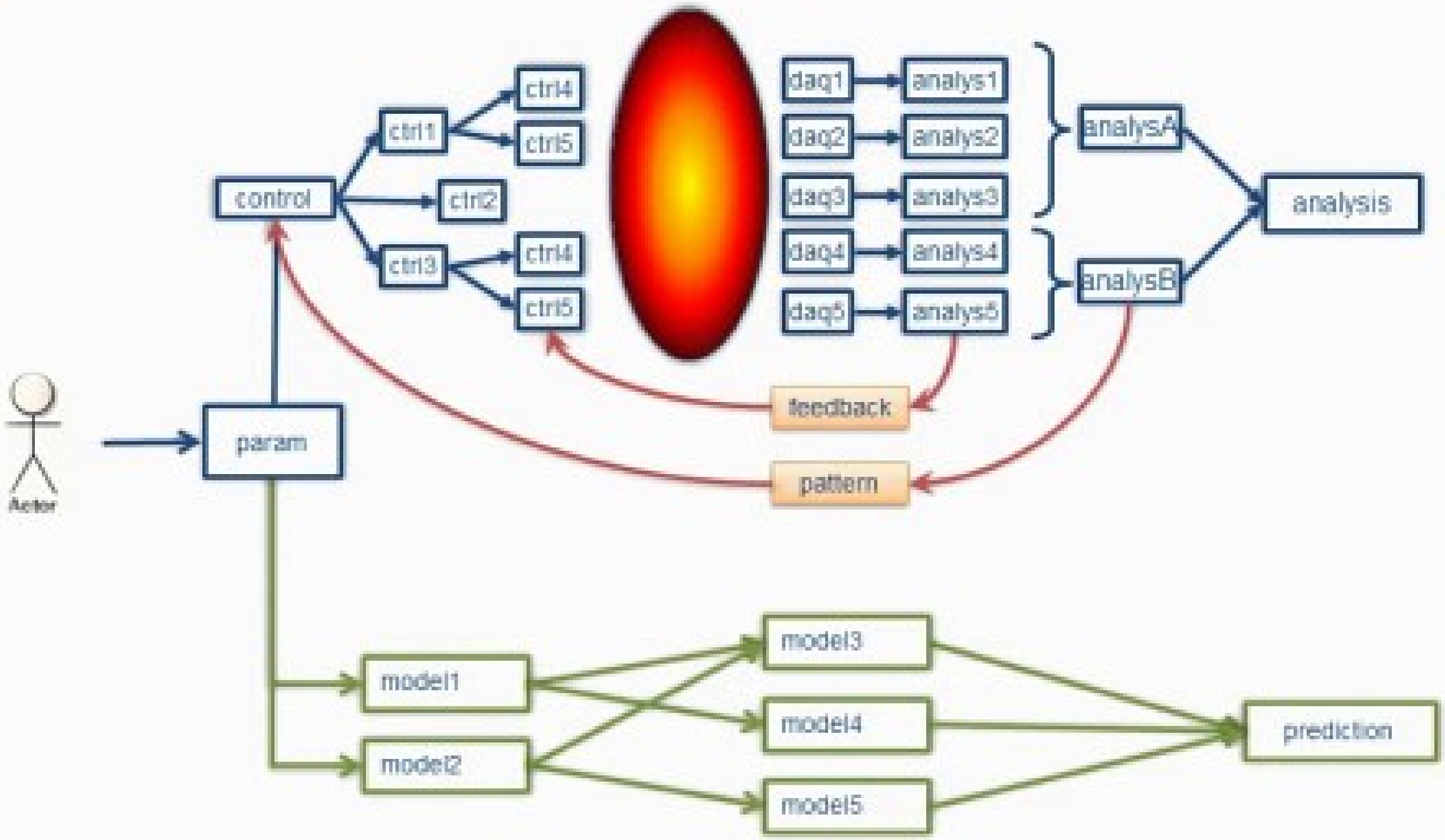

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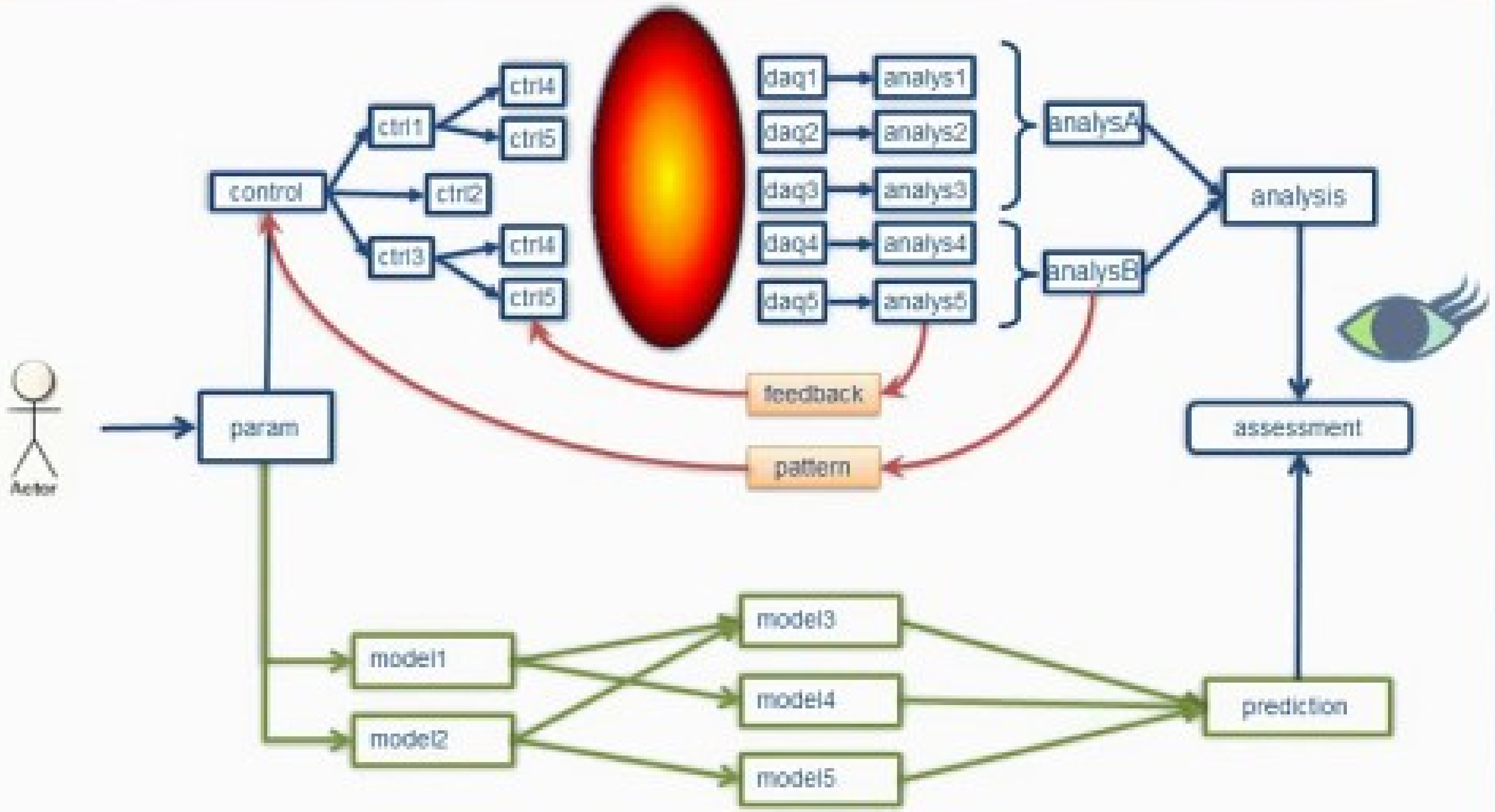

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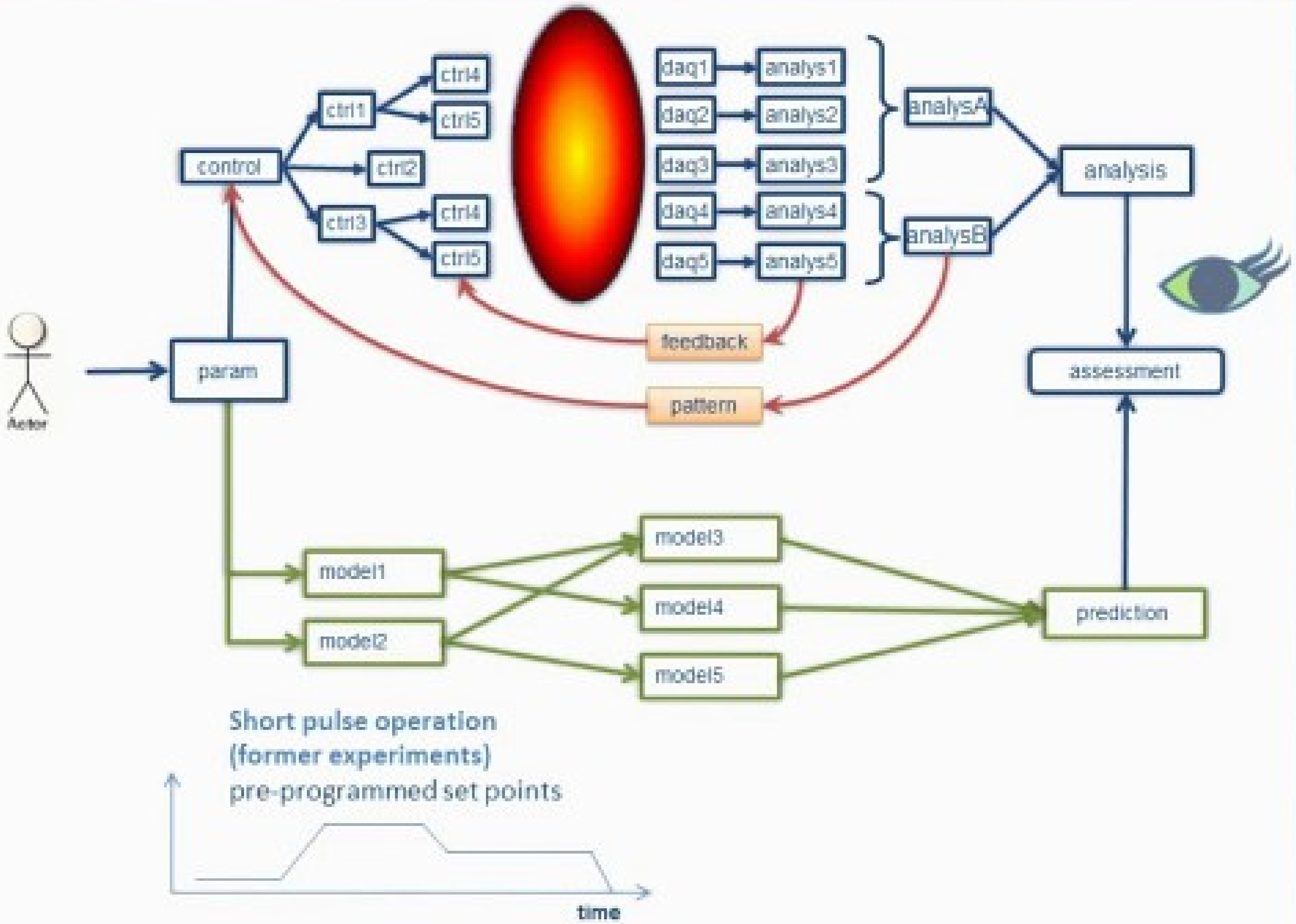
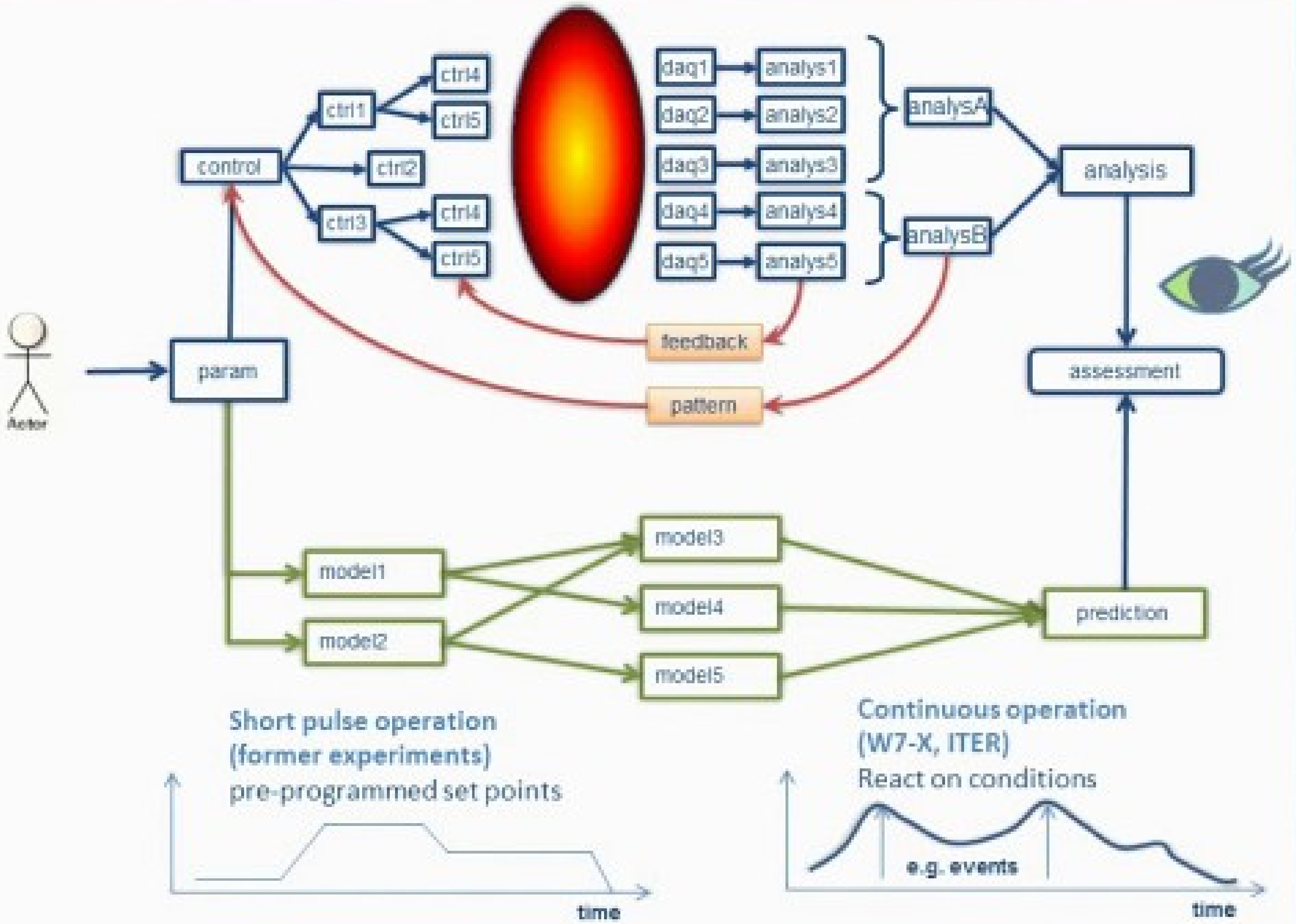


