Caracterización de plasmas termonucleares en reactores de fusión: Diagnósticos en JET y herramientas de análisis.

by <u>Andrea Murari</u>

Many thanks to the Associations because JET diagnostics are a real collective effort in Europe.

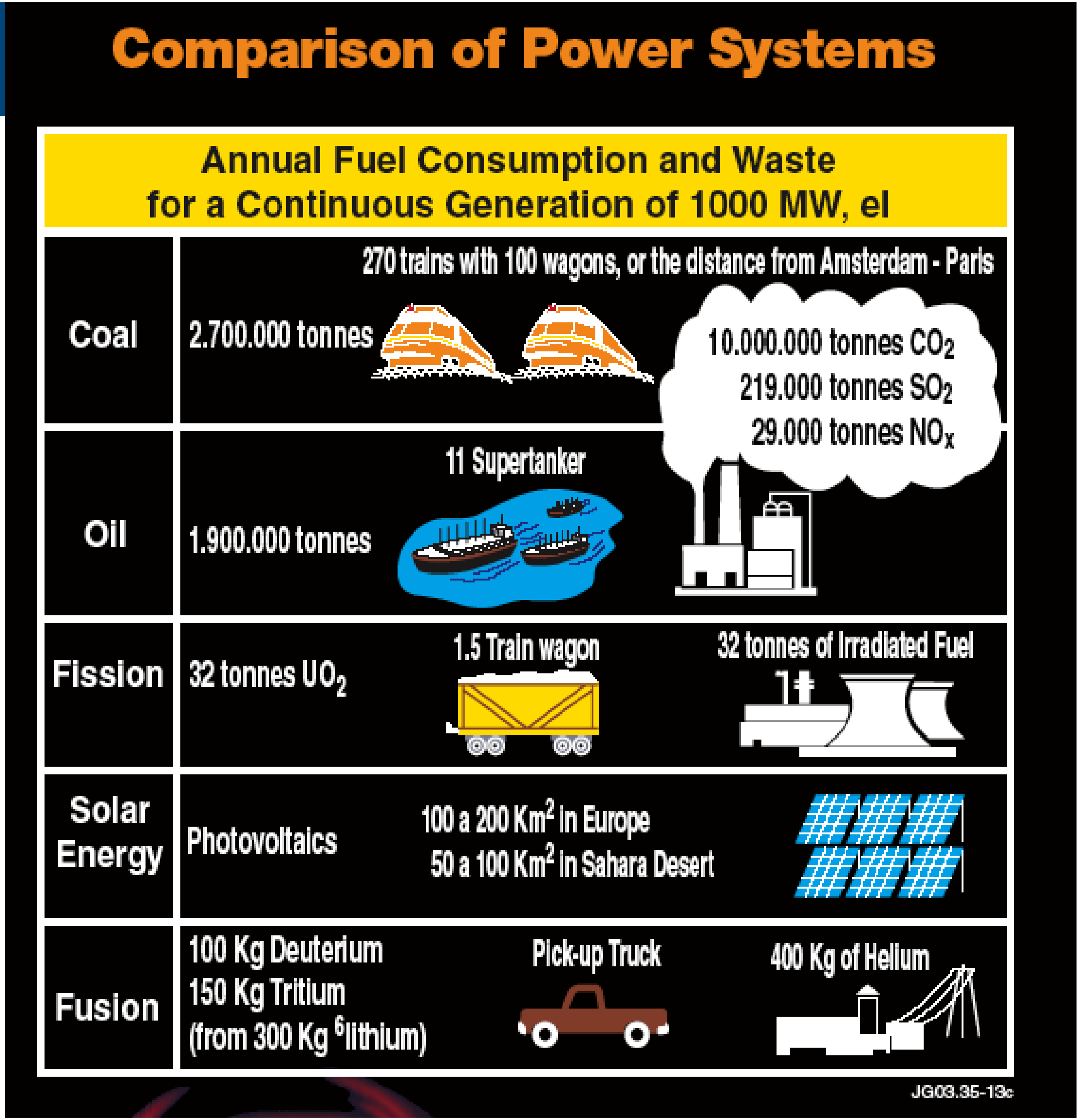
Why fusion?

Most exoenergetic reaction in the known universe

Highest power density per Kg

Lowest emission of greenhouse gases

Technically safe



Comparison of Power Systems

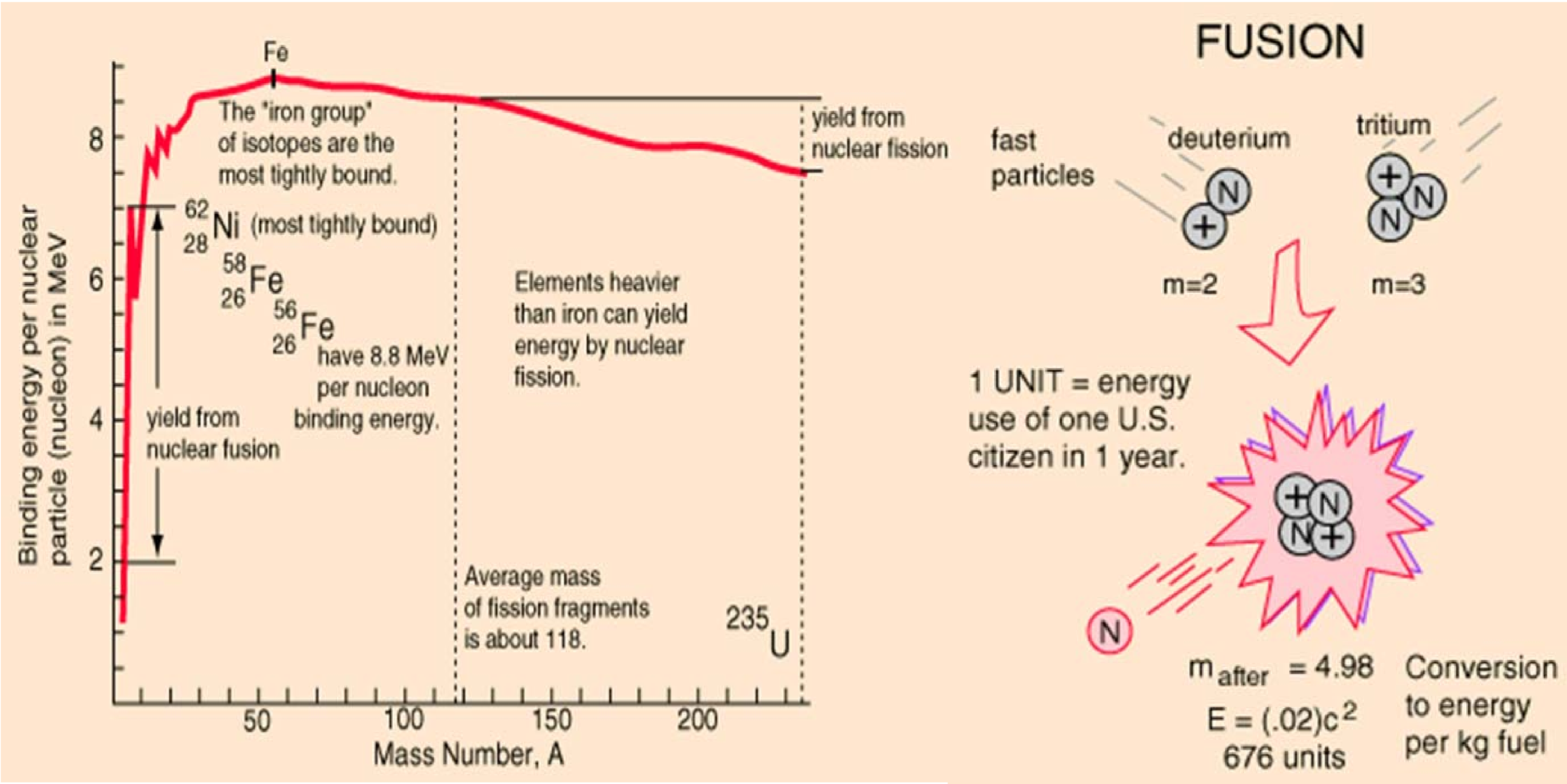
Annual Fuel Consumption and Waste for a Continuous Generation of 1000 MW, el

Coal	2.700.000 tonnes	270 trains with 100 wagons, or the distance from Amsterdam - Paris	10.000.000 tonnes CO_2 219.000 tonnes SO_2 29.000 tonnes NO_x
Oil	1.900.000 tonnes	11 Supertanker	
Fission	32 tonnes UO_2	1.5 Train wagon	32 tonnes of Irradiated Fuel
Solar Energy	Photovoltaics	100 a 200 Km^2 in Europe 50 a 100 Km^2 in Sahara Desert	
Fusion	100 Kg Deuterium 150 Kg Tritium (from 300 Kg ^{6}lithium)	Pick-up Truck	400 Kg of Helium

JG03.35-13c

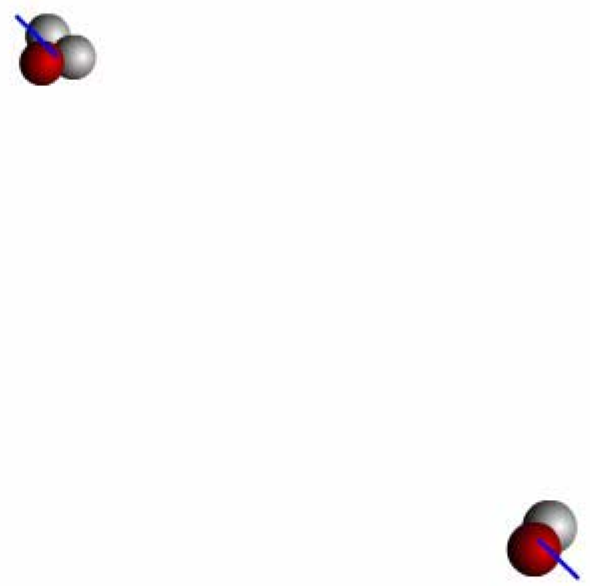
The fusion process

Light nuclei fuse into heavier nuclei

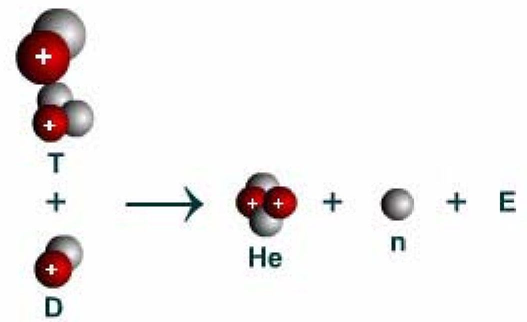


Fusion products; 14.1 MeV neutron and 3.5 MeV alpha particle

Fusion collisions



Collision without fusion reaction (electromagnetic forces prevail)



Collision with fusion reaction (strong interaction prevail)

For the nuclei to get close enough to fuse they have to overcome the Coulomb barrier.

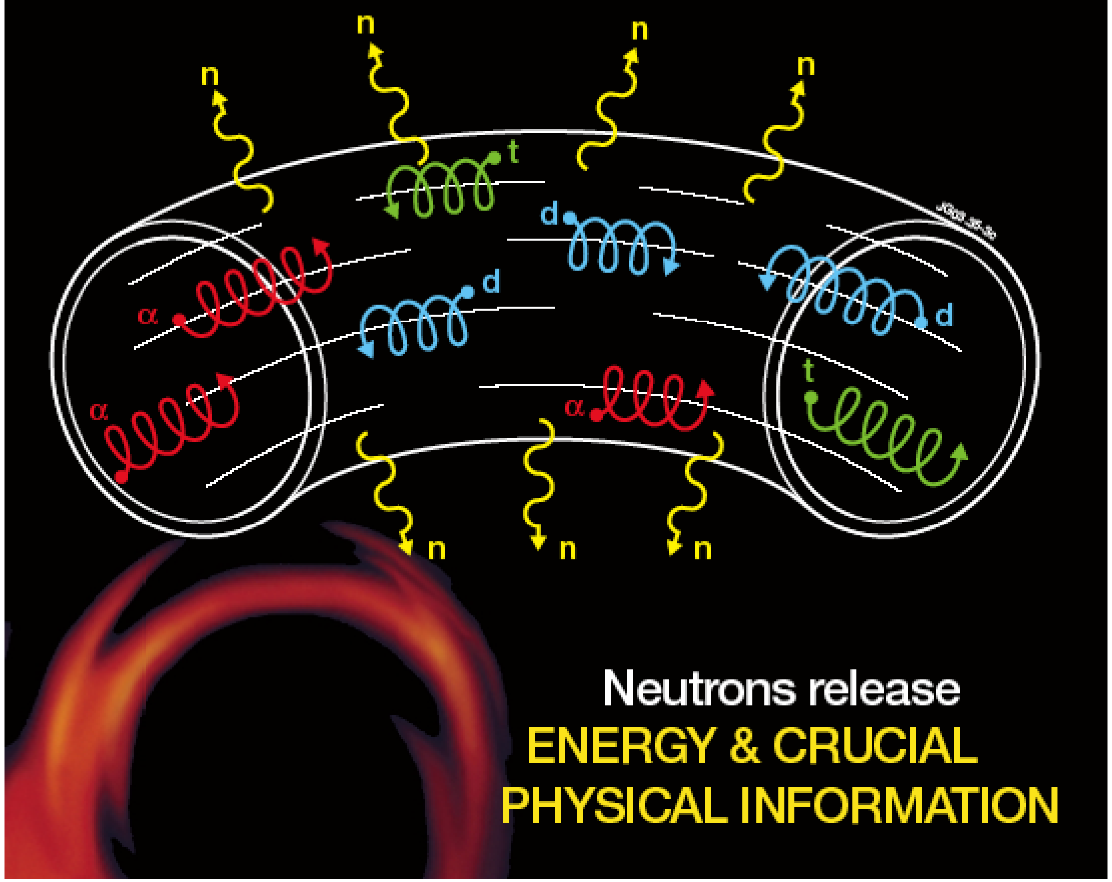
To achieve this an alternative are hot plasmas: a <u>plasma is a ionised gas</u> (ions and electrons are separated)

For fusion to be an energy source, a <u>hot</u> and <u>dense</u> fuel plasma must be confined in a tight volume for long times...