Short pulse operation
(former experiments)
pre-programmed set points

The Control "Business"



Short pulse operation
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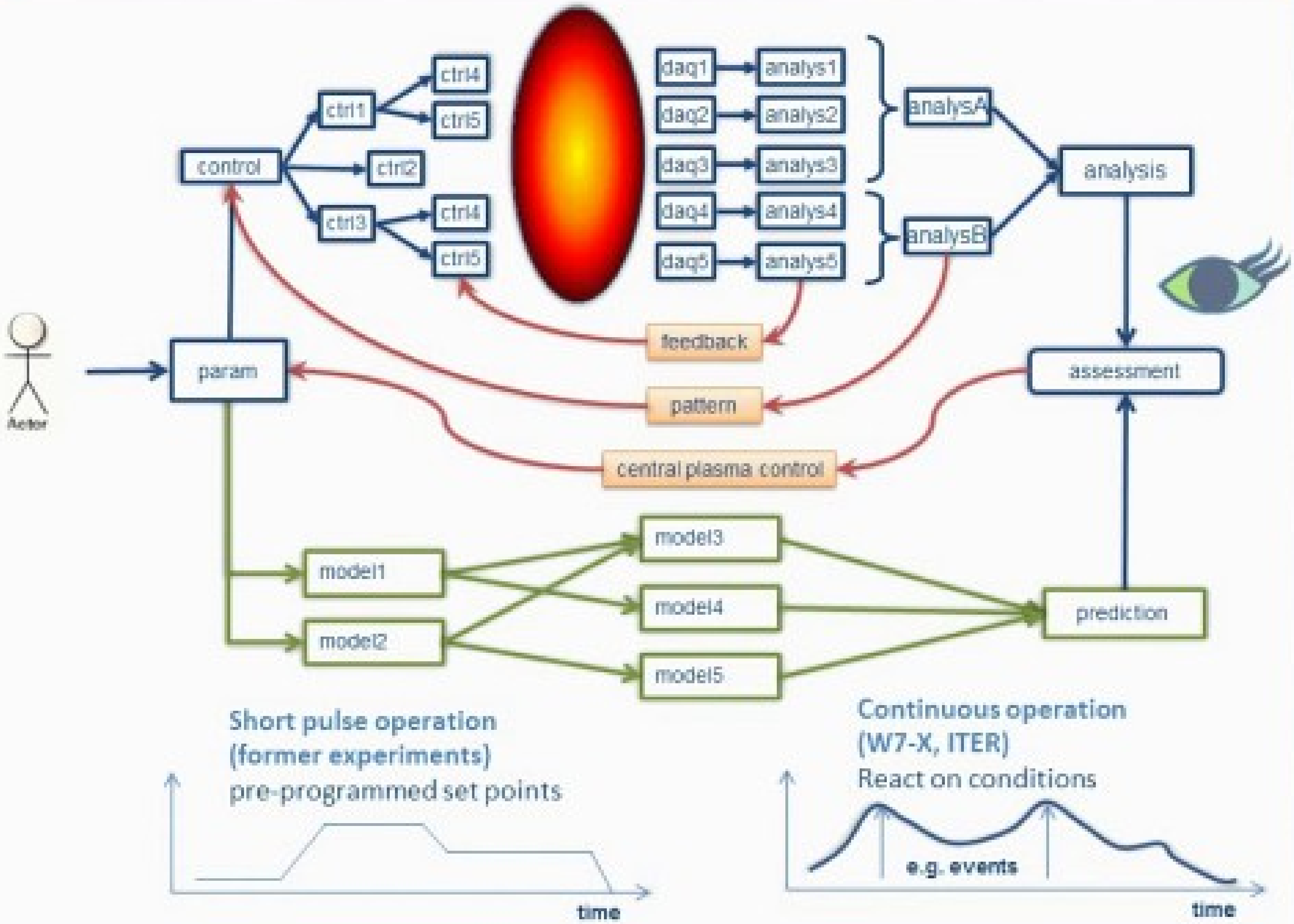
Continuous operation
(W7-X, ITER)
React on conditions

The Control "Business"



Short pulse operation
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pre-programmed set points

Continuous operation
(W7-X, ITER)
React on conditions

Data Acquisition Challenges

Short pulse experiment (W7-AS)

Data Acquisition Challenges

Short pulse experiment (W7-AS)

Steady state experiment (W7-X)

The Control Challenge

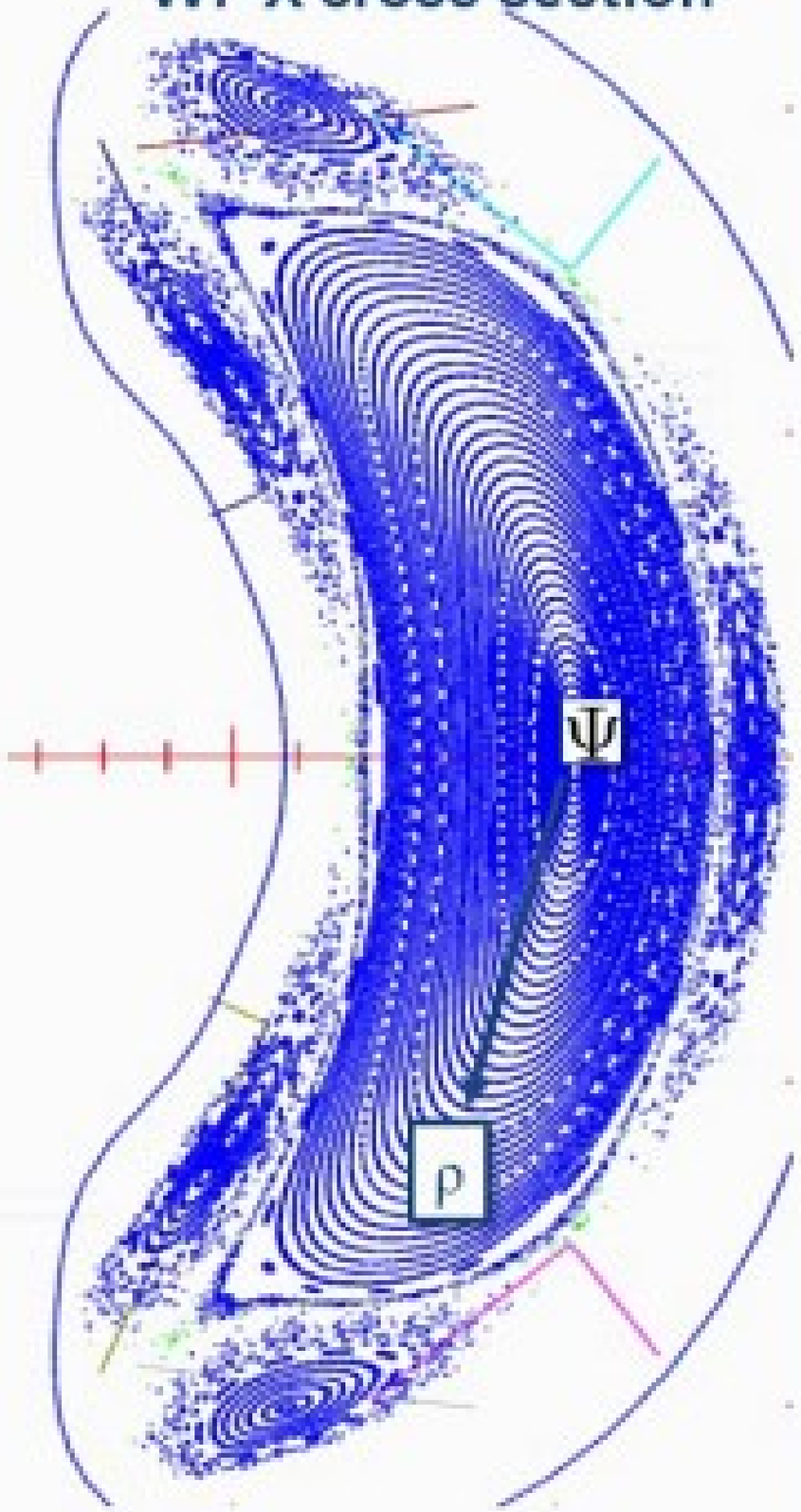
Sensors

Plasma diagnostics, indirect measurement of plasma parameters

Observations depend on multiple plasma parameters!

Information linked by magnetic surfaces

W7-X cross section



The Control Challenge

Sensors

Plasma diagnostics, indirect measurement of plasma parameters

Observations depend on multiple plasma parameters!

Information linked by magnetic surfaces

Radio Frequency *(RF, IC, ICRF, ICE)*

Infra-Red *(IR, Far IR)*

Vacuum Ultra Violet *(VUV, EUV, XUV)*

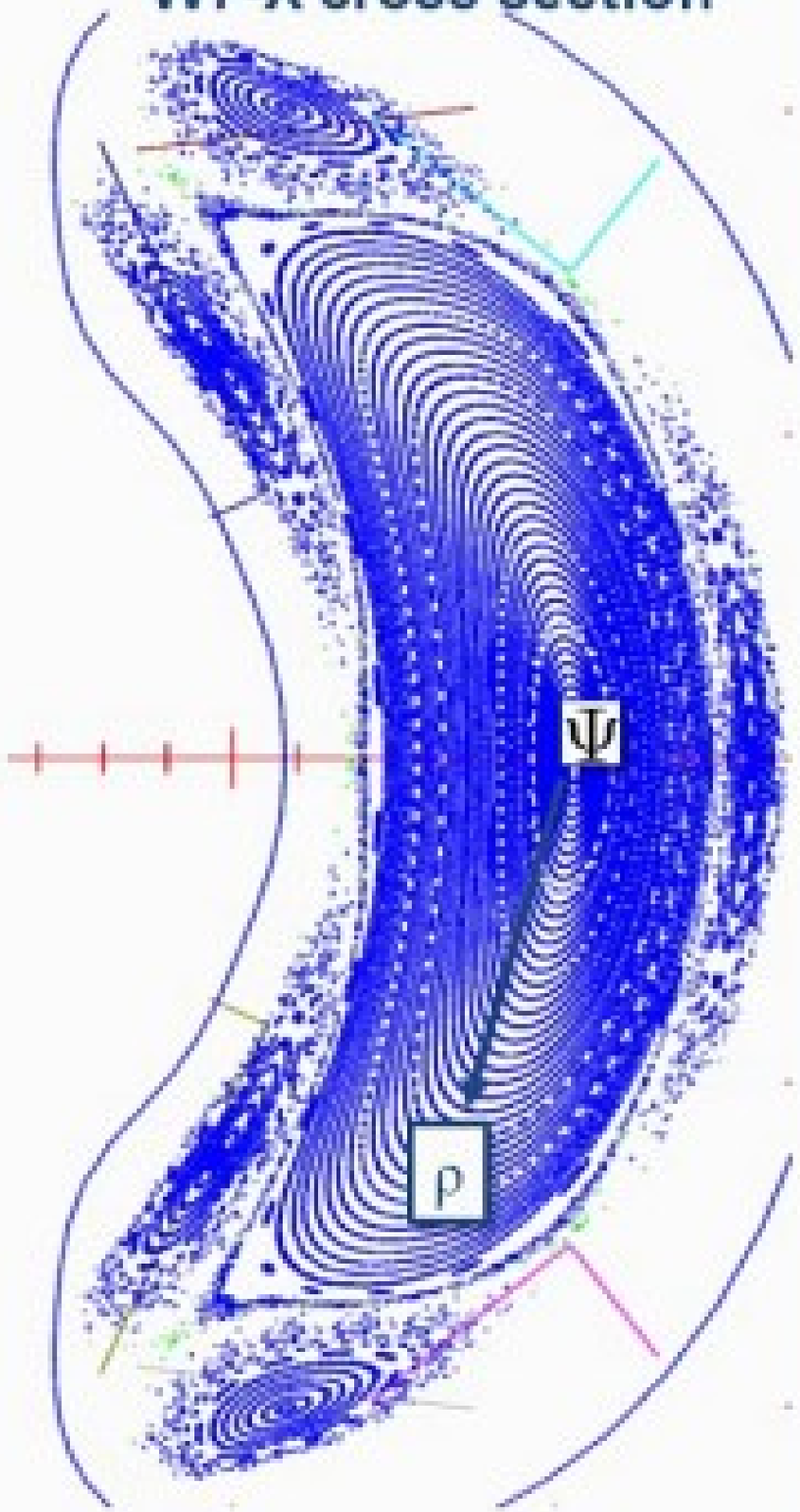
Micro Wave *(µw, ECE, mm-waves)*

Visible Light

X-Rays *(Soft, Hard)*

γ

W7-X cross section



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Micro Wave *(μw, ECE, mm-waves)*

Visible Light

X-Rays *(Soft, Hard)*

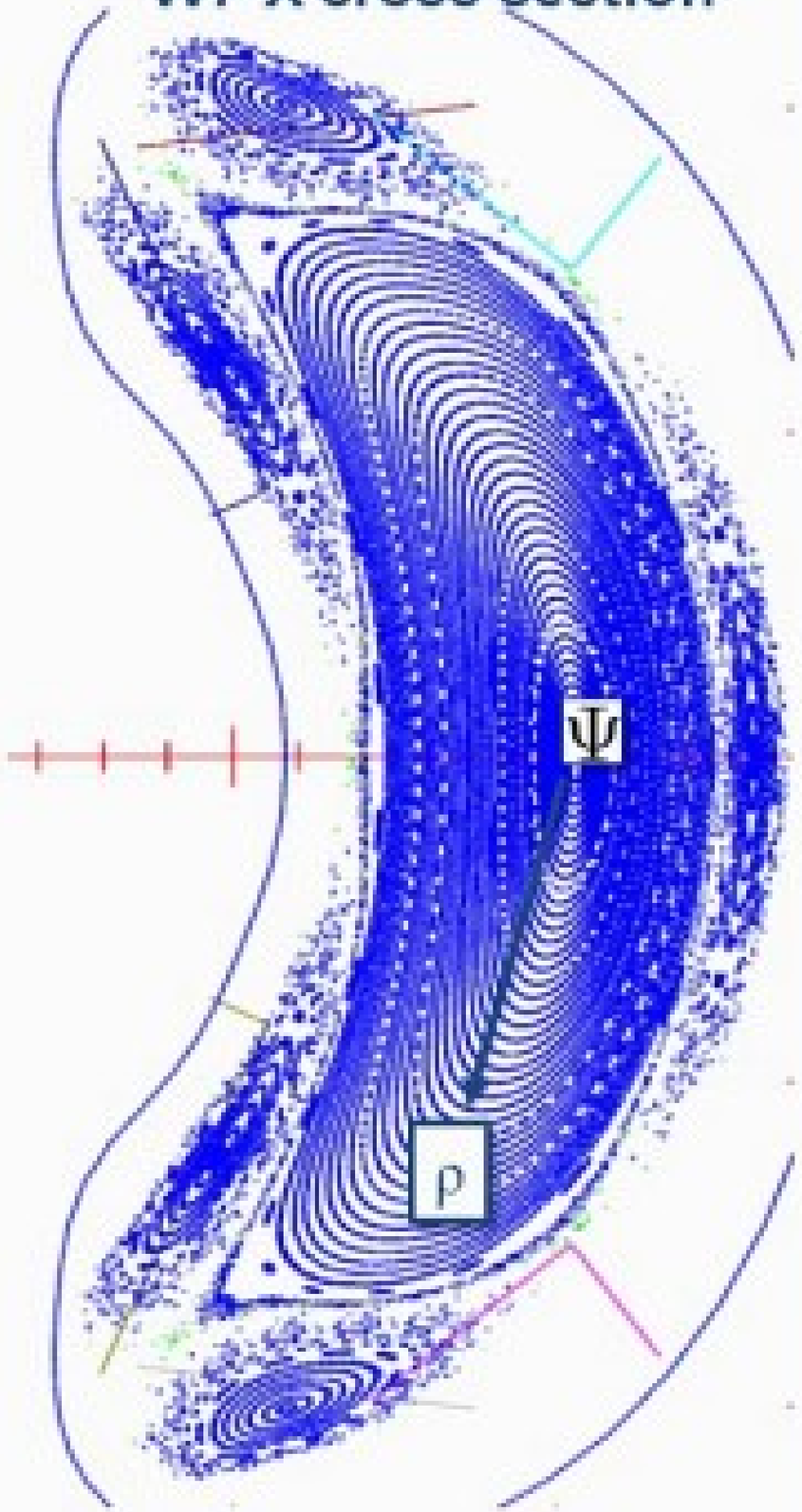
γ

Thermal Particles *($H, H_2, H^+, H_2^+, e, Z^n$)*

Heated Particles *(H^+, e)*

Fusion Products *(α, n)*

W7-X cross section



The Control Challenge

The Control Challenge

Actors

Plasma heating (> 10 MW): Radio Frequency (ion heating), Microwave (electron heating), Neutral Hydrogen beams (>50 keV)

Plasma current (up to 20 MA in ITER): Ohmic transformer, heating devices, magnetic field configuration, gas feed

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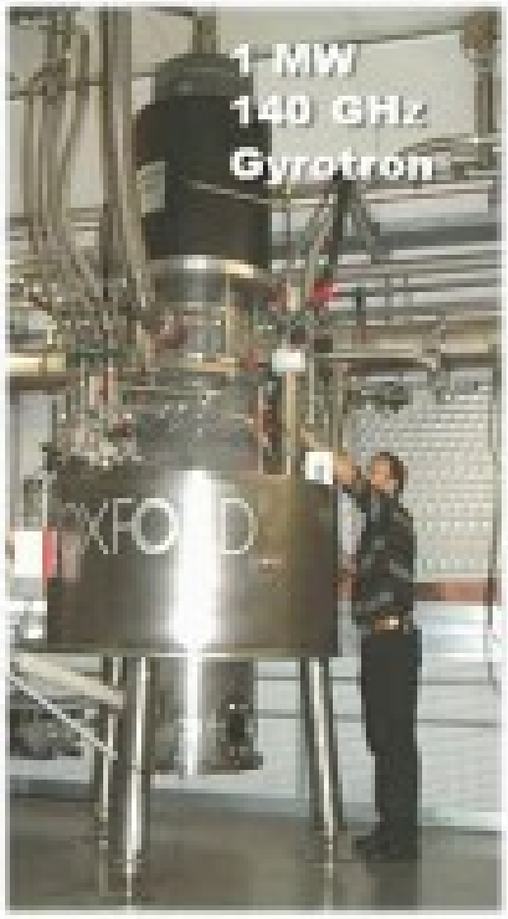