➔"Magnetic bottle"

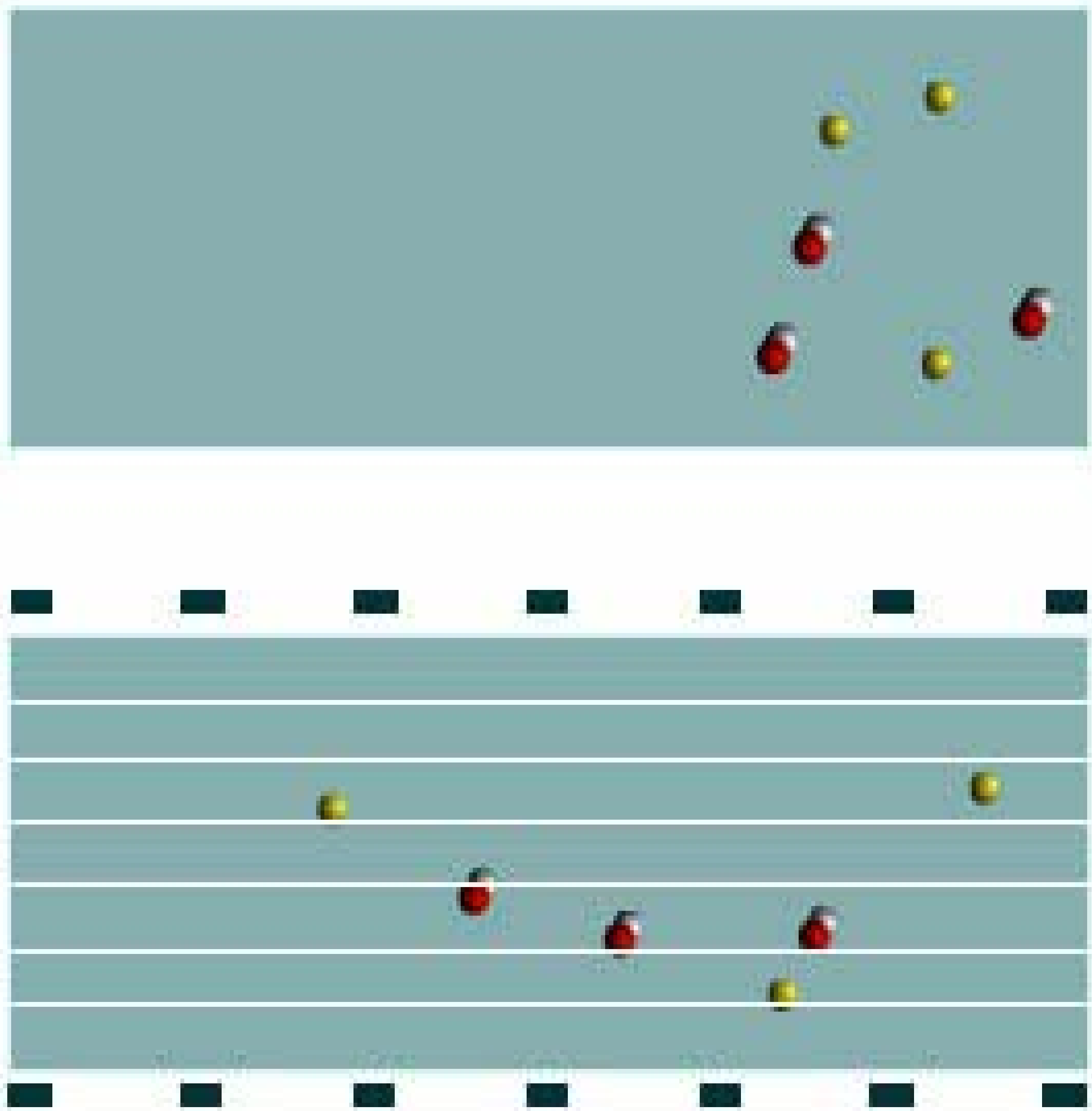
Principle of Energy Production with Magnetic Fusion

- Magnetic fields cause charged particles to spiral around field lines.
- Toroidal (ring shaped) device: a closed system to avoid end losses
- The most successful Magnetic Confinement device is the TOKAMAK (Russian for 'Toroidal Magnetic Chamber')

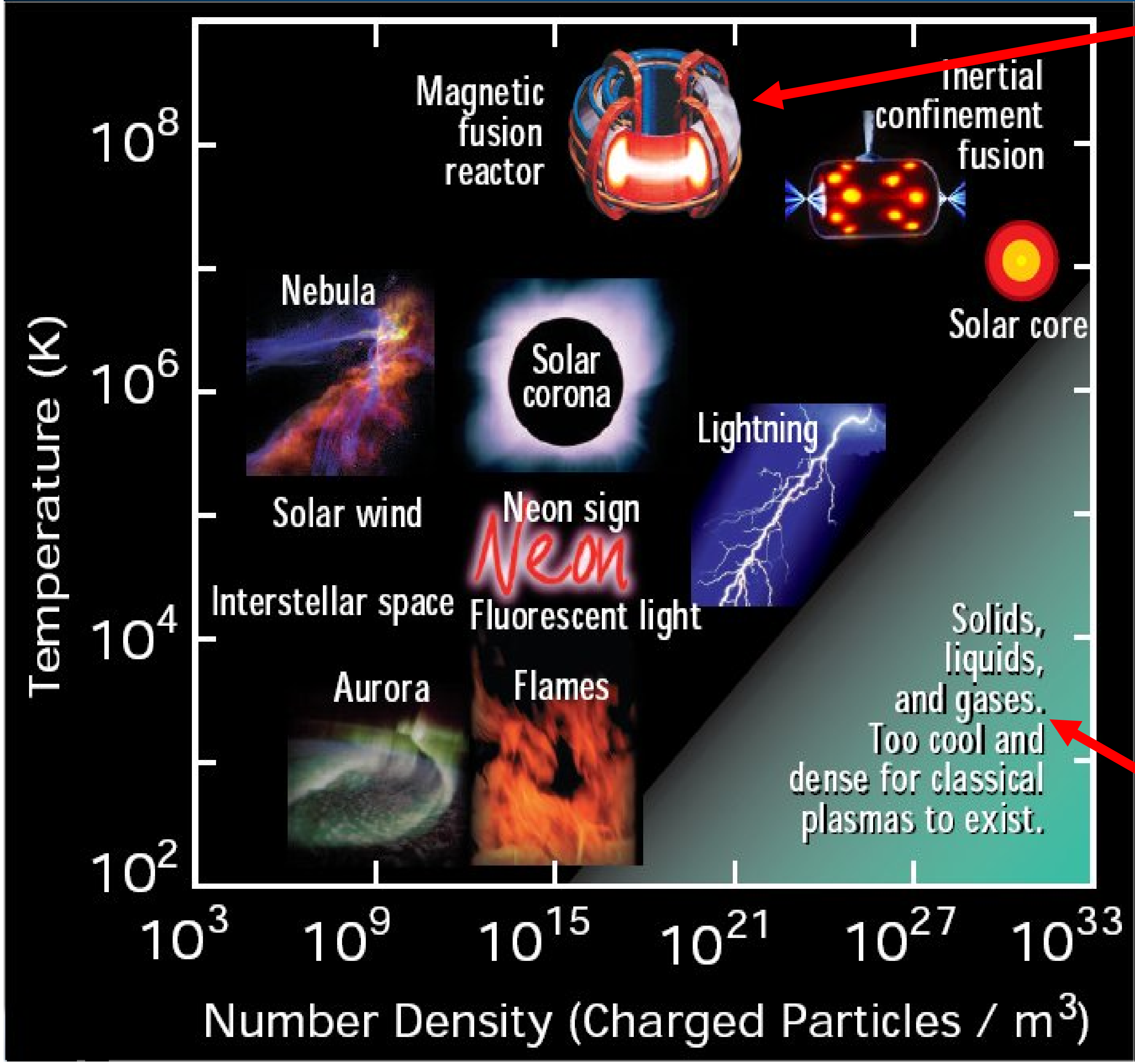


Magnetic confinement

The magnetic field (in reality the magnetic pressure), represented by horizontal white lines, reduces the random motion of the particles and confines the plasma (in the direction perpendicular to the magnetic field lines).



Parameters of Fusion Plasmas

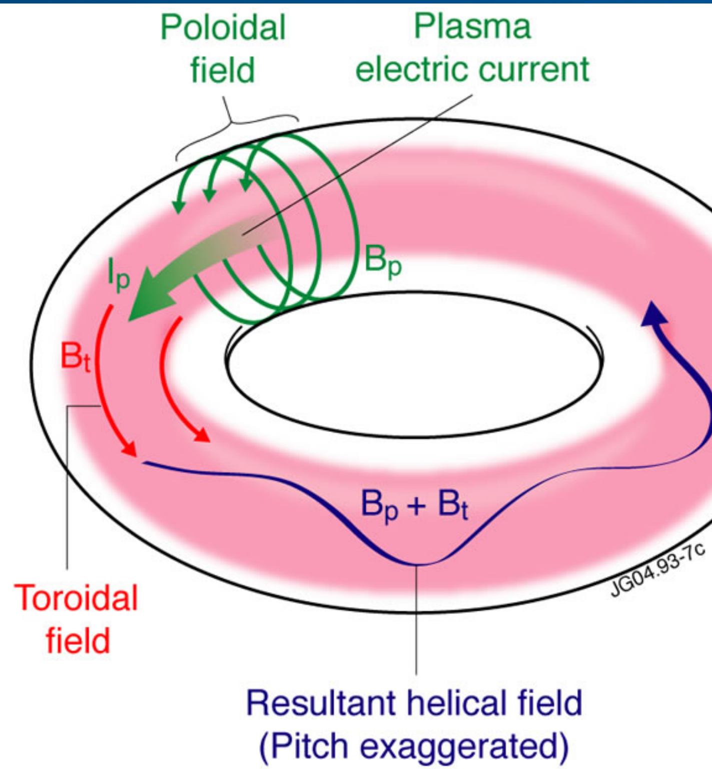


Magnetic fusion plasmas have temperature and pressure higher than the solar corona and temperature one order of magnitude higher than the Sun core

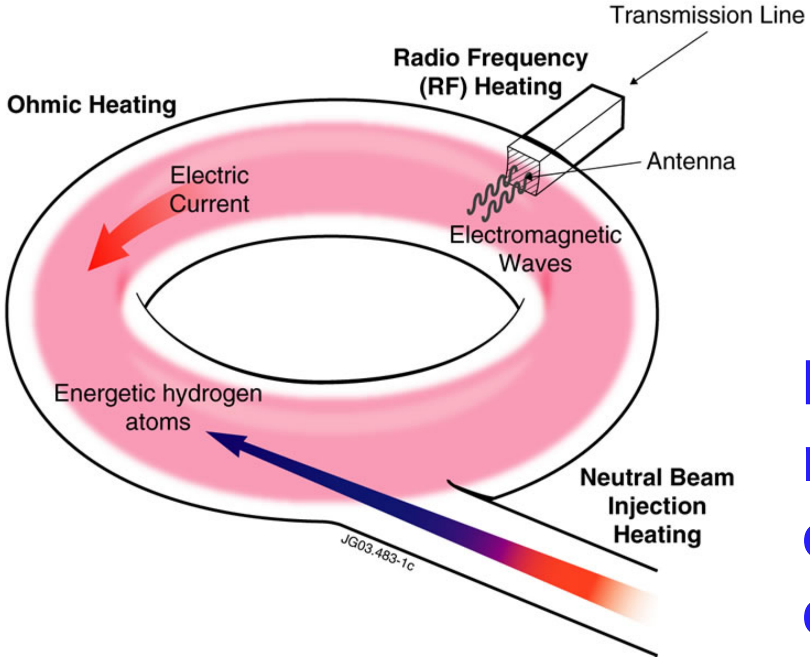
Region of Quantum plasmas

Tokamak overview

Magnetic field configuration



Heating schemes

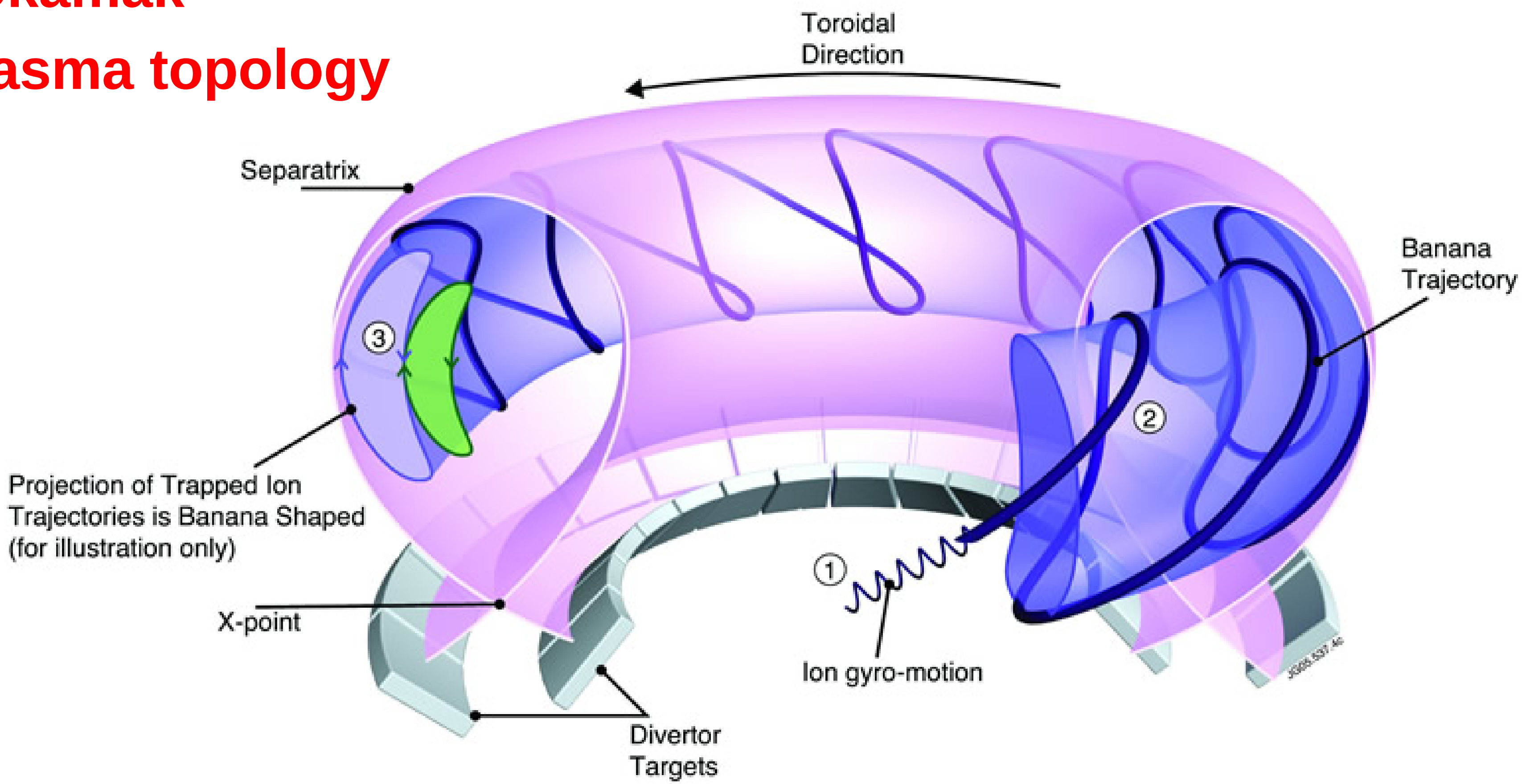


Fusion products. 14.1 MeV neutrons to provide the energy output. 3.5 MeV alpha particles confined to keep the plasma hot

Plasma current: at present generated inductively

Tokamak Plasma Overview

Tokamak plasma topology



The plasma has an elongated cross section to improve confinement. The divertor is the part of the device explicitly designed to cope with he energy and particle exhaust. The particles follow complicated orbits.