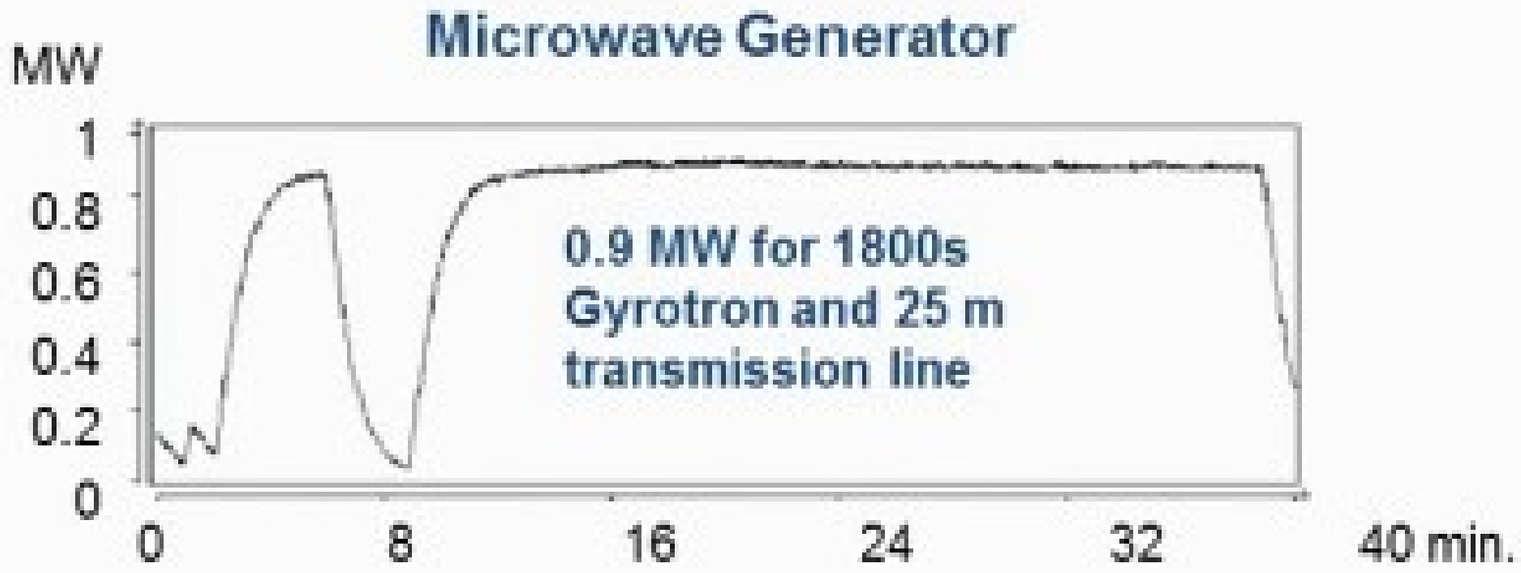

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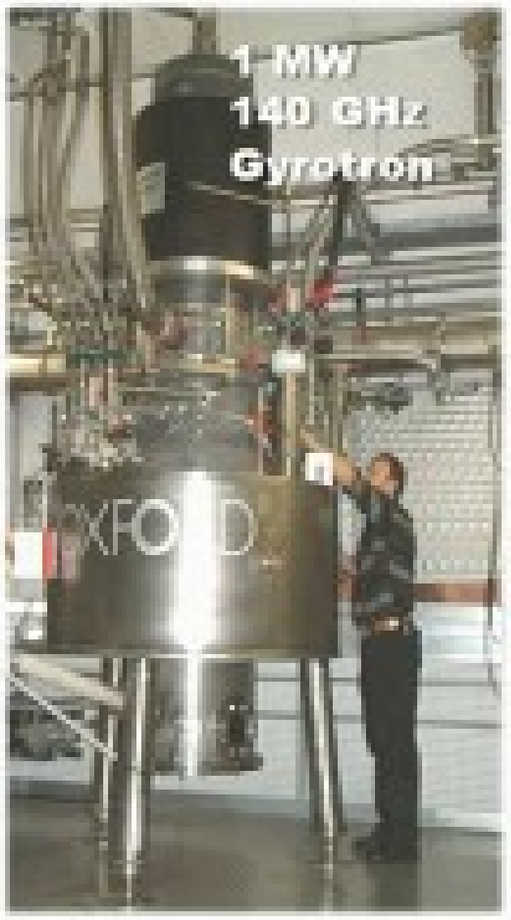
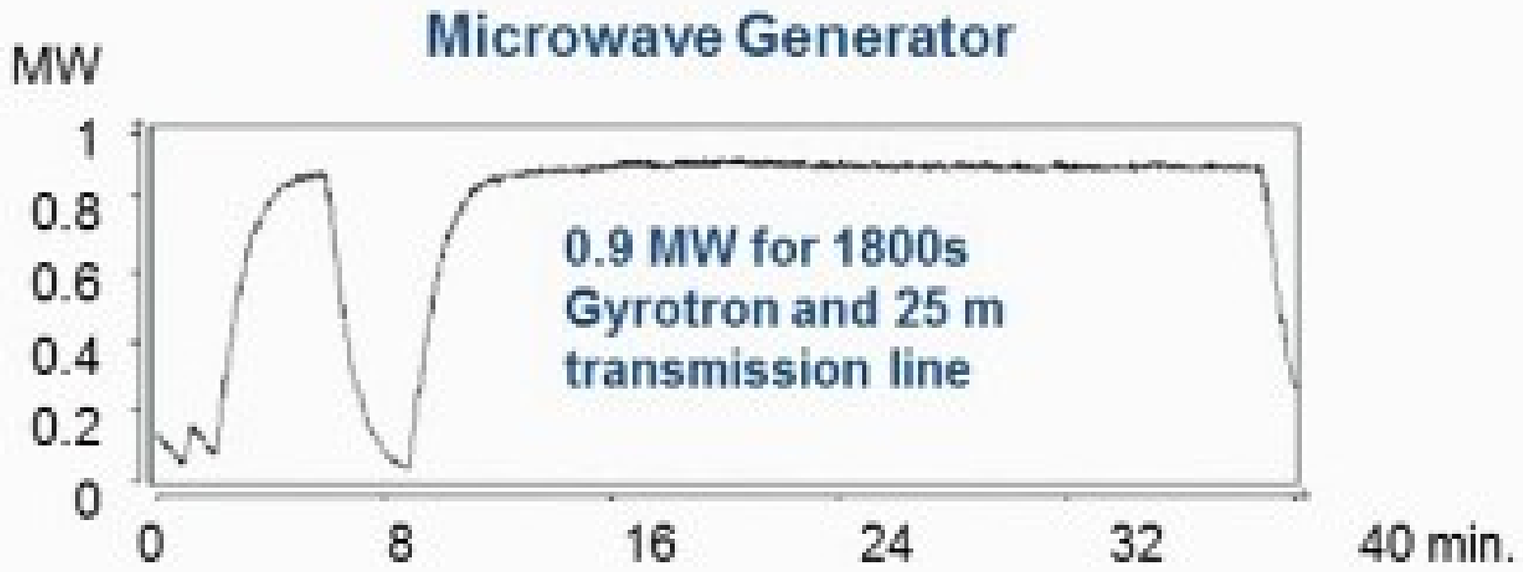




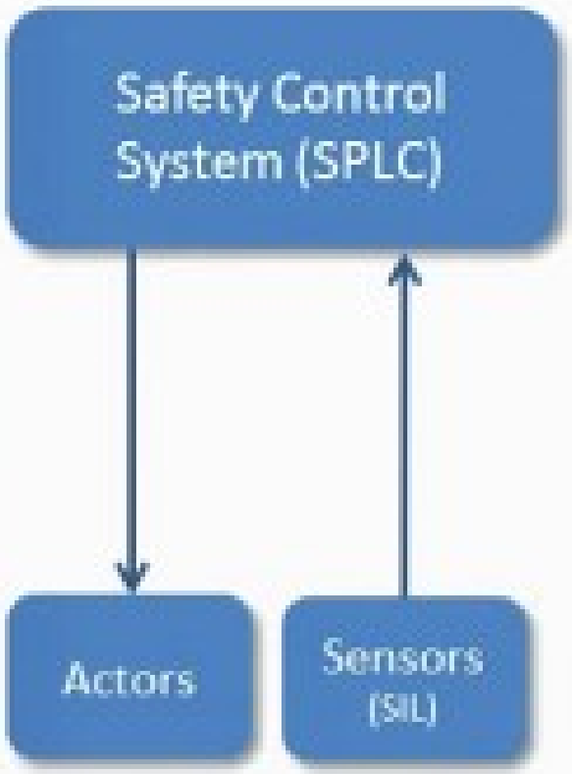
Response times relevant to control loops: **1 ms – 100 s**

Hierarchical Control System for W7-X

safe, slow → experimental, fast

Hierarchical Control System for W7-X

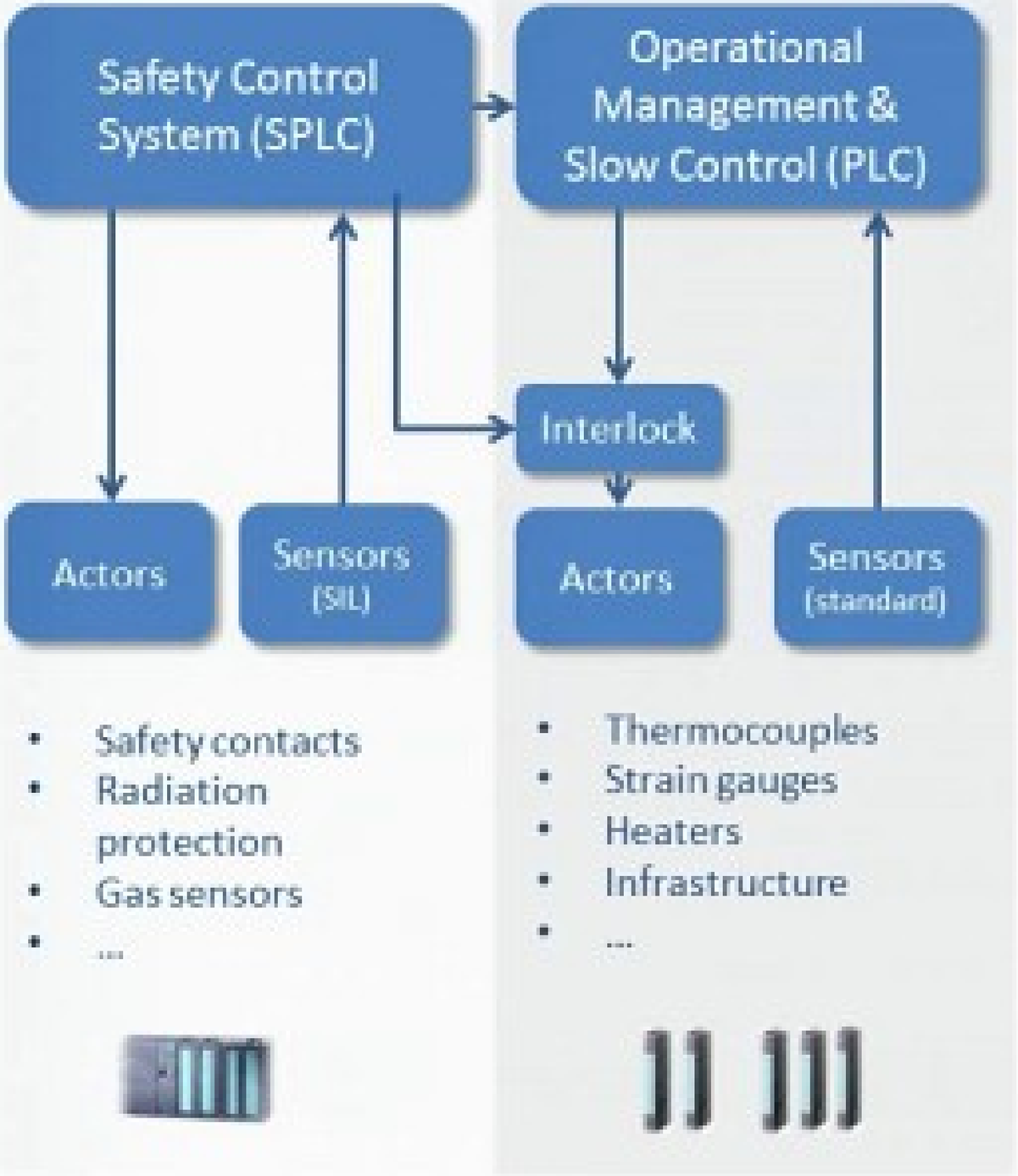
safe, slow → experimental, fast



- Safety contacts
- Radiation protection
- Gas sensors
- ...

Hierarchical Control System for W7-X

safe, slow → experimental, fast



Hierarchical Control System for W7-X

safe, slow → experimental, fast

Safety Control System (SPLC)

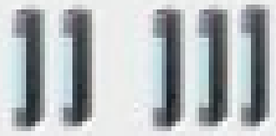
- Actors
- Sensors (SIL)

- Safety contacts
- Radiation protection
- Gas sensors
- ...

Operational Management & Slow Control (PLC)

- Interlock
- Actors
- Sensors (standard)

- Thermocouples
- Strain gauges
- Heaters
- Infrastructure
- ...