Challenges for continuous operation

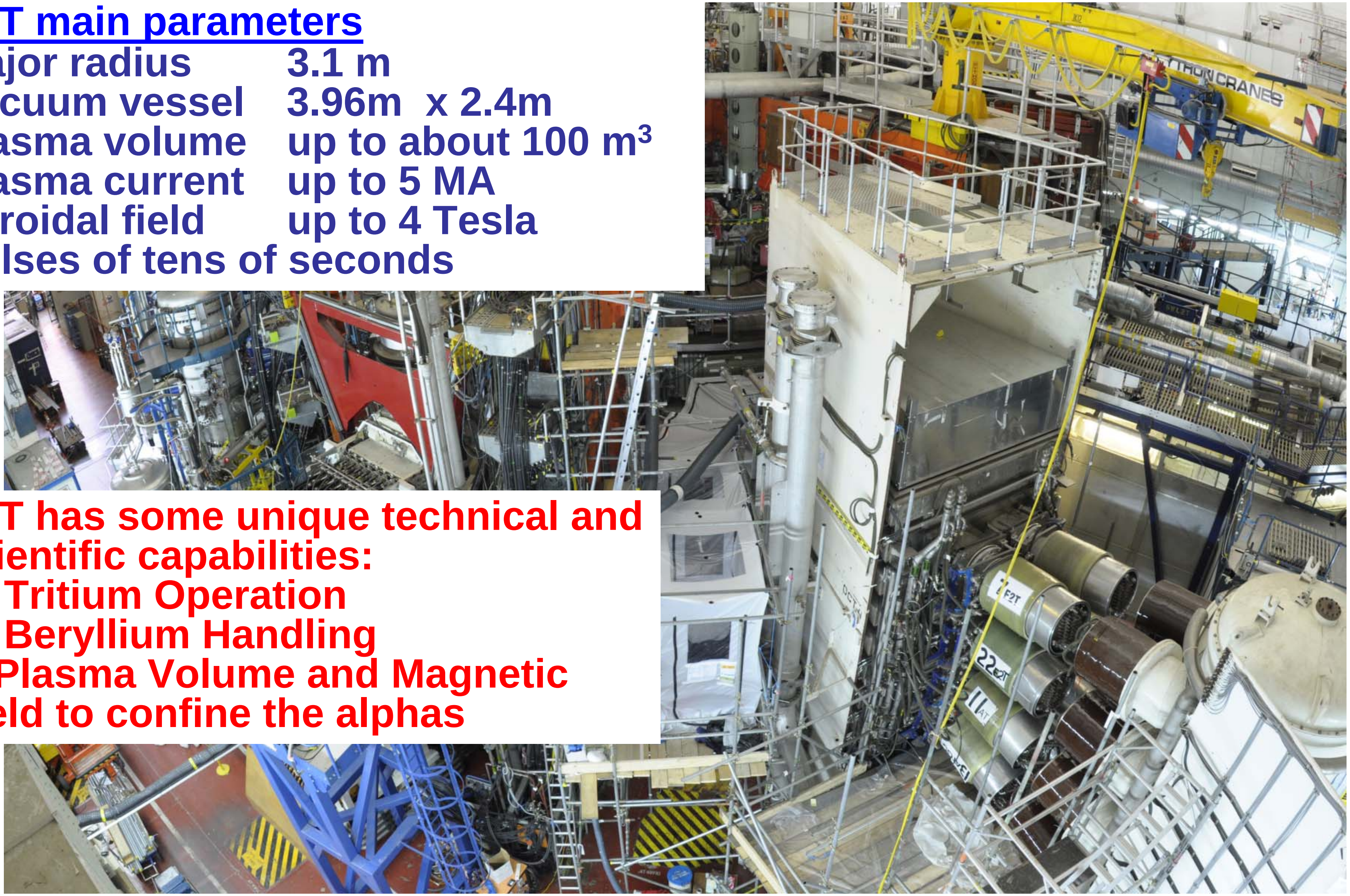
P_{fusion}/P_{add}	Q ~ 0	Q ~ 1	Q ~ 0	Q ~ 10	Q ~ 30
duration	~400s	2s	~100s	400-3600s	Continuous
self-heating	0%	10%	0%	70%	80 to 90%
bootstrap	20%	20%	>60%	<50%	>60%

JET – The largest Tokamak to date

JET main parameters

Major radius	3.1 m
Vacuum vessel	3.96m x 2.4m
Plasma volume	up to about 100 m^3
Plasma current	up to 5 MA
Toroidal field	up to 4 Tesla

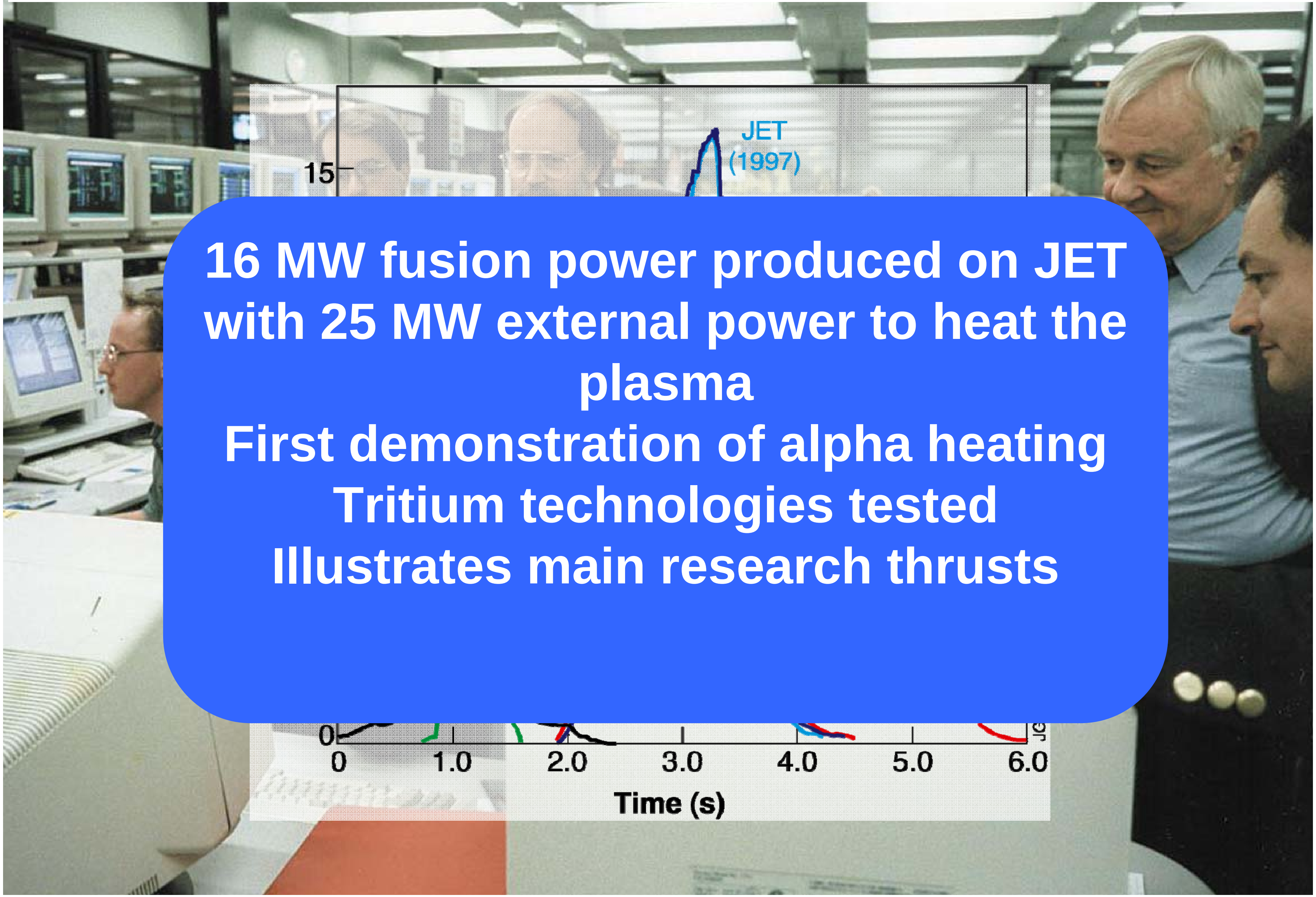
Pulses of tens of seconds



JET has some unique technical and scientific capabilities:

- Tritium Operation
- Beryllium Handling
- Plasma Volume and Magnetic Field to confine the alphas

Fusion power has been produced on JET



16 MW fusion power produced on JET with 25 MW external power to heat the plasma

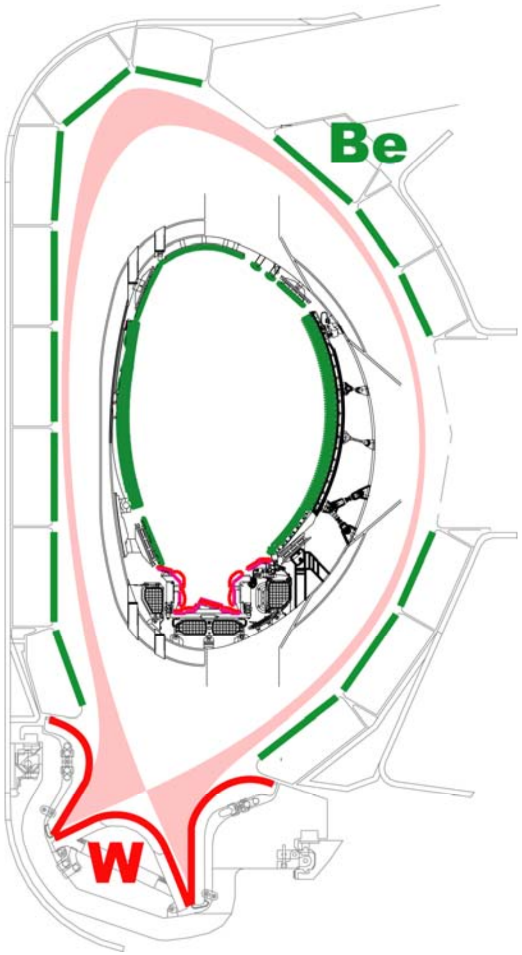
First demonstration of alpha heating

Tritium technologies tested

Illustrates main research thrusts

Tokamak plasmas as Open Systems

A Tokamak plasma is an open system fuelled by injection of both energy and mass and therefore presents all the problems of control typical of open systems.