Plasma Control System (RTOS) (High Performance DAQ + Control)

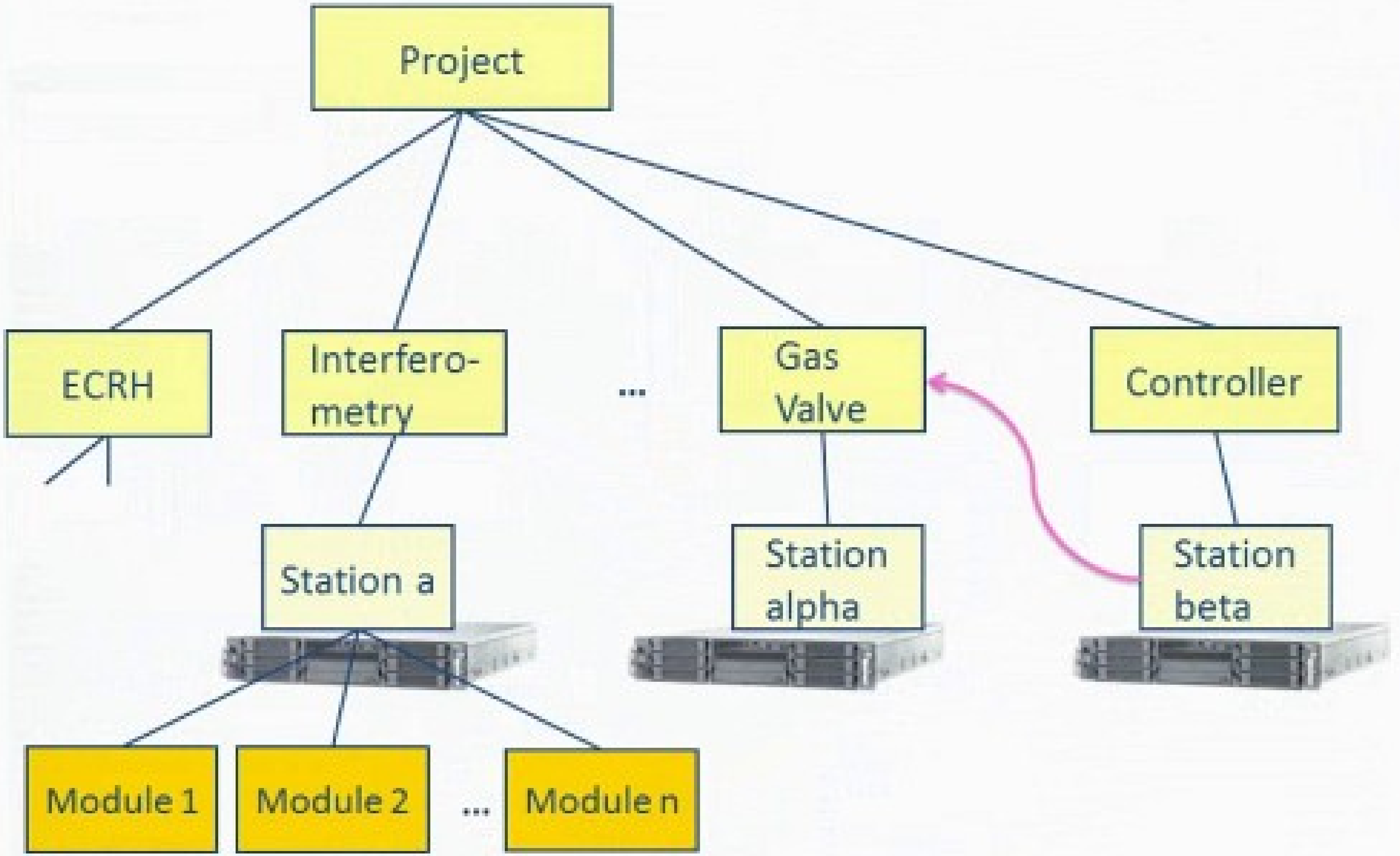
RT cycle 1ms

30 Gbyte/s continuous

- Interlock
- Actors
- Sensors (standard + intelligent)

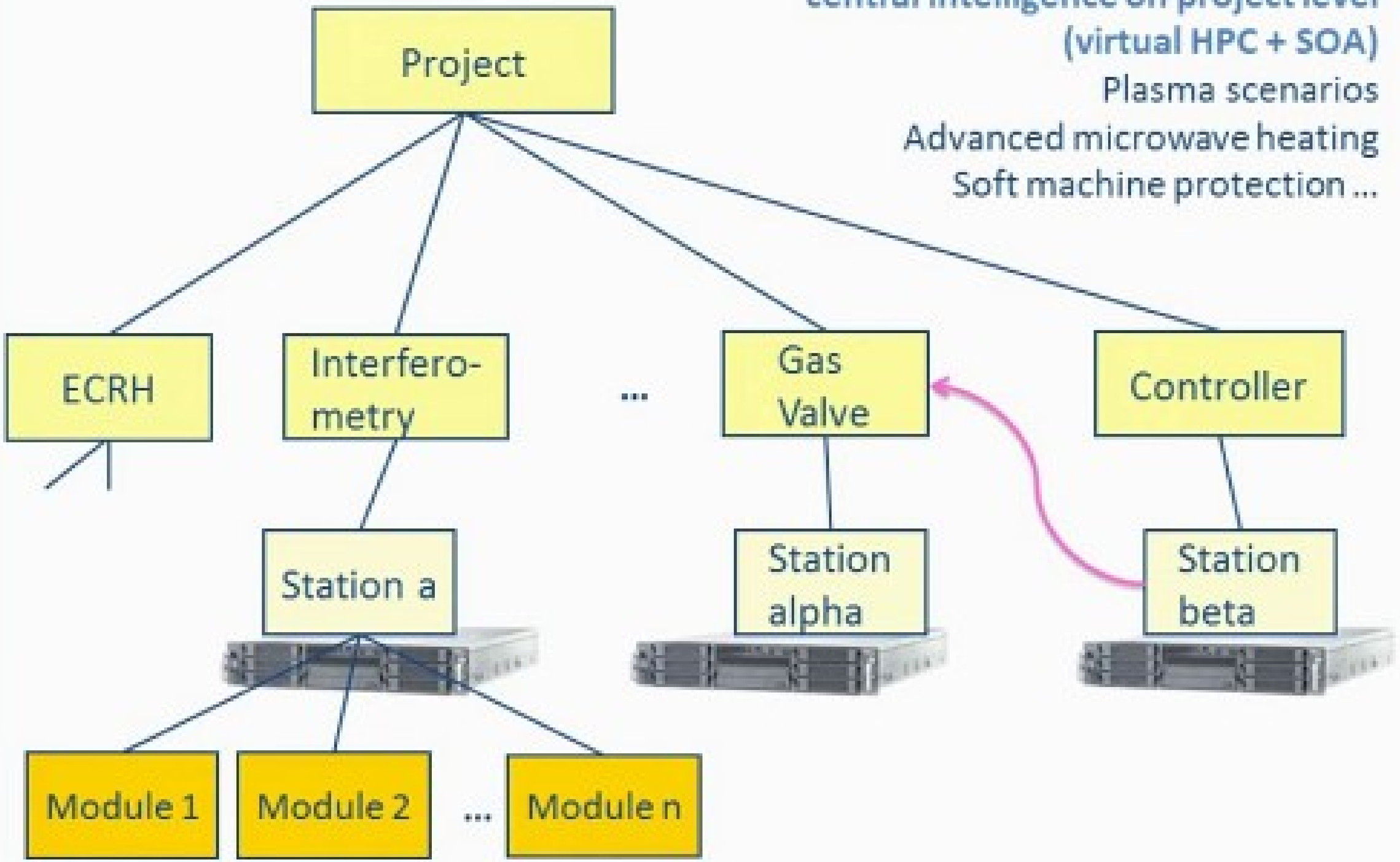
- ADC (<5 MSPS)
- DAC (<1 MSPS)
- Video/IR cameras
- (automatic region of interest, hot spot detection, safety signals)
- FPGA based systems for real time analysis and reaction (100 MSPS)

Distributed Control System



Distributed Control System

central intelligence on project level
(virtual HPC + SOA)
Plasma scenarios
Advanced microwave heating
Soft machine protection ...



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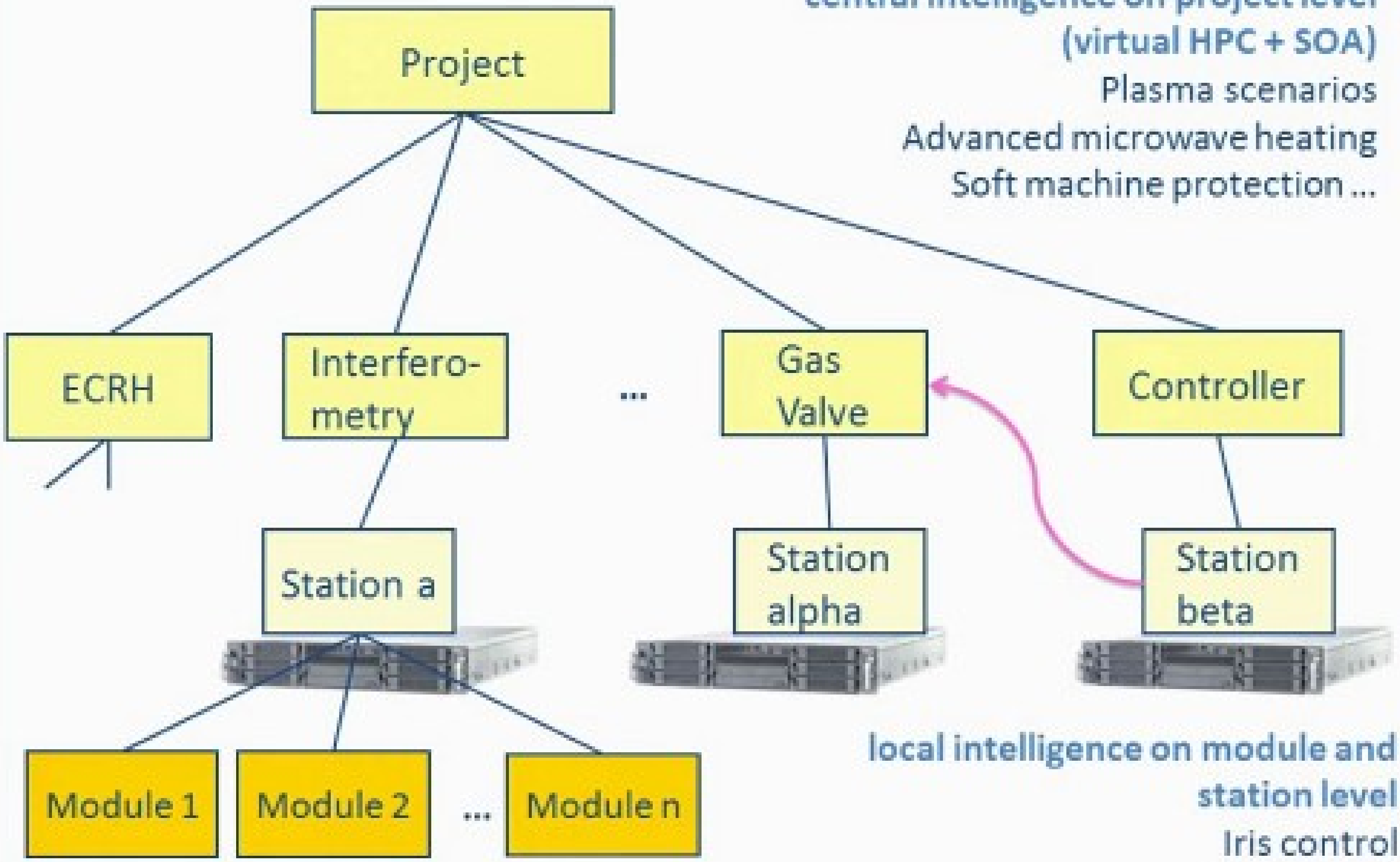