- Input of energy and matter: fuelling and additional heating systems
- Internal Transformation: optimization of the plasma configuration to maintain the internal structure and maximise energy production.
- Elimination of the waste: power and particle exhaust.
- Contamination: Helium Ash

Issues with Control in Fusion

The control challenges in Fusion are:

- A different matter state
- Many variables (complex system)
- Nonlinear quantities (nonlinear phenomena)
- Non separability
- No theory available (no derivation from first principles)
- Poor accessibility for measurement
- Enormous amounts of information (more than 50 Gbytes/shot)

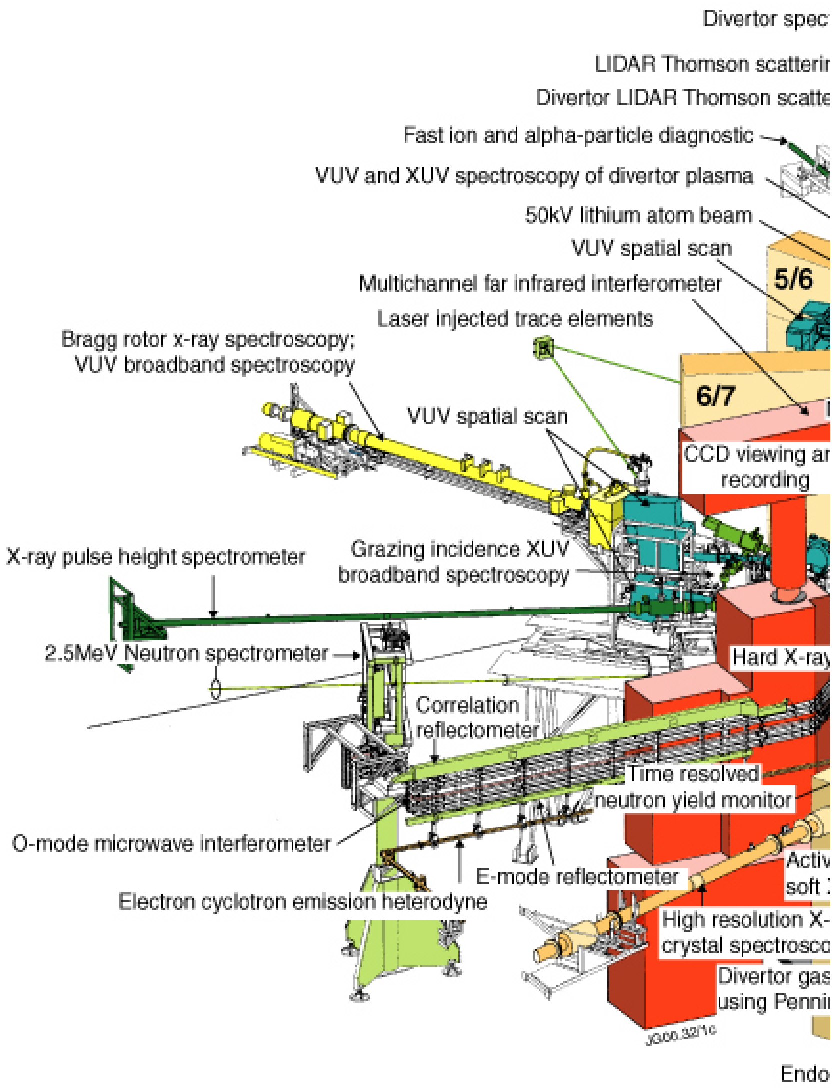
Goals of Diagnostics

- Obtain the magnetic topology (magnetic and electric fields)
- Determine the Plasma Energetic Content (Temperature and Density)
- Measure the Plasma losses (radiation, particles)
- Determine the flow and turbulence

Final goal

Measure the fusion products, neutrons and alpha particles, to control the energy production

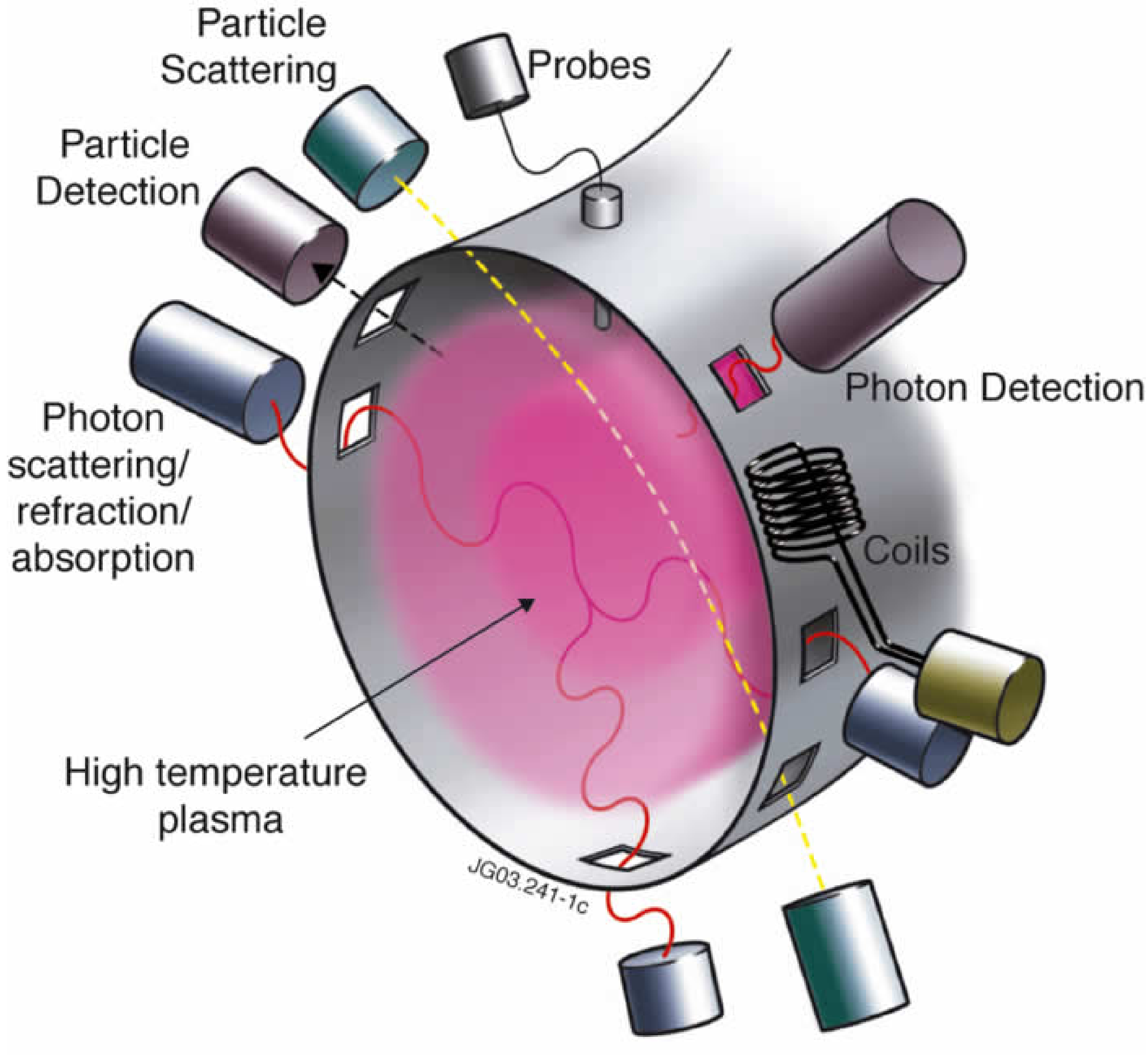
JET diagnostics



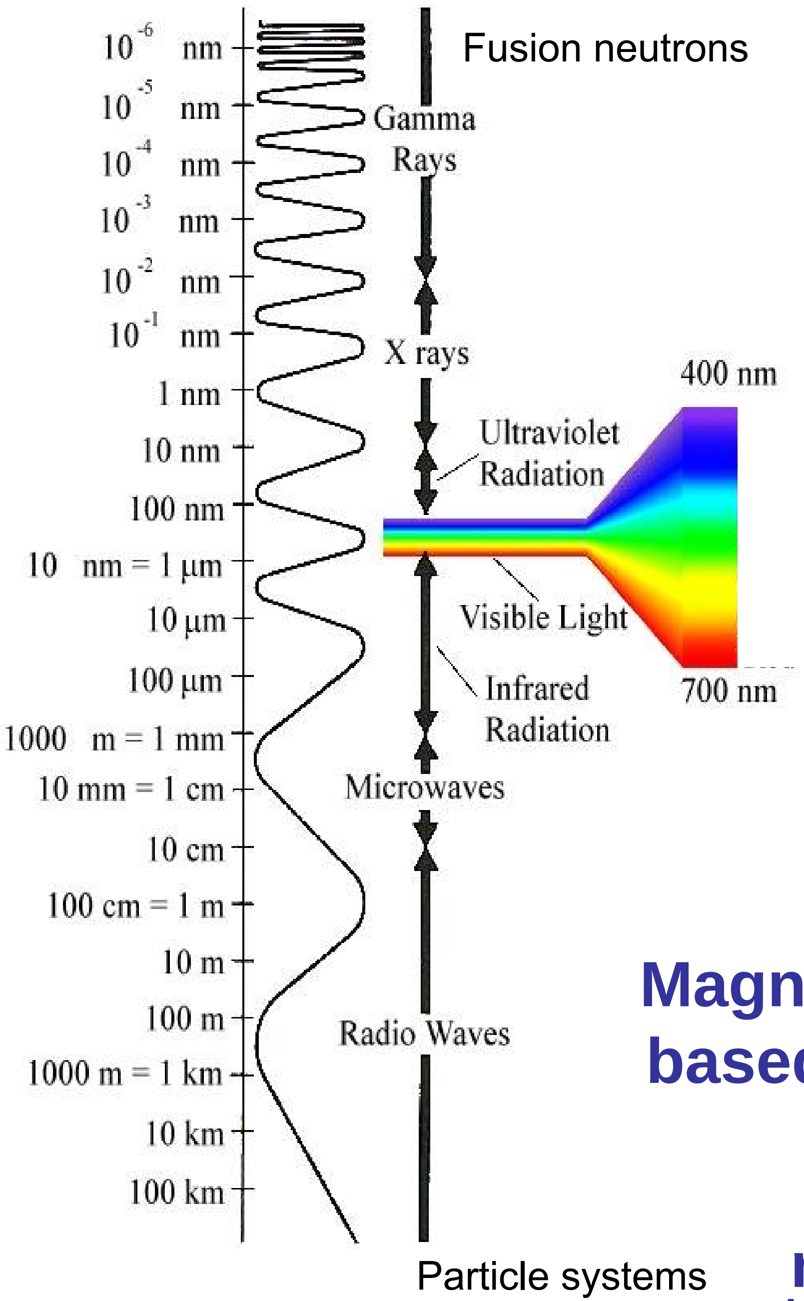
- All major measurement techniques in physics are represented
- At JET about 100 diagnostics operational and about 20 more in the design phase
- The measuring instruments are different but must be coordinated in a single experiments
- Already acquired a maximum of more than 50 GBytes of data per shot. Database: more than 250 Tbytes
- All the information is relevant and should be interpreted.

Plasma Diagnostics

- Plasmas are very delicate physical systems
- Diagnostics are mainly passive and measure the natural emission from the plasma
- Active probing can be done with laser or particle beams
- Solid probes are possible only at the very edge



Outline



γ-ray and neutron diagnostics: based on nuclear physics

Spectroscopy (IR, visible, UV and SXR): based on atomic physics

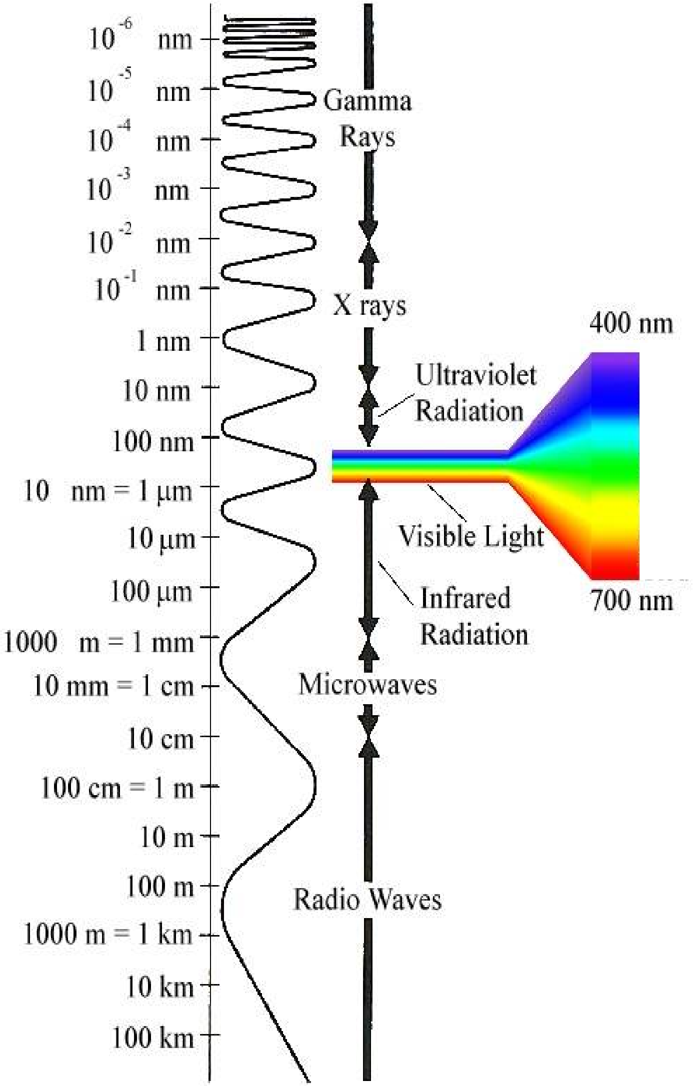
Interferometry in the IR, Thomson Scattering (visible): based on Classical Electrodynamics

Magnetic topology with pick-up coils based on Classical Electrodynamics

In Magnetic Confinement Fusion measurements are performed along the whole electromagnetic spectrum