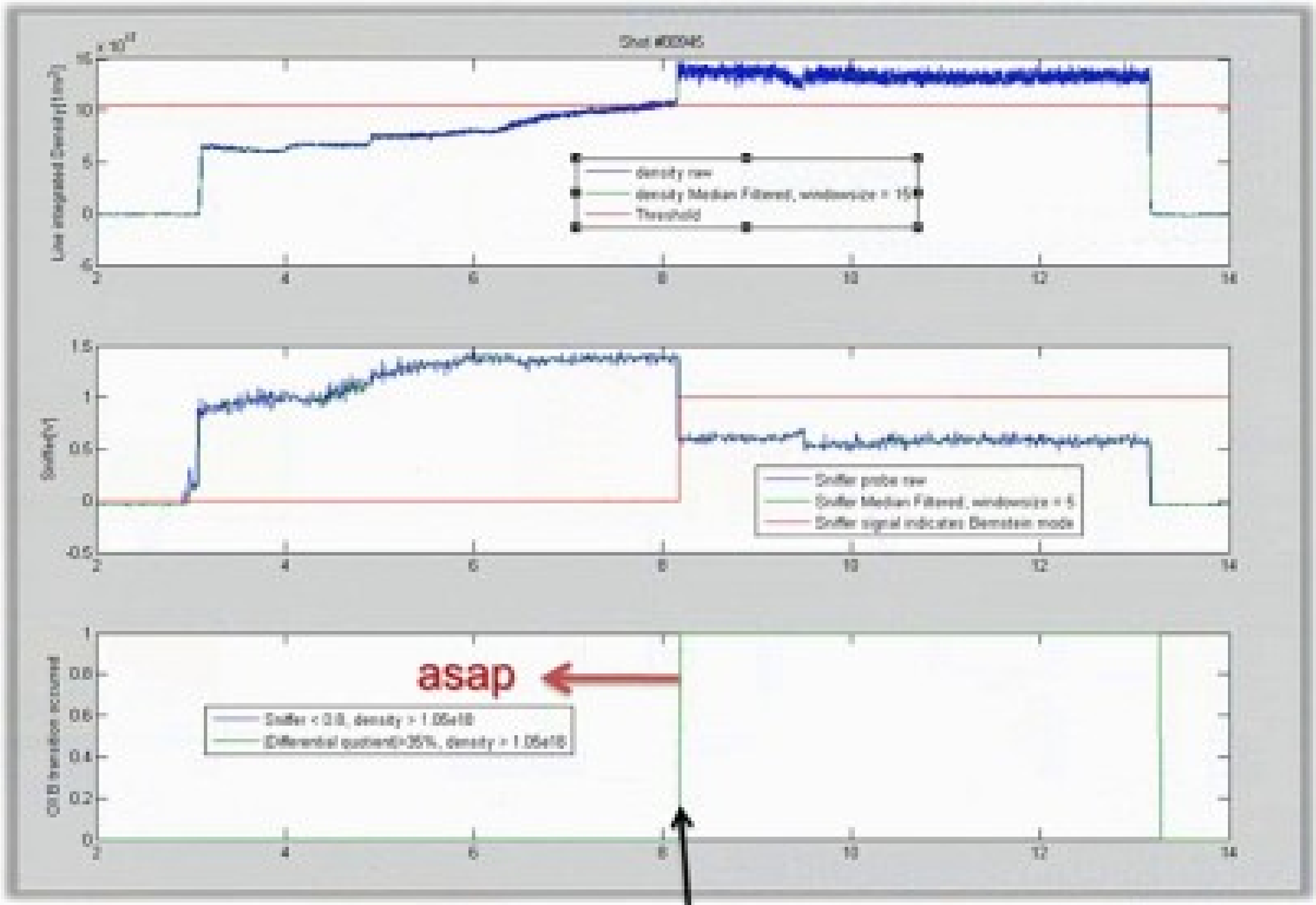
local intelligence on module and station level
Iris control
Ion current
Mirror control ...

Control System Reacting on Plasma States

At WEGA, density rises with power

μWave stray radiation drops in Bernstein wave heating scenario

Combined signal by stray radiation and density



Magnetron + Gyrotron heating

Segment switch by Plasma state

Gyrotron heating, central deposition only

How to obtain certain information ...

... from uncertain sensor data?

Many sensors depend in multiple plasma parameter

Make use of it!

⇒ Combined modeling, plasma and diagnostic physics
⇒ In general inversion of non-linear problems for data analysis
⇒ Inclusion of uncertainties and application of Bayes theorem

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$$p(n_e, T_e, P_i)$$

Prior probability of plasma Parameter ($T_e > 0$, $n_e < 10^{21}$ m^{-3})

$$p(Data|n_e, T_e, P_i)$$

Likelihood of diagnostic data for given plasma parameter

How to obtain certain information ...

... from uncertain sensor data?

Many sensors depend in multiple plasma parameter

Make use of it!

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$p(n_e, T_e, P_i)$

Prior probability of plasma Parameter ($T_e > 0$, $n_e < 10^{21}$ m^{-3})

$p(Data|n_e, T_e, P_i)$

Likelihood of diagnostic data for given plasma parameter

$p(n_e, T_e, P_i|Data) = ?$

How to obtain certain information ...

... from uncertain sensor data?

Many sensors depend in multiple plasma parameter

Make use of it!

⇒ Combined modeling, plasma and diagnostic physics
⇒ In general inversion of non-linear problems for data analysis
⇒ Inclusion of uncertainties and application of Bayes theorem

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Prior probability of plasma Parameter ($T_e > 0$, $n_e < 10^{21}$ m^{-3})

$p(Data|n_e, T_e, P_i)$

Likelihood of diagnostic data for given plasma parameter

$$p(n_e, T_e, P_i|Data) = ?$$

$$= \frac{p(n_e, T_e, P_i)\, p(Data|n_e, T_e, P_i)}{p(Data)}$$

Inversion by **Bayes Theorem**

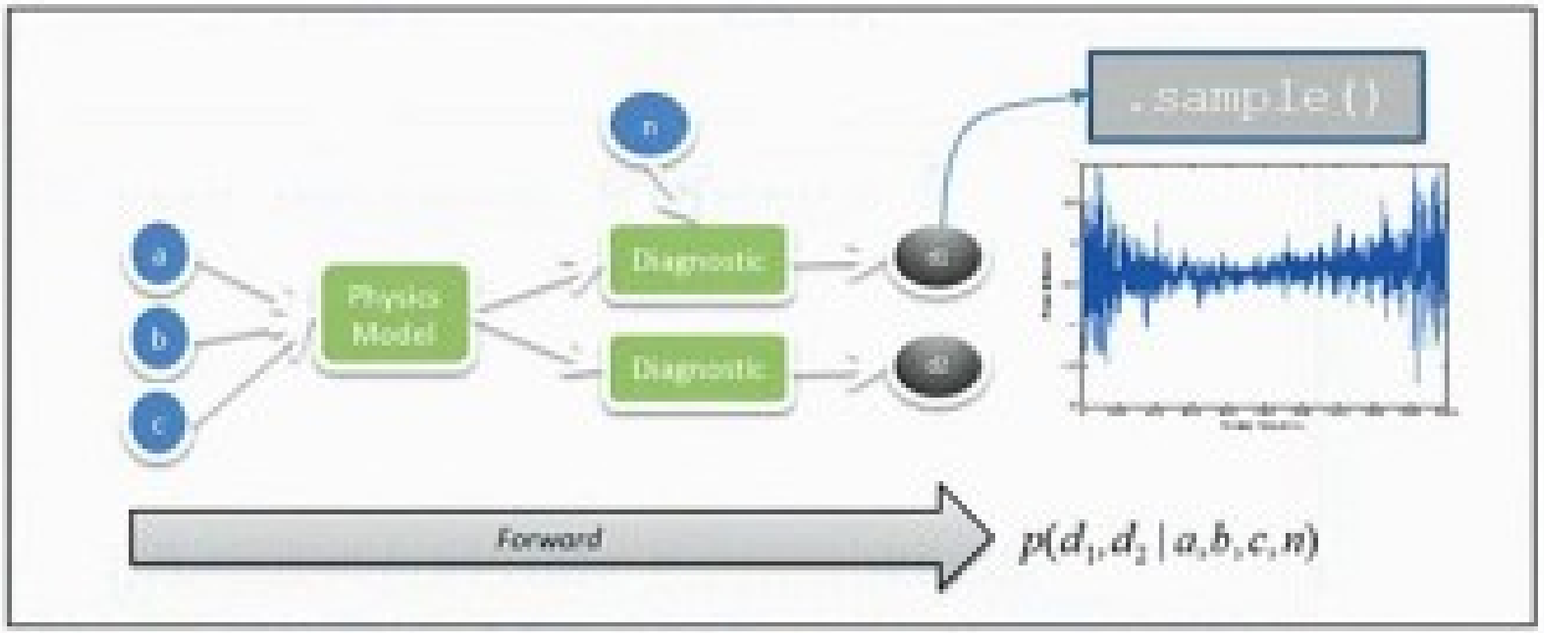
Bayesian Modeling with Seed Minerva

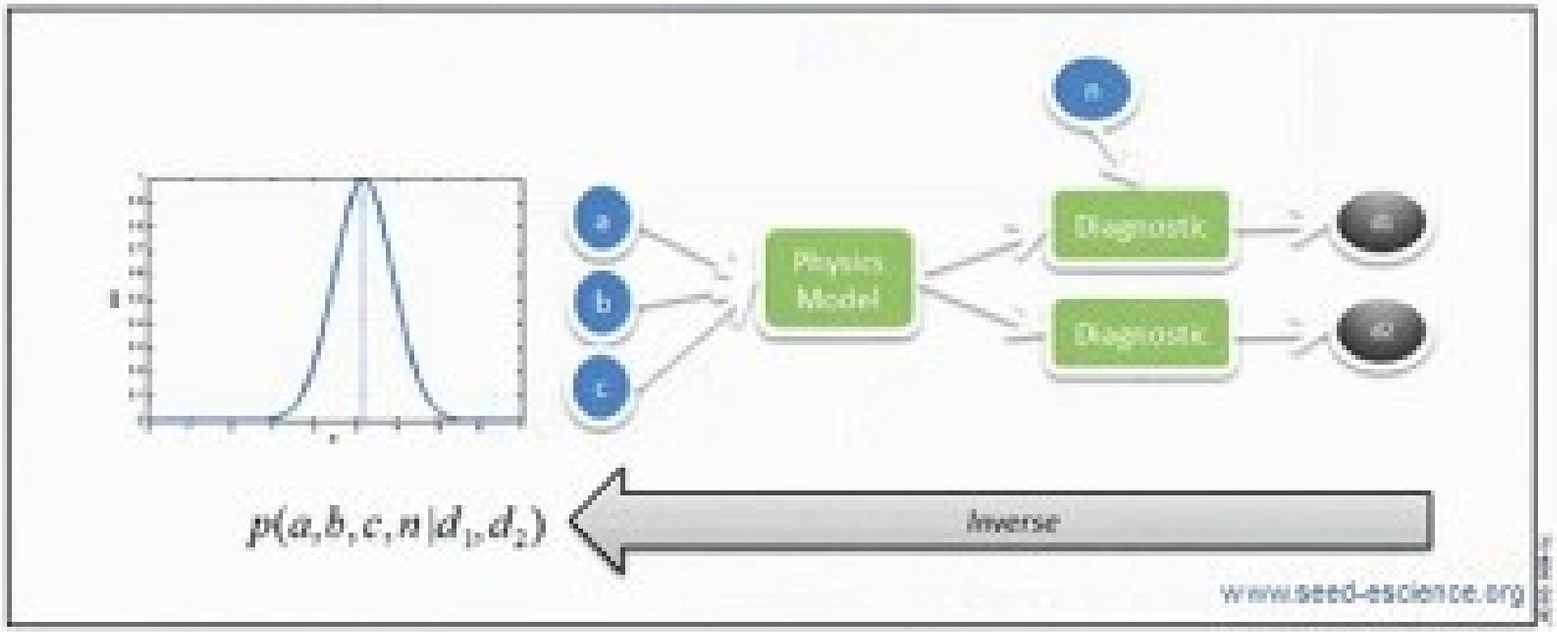
Graph theory + Bayesian statistical models