Objectives of the rest of the talk

Fusion neutrons

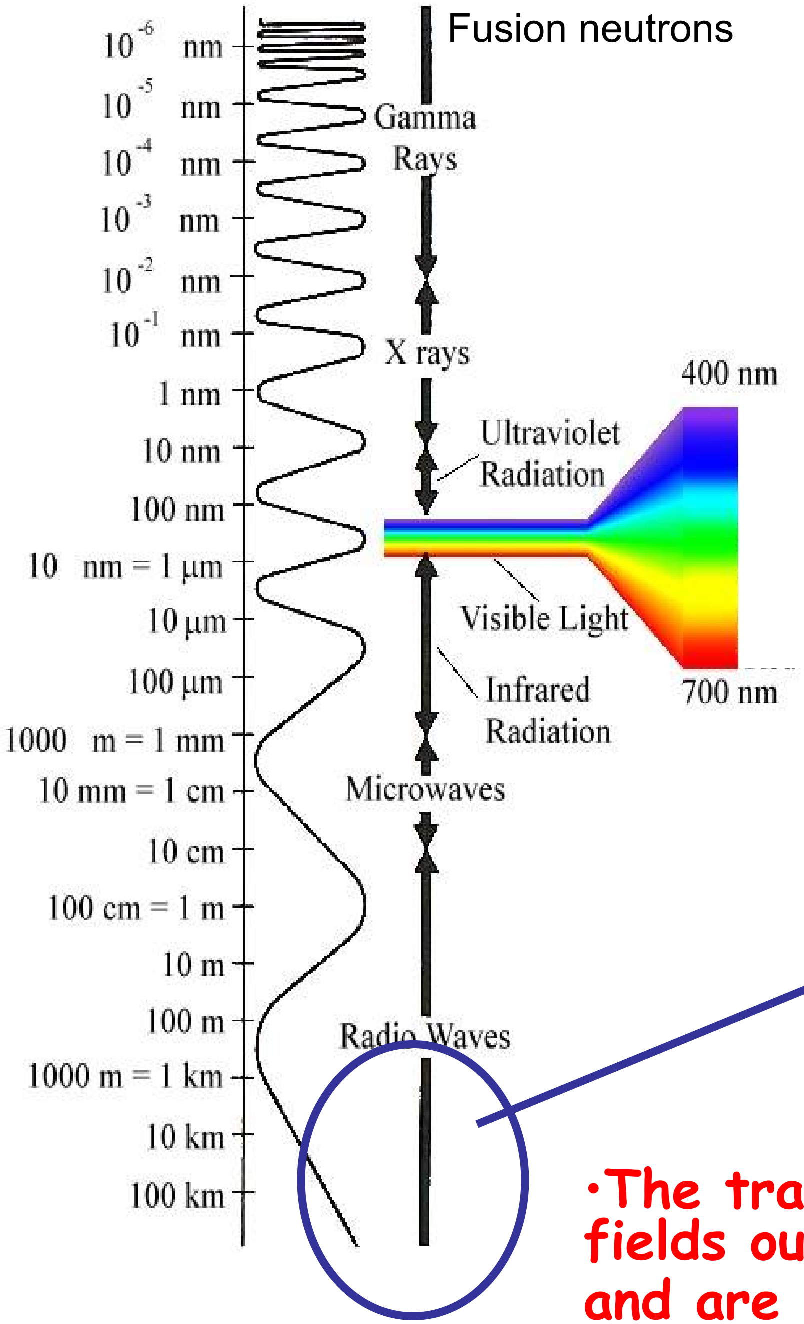


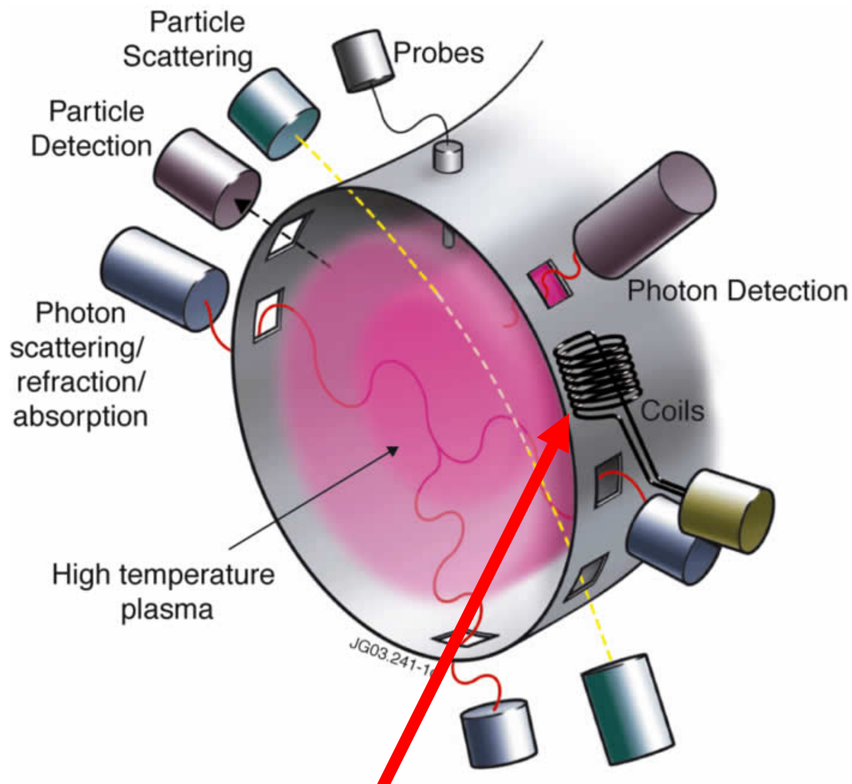
Particle systems

- Describe the basic physical principles behind the main measurement methods
- Identify the main plasma parameters which can be measured
- Show main results and their validity by cross validation comparing measurements obtained with completely independent measuring techniques
- Provide an idea of how the various diagnostics (independent experiments) are implemented in real life.
- Highlight some advanced developments of the techniques

Measuring the Magnetic Topology

Magnetic fields





Coil systems

$$V = -\frac{d\phi}{dt}$$

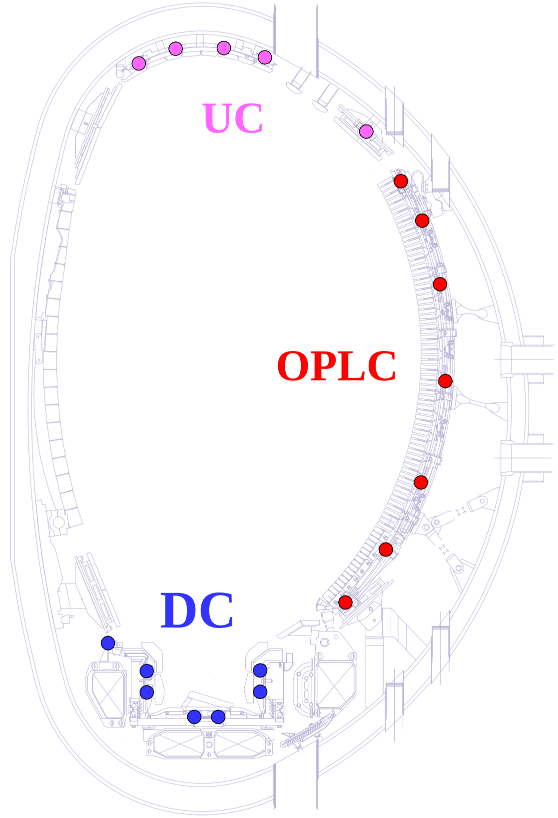
- The traditional measurements of the magnetic fields outside the plasma are performed with coils and are based on induction.

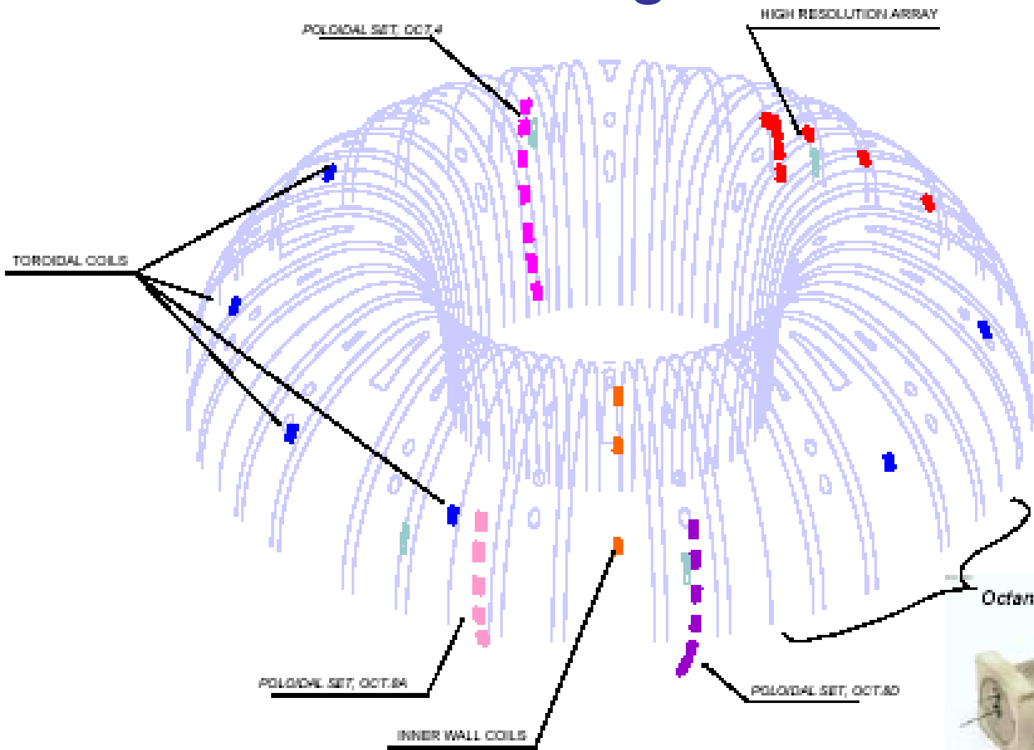
Location of the pick-up coils

Hundreds of coils of various nature are typically located around the vacuum vessel of a Fusion device and some inside.

Various methods based on Classical electrodynamics (vacuum) are used to derive the plasma boundary from the external magnetic fields

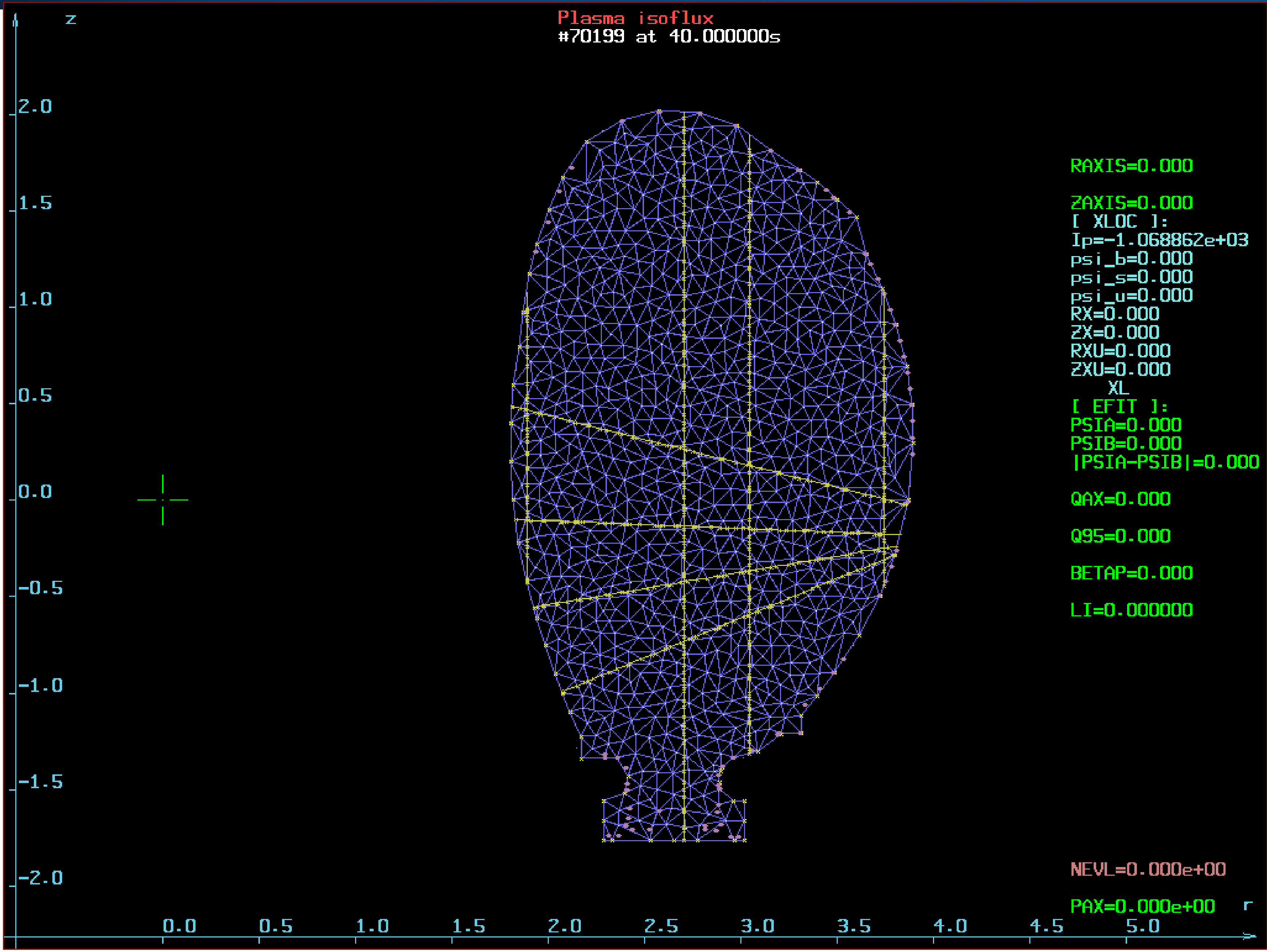
Poloidal cross section





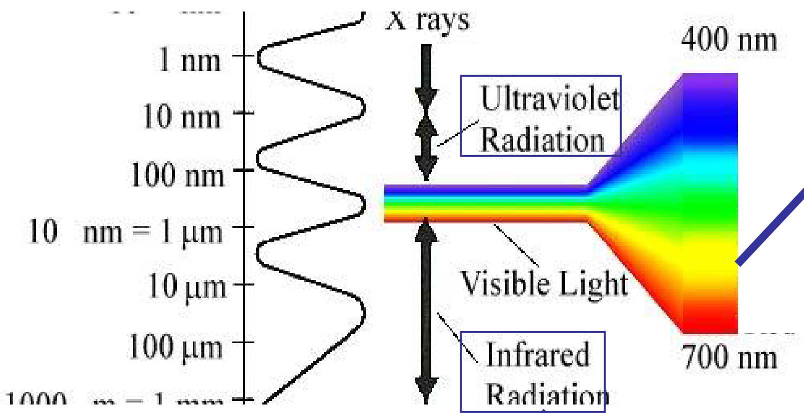
High Resolution Magnetic Coils

Equinox in the ATM Network



Measuring the properties of the electron fluid

Visible+ near UV- IR



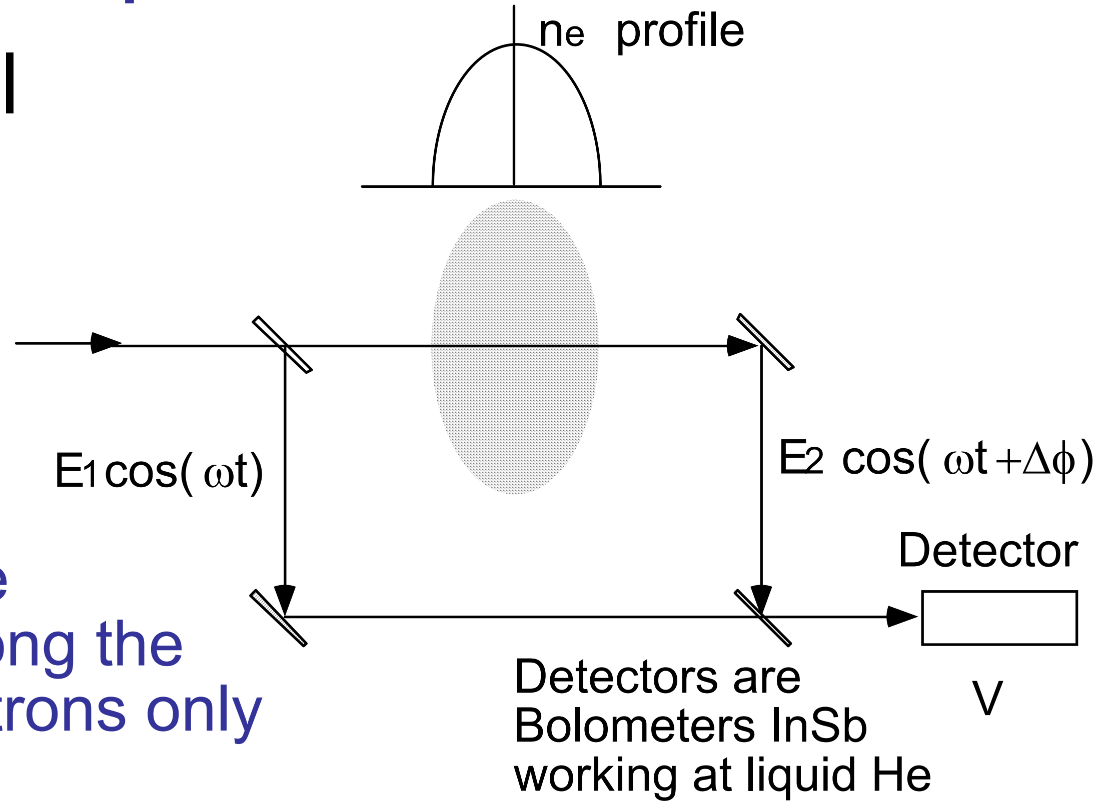
Laser Thomson Scattering (T_e, n_e)
- Ruby Nd YAG /double Nd YAG

Infrared interferometry & polarimetry for n_e and B

Interferometry

What is measured is the phase difference between a laser beam (112 μm) crossing the plasma and a second reference beam:

$$\Delta\phi = r_e \lambda \int_L n_e \cdot dl$$



where:

$$r_e = \frac{e^2}{4\pi c^2 \varepsilon_0 m_e} = 2.82 x 10^{15} m$$

The phase shift provides the average electron density along the beam line because the electrons only interact with the wave!

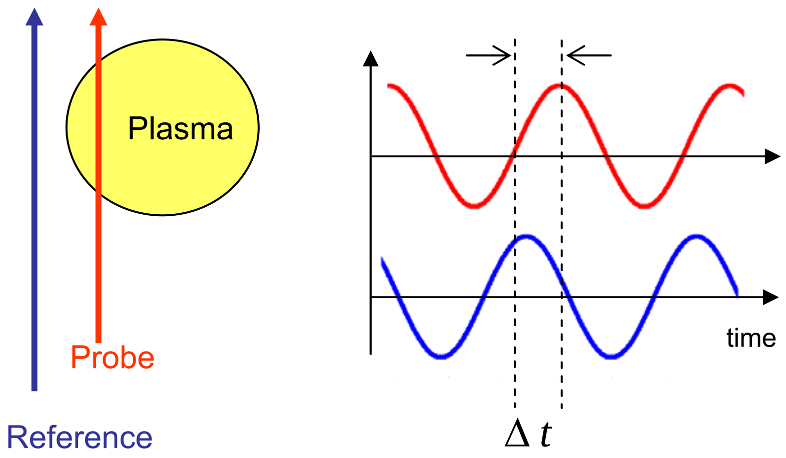
$\Delta\phi$ can be determined by interference:

$$V = \frac{E_1^2}{2} + \frac{E_2^2}{2} + E_1 \cdot E_2 \cos(\Delta\phi)$$

In Fusion interferometers are of the Mach-Zender type and use a super-heterodyne approach for the detection

Since the electrons are immersed in a strong magnetic field they constitute an anisotropic medium optically active (due to their gyration around the field lines).

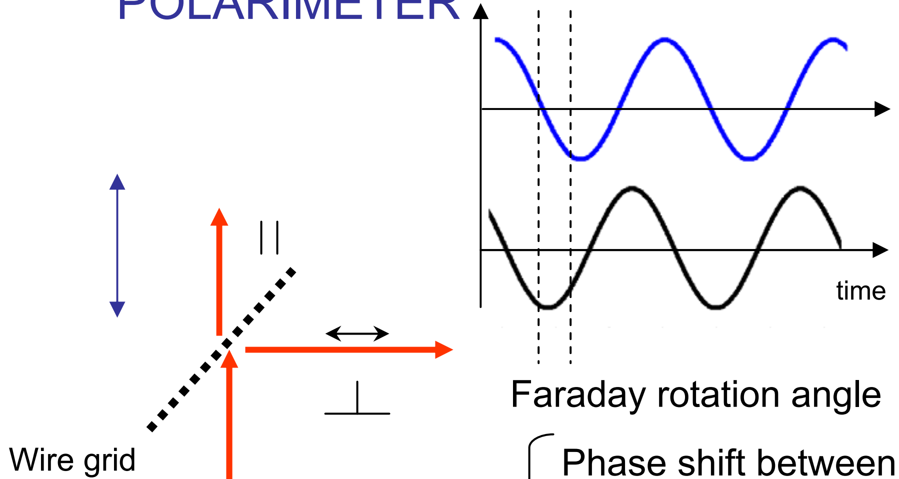
INTERFEROMETER



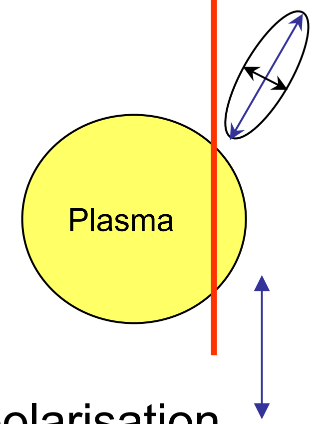
Phase shift between *reference* and *probe* signals

$$F = \frac{\varphi}{2\pi} = C\,\lambda \int_{z_1}^{z_2} n(z)\,dz$$

POLARIMETER



Phase shift between *two orthogonal polarisation components*



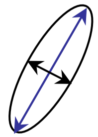
Rotated Elliptical polarisation:
due to the anisotropy and optical activity of the medium

KG4 polarimeter

Faraday Rotation effect

The plane of linearly polarised light passing through a plasma is rotated when a magnetic field is applied PARALLEL to the direction of propagation.

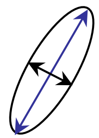
Faraday Rotation angle $$\Delta\Psi \approx \lambda^2 \int n_e B_{p||} dz$$



Cotton-Mouton effect

The ellipticity acquired by a linearly polarised light passing through a plasma is dependent on the magnetic field PERPENDICULAR to the direction of propagation.

Cotton-Mouton angle $$\Phi \approx \lambda^3 \int n_\mathrm{e} B_\mathrm{t}^{\,2} dz$$



At JET, for the vertical channels, B_t being largely constant along the line of sight is reducing the previous equation in

$$\Phi \approx \lambda^3 B_\mathrm{t}^{\,2} \int n_\mathrm{e} dz$$

Interferometric Diagnostic at JET

4 vertical channels 1÷4

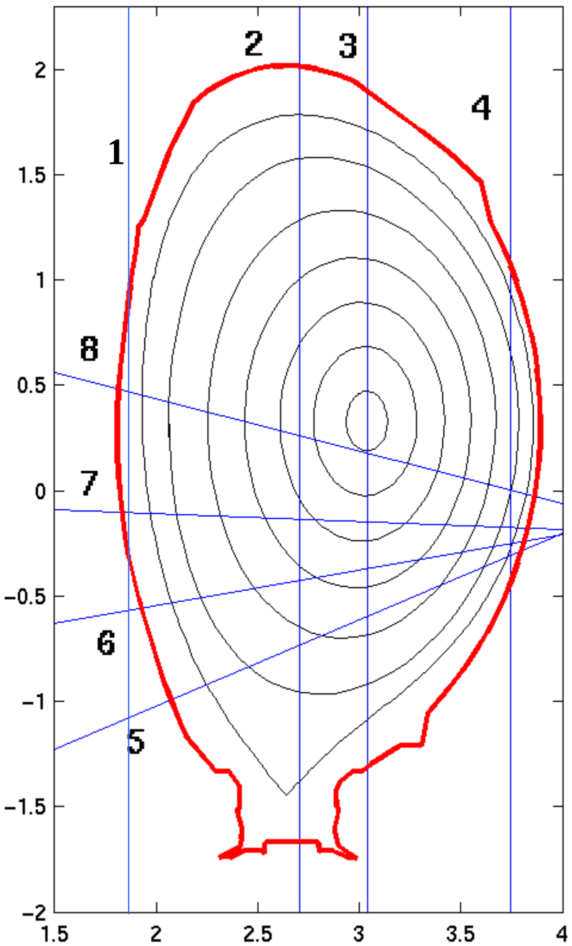
Single Colour Interferometer
λ=195μm

4 lateral channels 5÷8

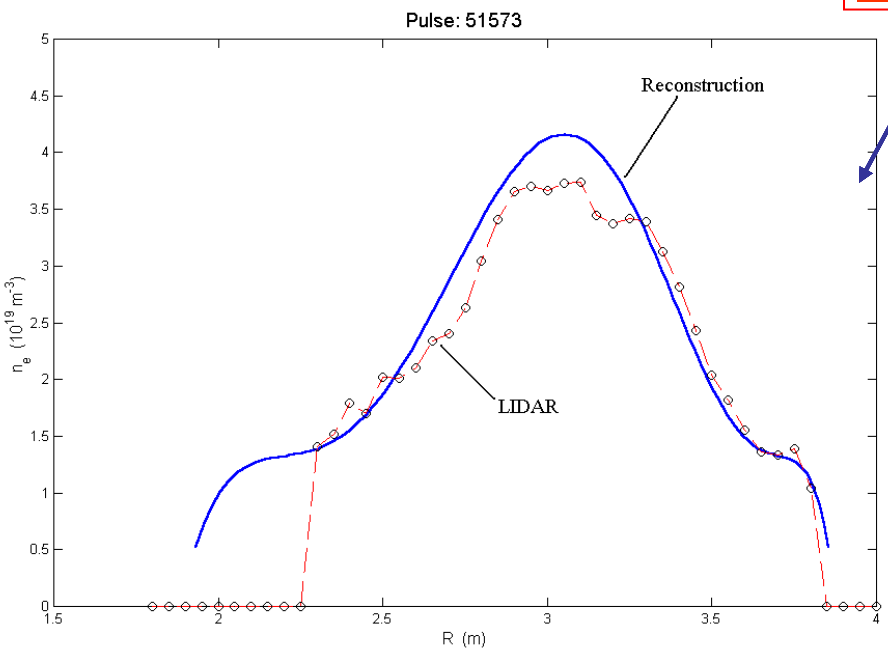
2 Colours Interferometer

λ=195μm (DCN laser) main laser

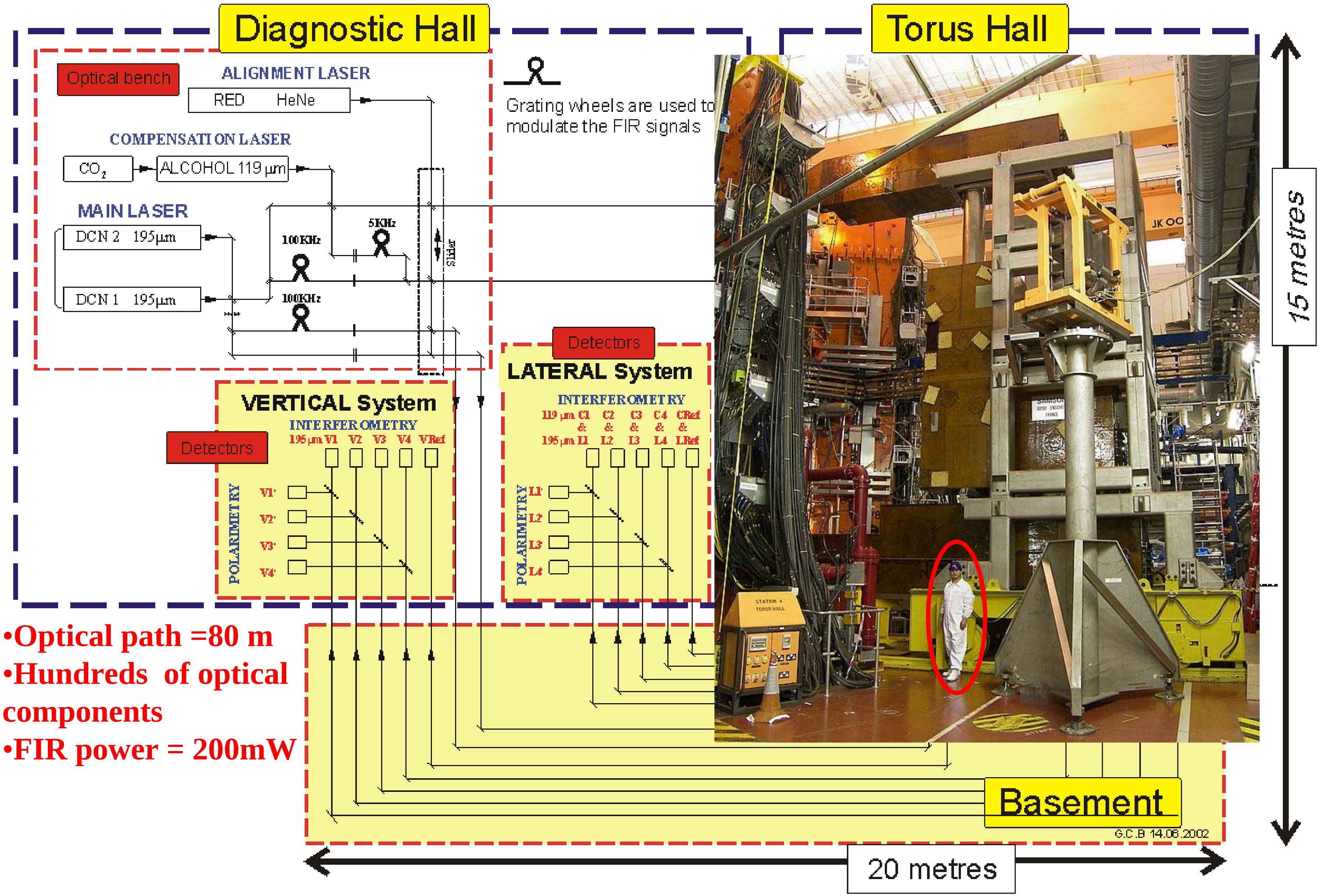
λ=118.8μm (Alcohol laser) compensation laser