Setup of a (complete, nonlinear) model including uncertainties

Prediction of sensor data

Application of inversion methods with measured data





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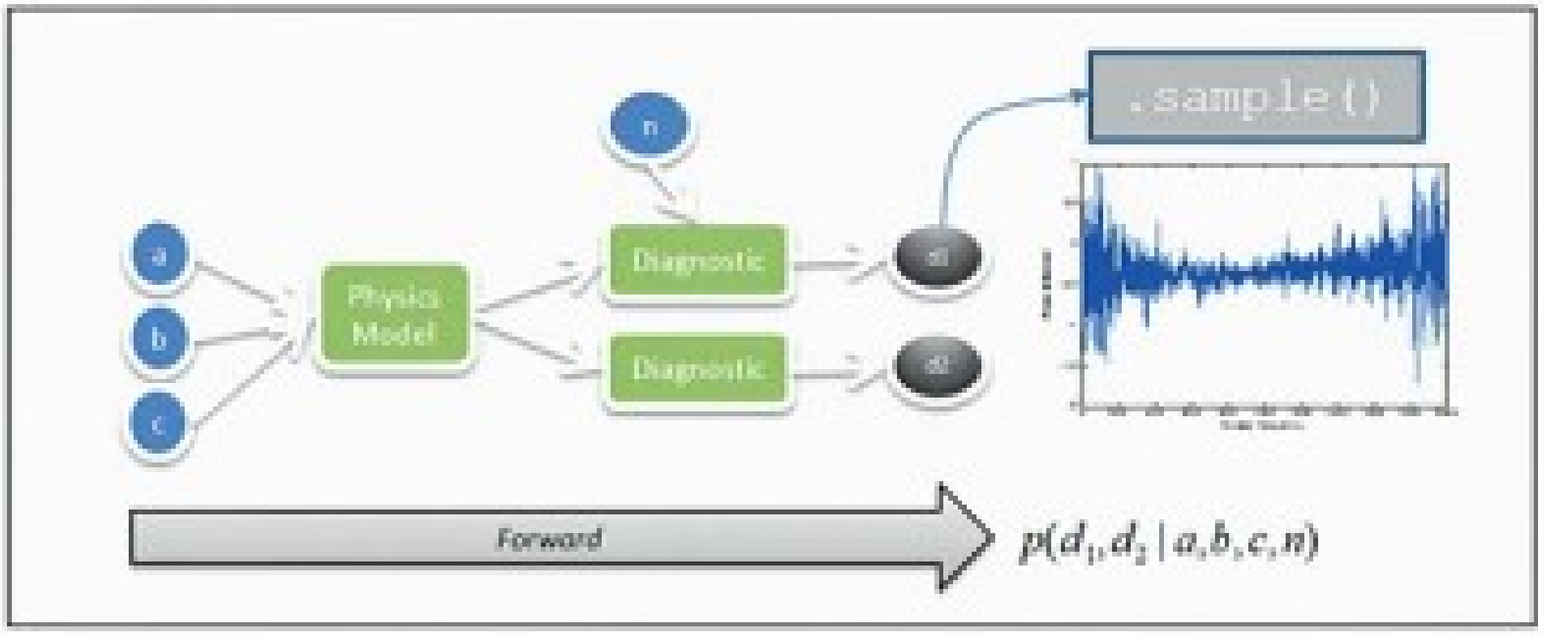
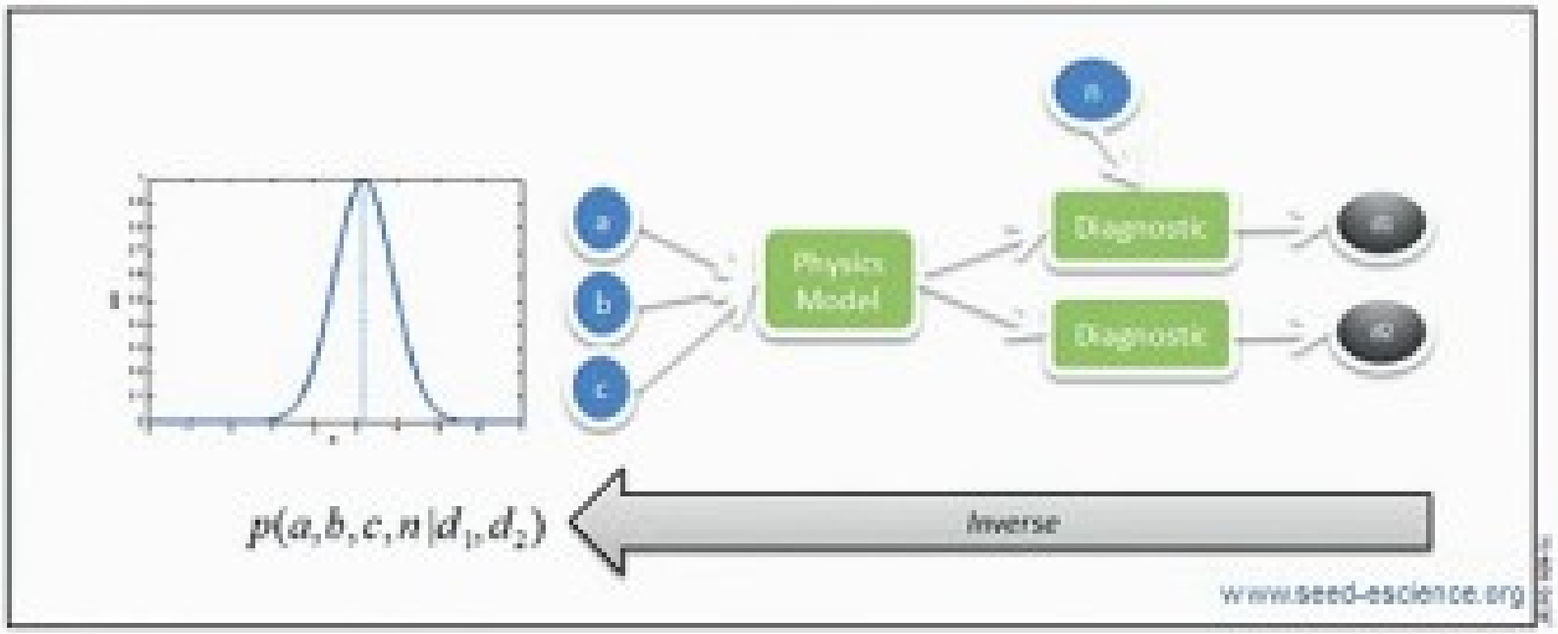
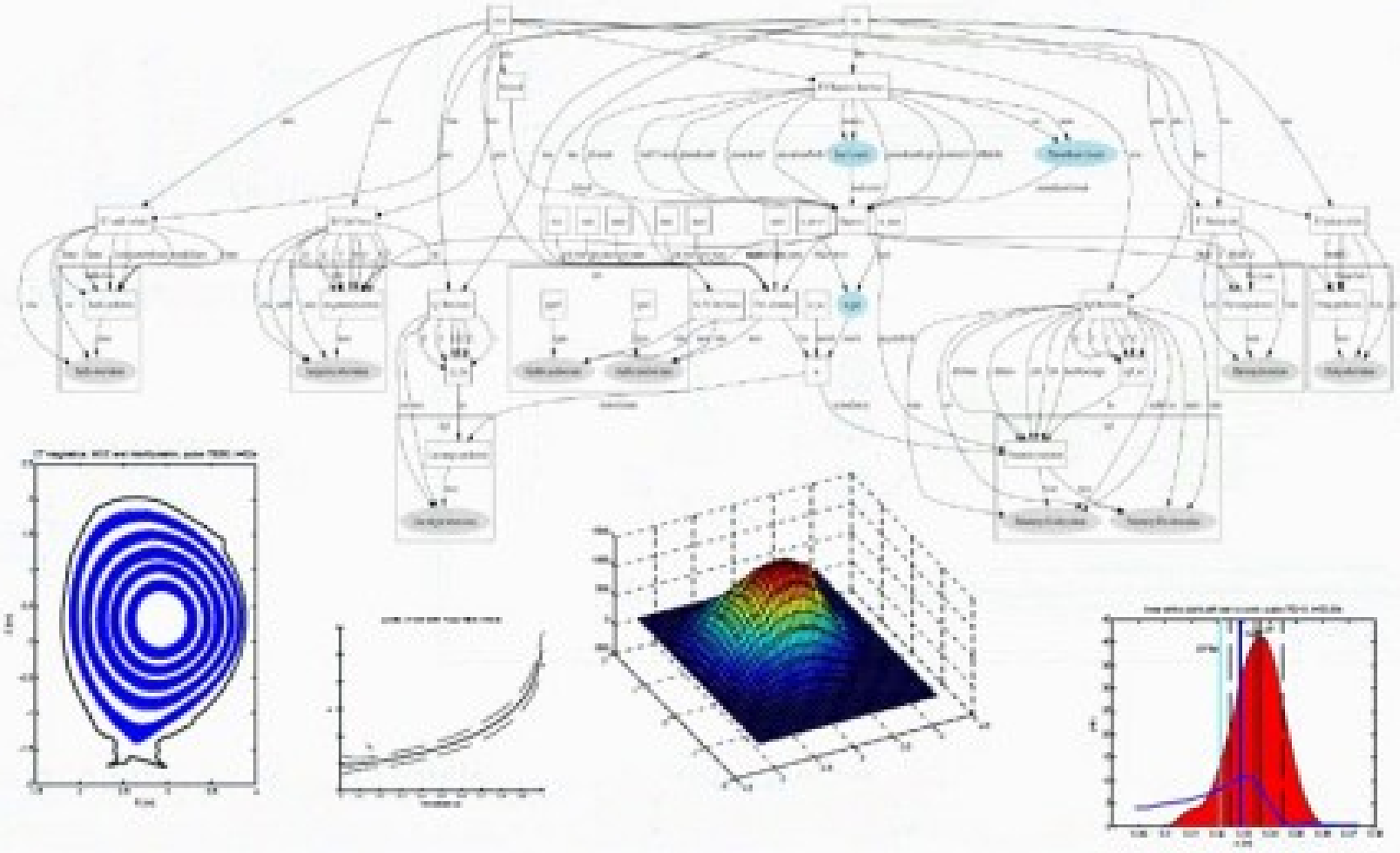




Improved inference by considering all measurements!
=> Better automated data analysis and, consequently, better plasma control