Comparison with LIDAR: profile

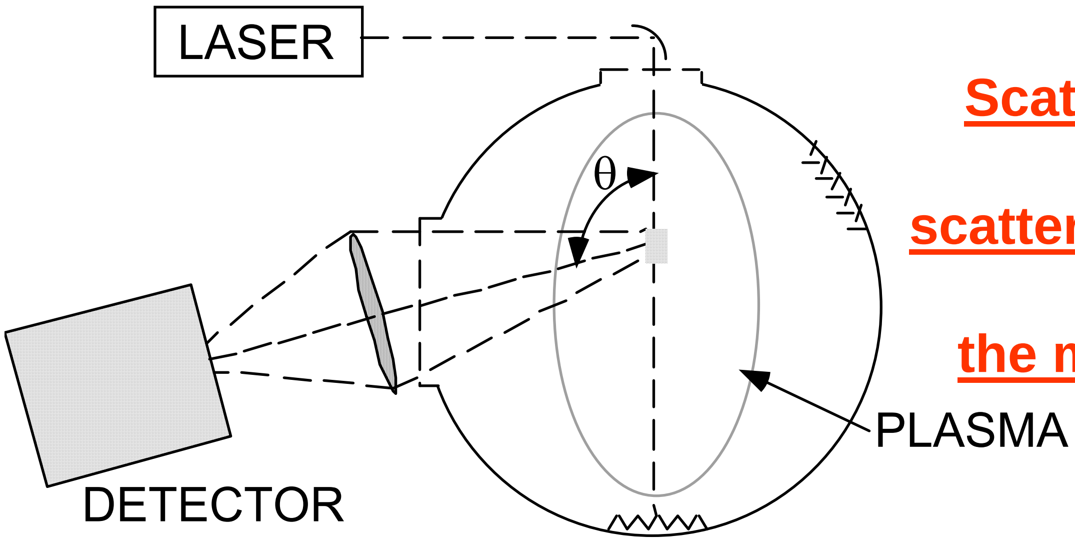


JET FIR Interferometer/polarimeter diagnostics in reality



- Optical path =80 m
- Hundreds of optical components
- FIR power = 200mW

Incoherent Thomson Scattering



Thomson Scattering

Scattering from free electrons: contrary to Compton scattering radiation of low energy: no change in the momentum of the particles

A laser beam is launched to the plasma. The scattered radiation from a given area is observed with angle θ.

The spectrum of the scattered radiation carries the information on the plasma properties (electron density and temperature).

The particles scattering the light independently are the electrons

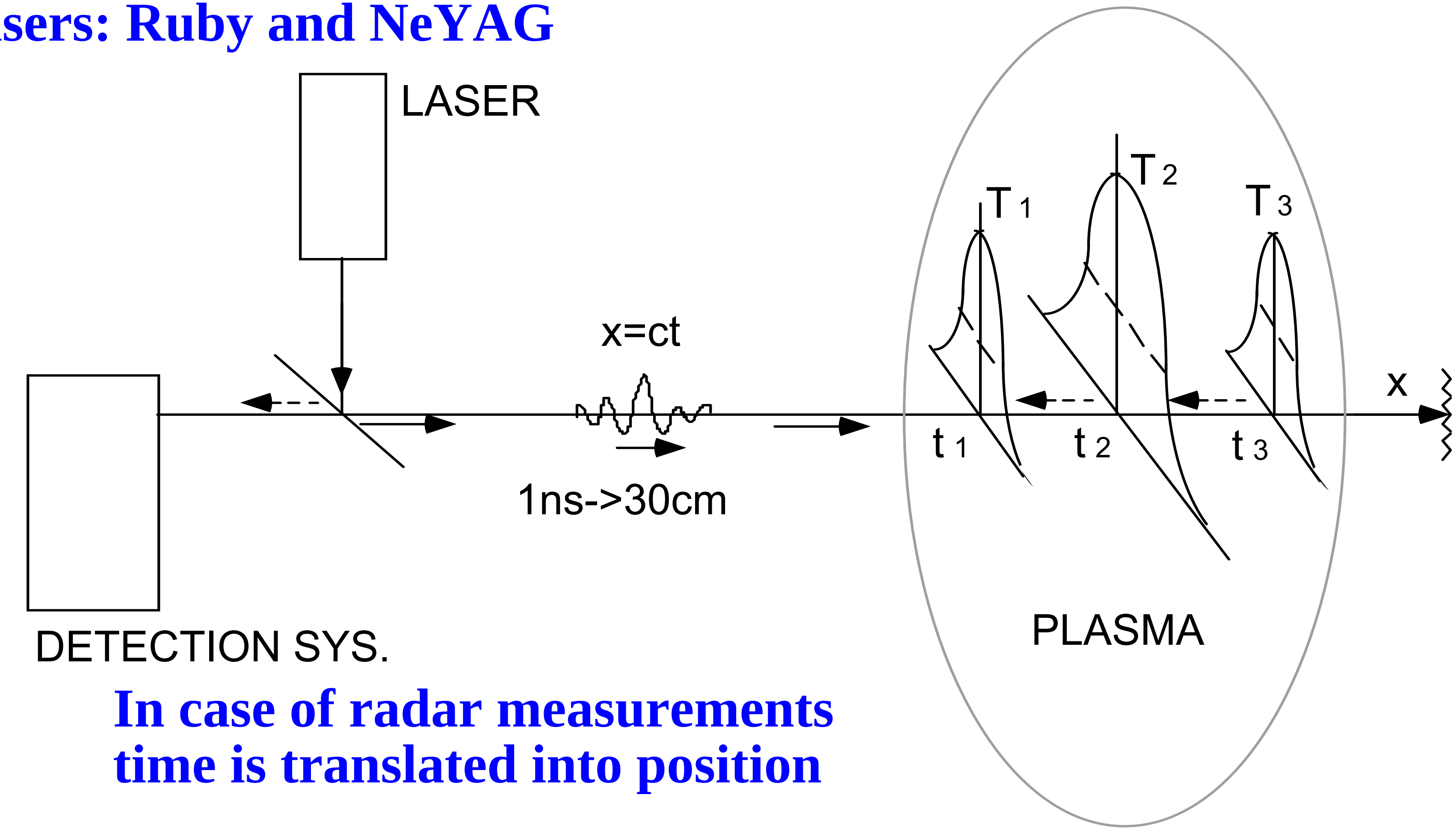
This diagnostic was used by scientists from Culham in 1968 to confirm the high temperatures reached in the first Russian Tokamak, leading to the development of Tokamak devices all over the world.

Incoherent Thomson Scattering: LIDAR

Broadening gives the electron temperature Te

Absolute intensity gives the electron density ne

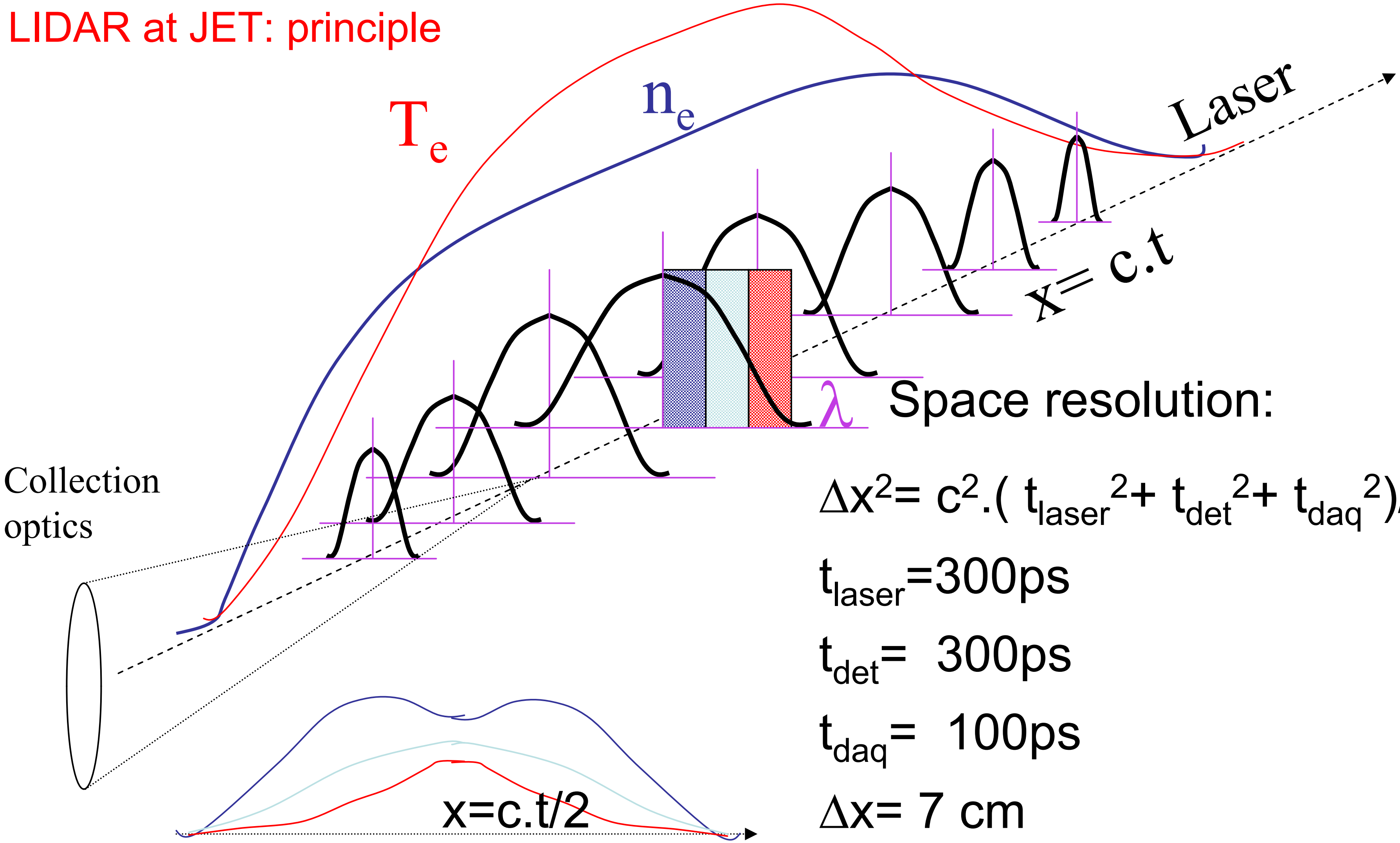
Lasers: Ruby and NeYAG



In case of radar measurements time is translated into position

Incoherent Thomson Scattering

LIDAR at JET: principle



Space resolution:

$\Delta x^2 = c^2.(\,t_{laser}^{\;2} + t_{det}^{\;2} + t_{daq}^{\;2})/4$

t_{laser}=300ps

t_{det}= 300ps

t_{daq}= 100ps

Δx= 7 cm

Number of photons reaching the detectors can be ten orders of magnitude lower than the beam. Detectors GaAs (P) specially developed for fast response and high QE