Example6: Current tomography+interf.+polarim+MSE+IR cameras

seed

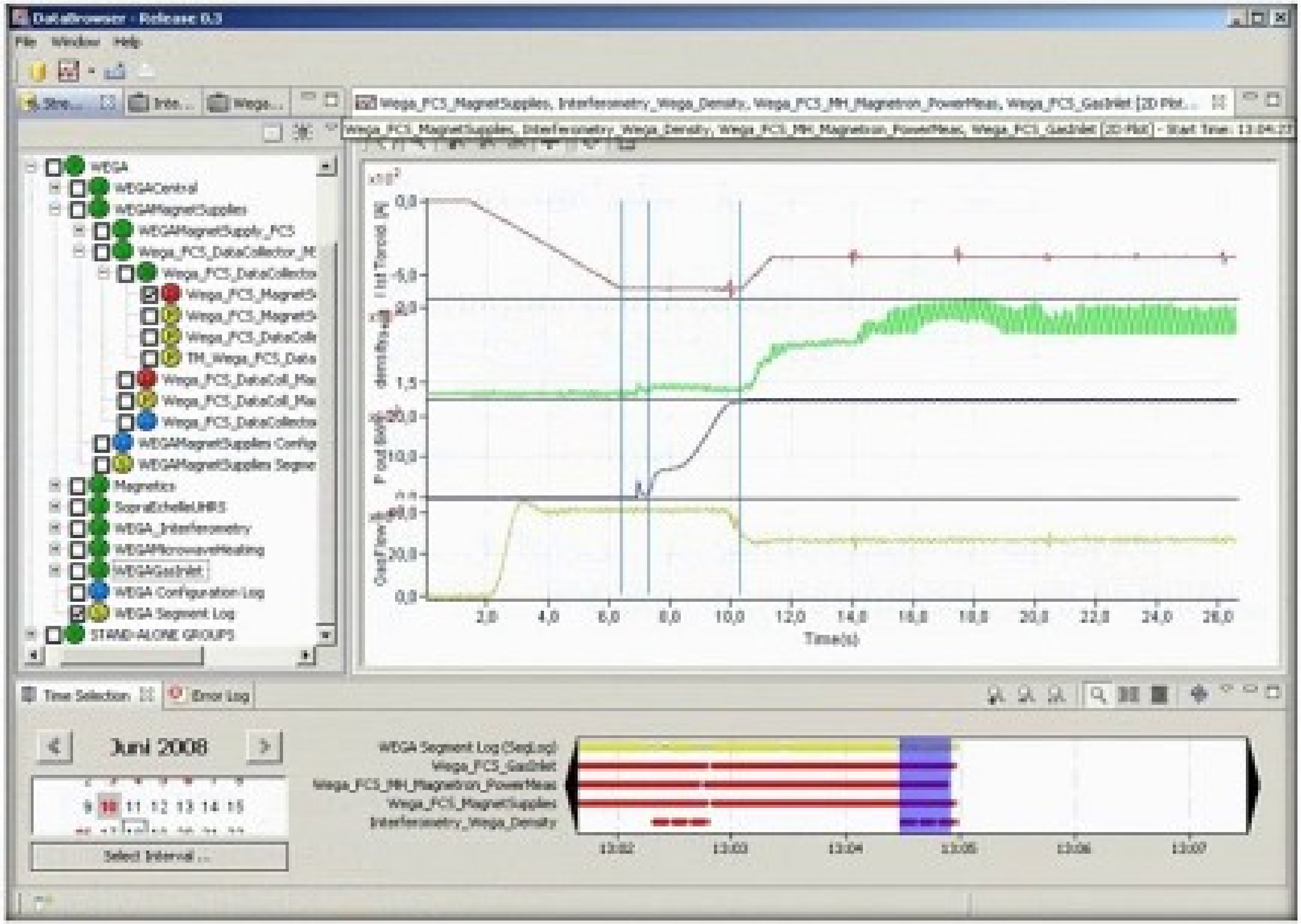


W7-X Software

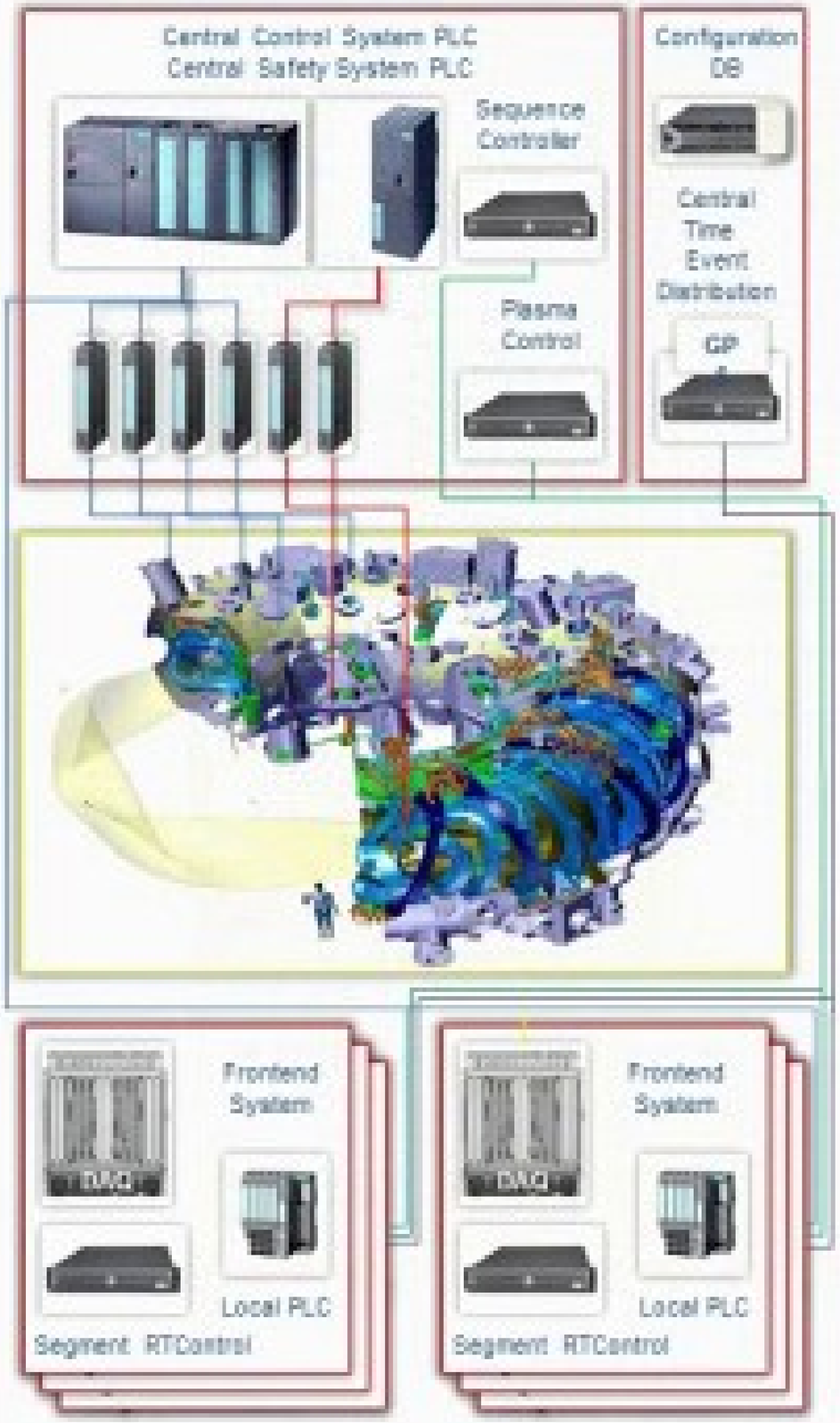
Fast Control Station	Real time (1ms cycle) control system
CoDaStation	High performance data acquisition software
Xedit, Xcontrol	Experiment planning and execution
ConfigDB	Configuration database for hardware description
Archive DB	Arching of experiment data, Pbyte class
DataBrowser, Monitor	Viewing of data
SOA	WSO_2 based, scientific (stateful) services for petri net like analyses/models and parallelisation
...	

- Languages mainly Java, C, C++, C#, Fortran
- Software development process close to SPICE
- Agile software project management
- Eclipse RCP for applications, OSGi bundles for base software

W7-X Software Example: DataBrowser



W7-X Hardware



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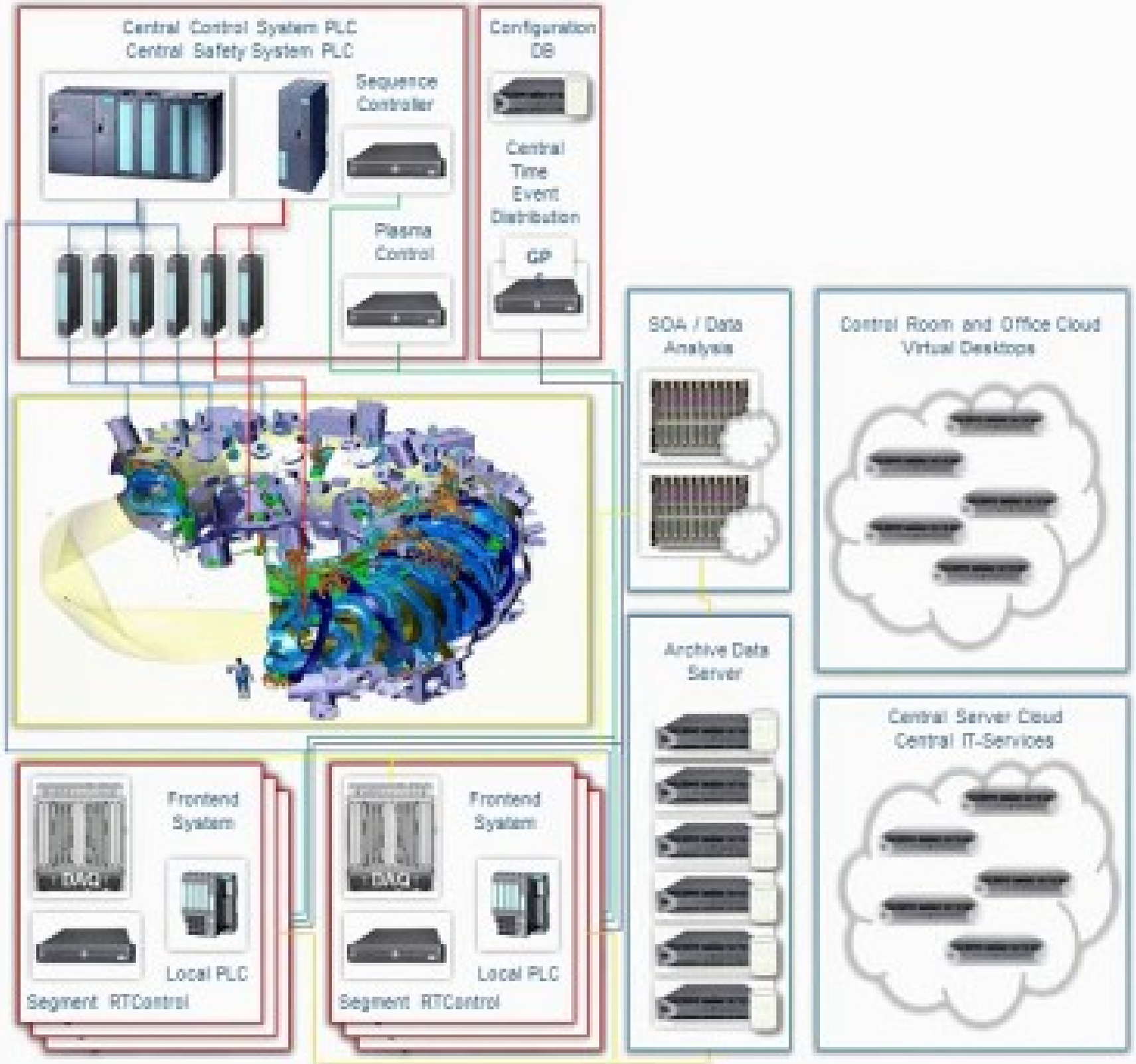

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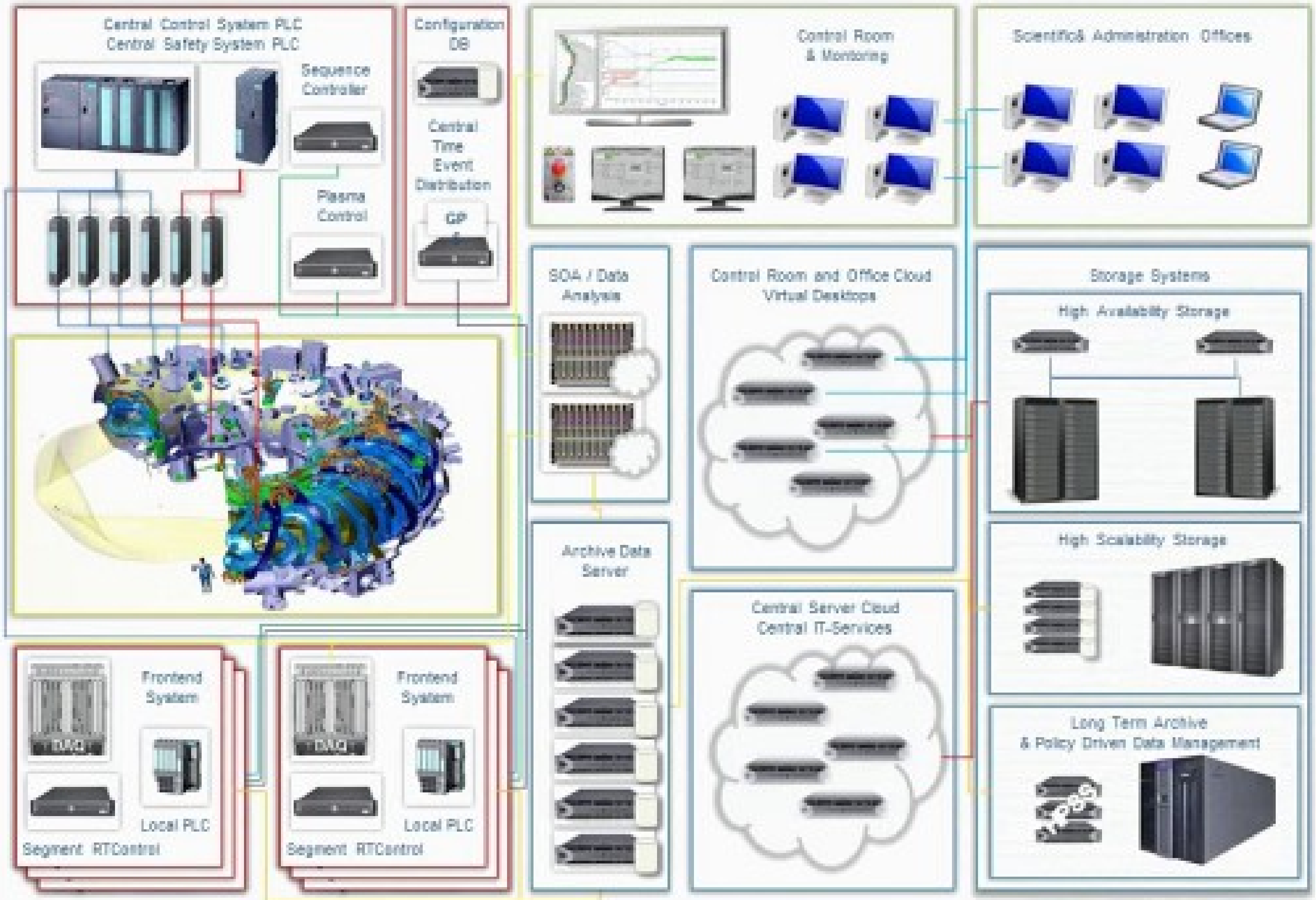

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- Application of Bayesian modeling for deriving **certain information** out of (many) **uncertain sensor data**!