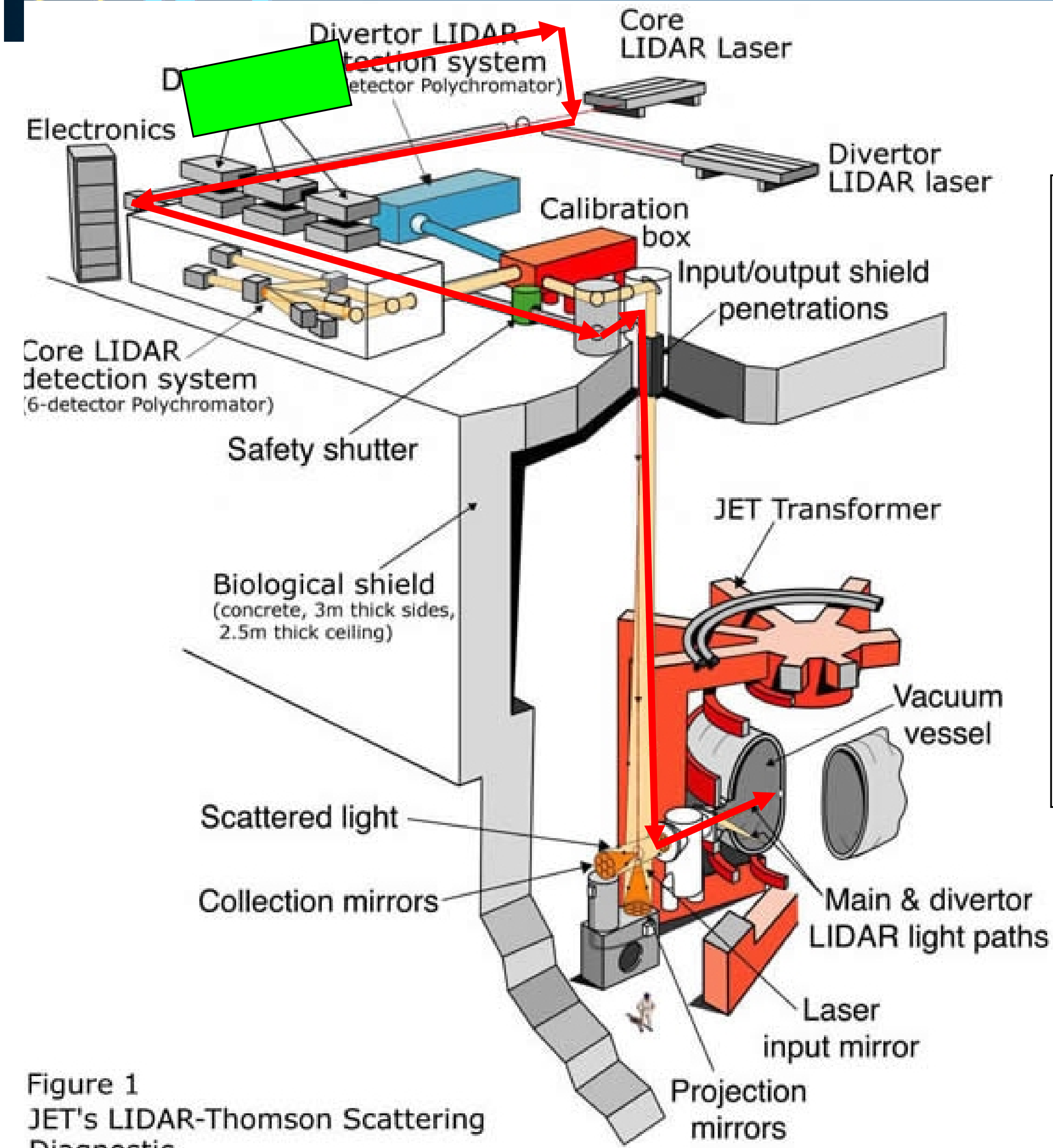


Figure 1
JET's LIDAR-Thomson Scattering
Diagnostic

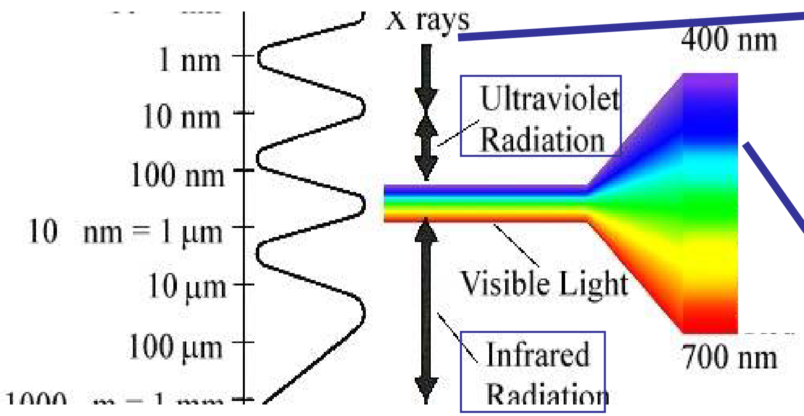
Thomson scattering optical path: about 50 meters

- Power density of about 10 GW (for only 300 picoseconds)
- Frequency of laser pulses: 20 Hz

Measuring the properties of the Ion Fluid and impurities

Visible+ near UV- IR

Plasma ions, being fully stripped, are nearly invisible but the impurities in the plasma thermalise with the ion fluid and emit characteristic radiation which can be analysed spectroscopically.



Passive spectroscopy: from IR to SXR. Ti, rotation…

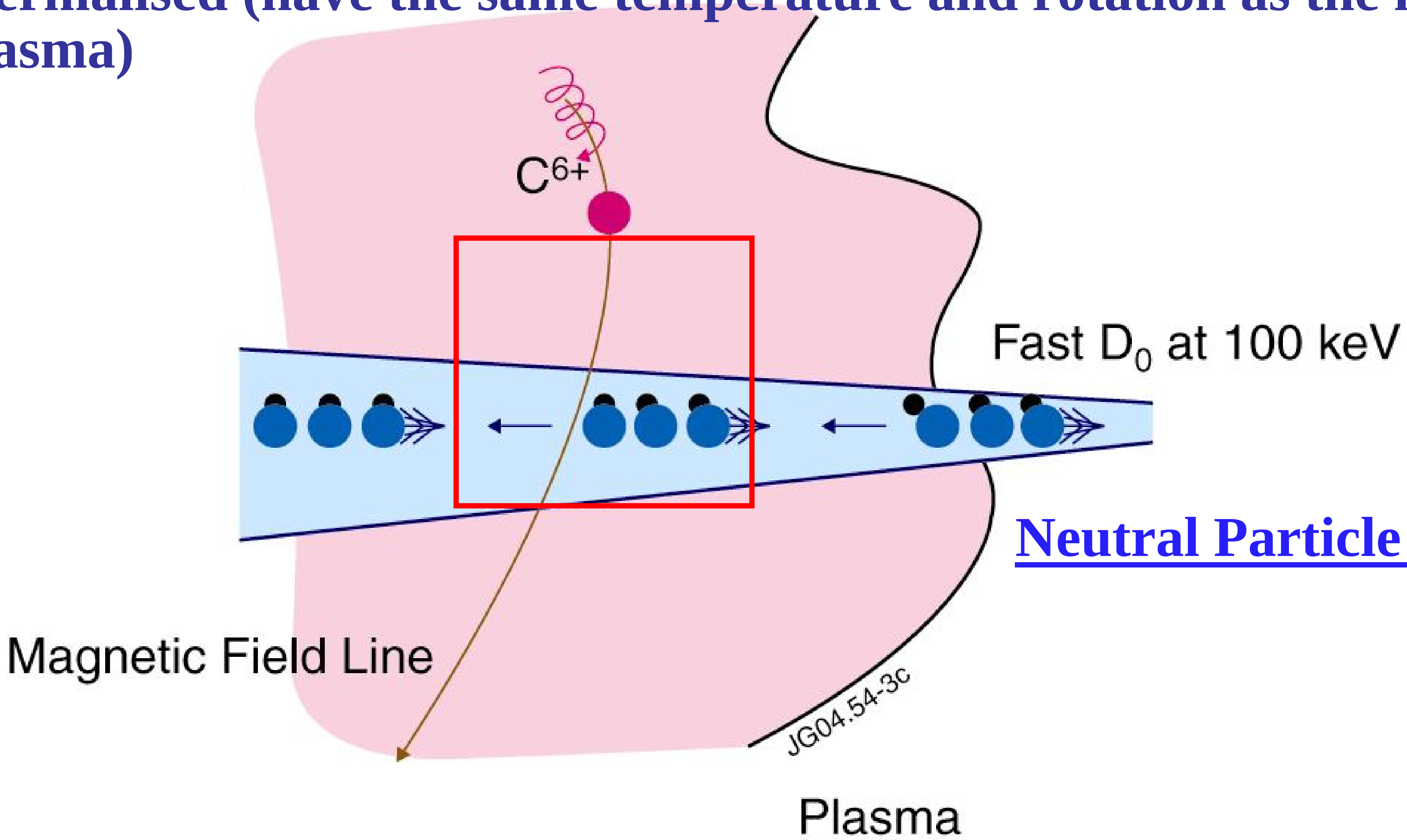
<u>Charge-exchange recombination spectroscopy</u>:

Visible lines for ion fluid and impurity studies

Need extensive database on atomic physics

Ion Diagnostic: Charge eXchange Recombination Spectroscopy (CXRS)

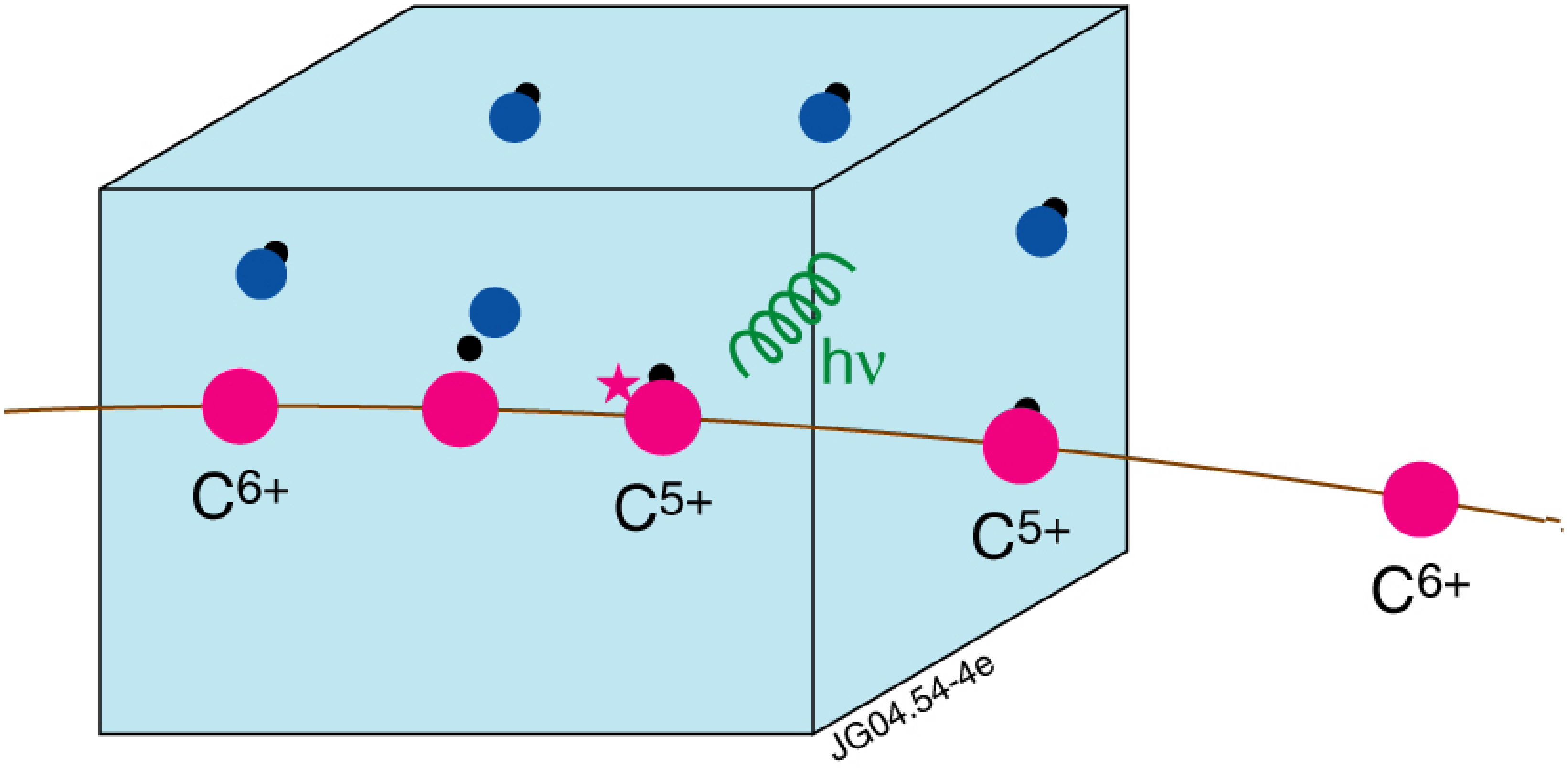
Principle: derive information about the main plasma ion fluid by measuring the properties of intrinsic impurities which are thermalised (have the same temperature and rotation as the main plasma)



Neutral Particle beam

Charge exchange excitation process between an impurity C^{6+} and the neutrals of the beam

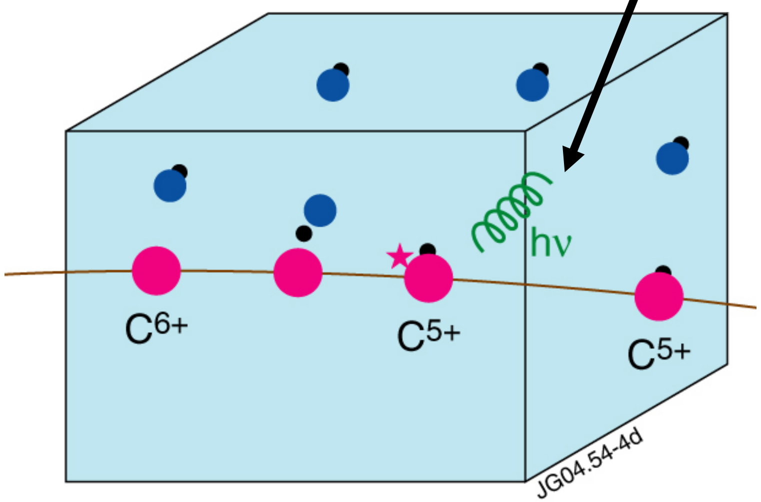
Charge eXchange Process



Charge exchange excitation process

Information derived by CXRS

Principle of Charge Exchange spectroscopy



The emitted radiation carries the information about C^{5+}

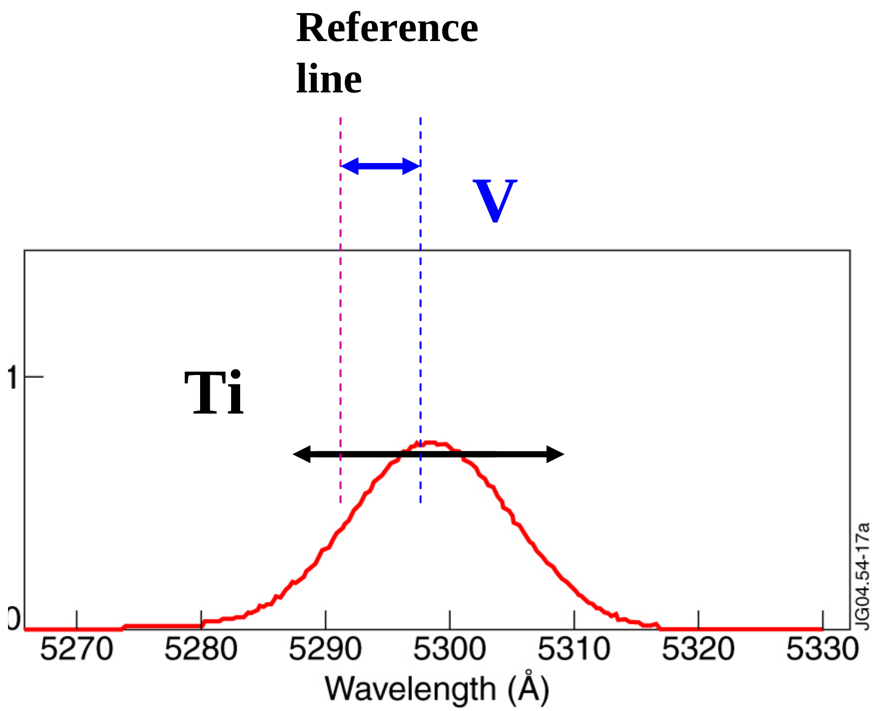
- **temperature**
- **momentum :** The CX reaction does produces very little momentum change for the recombined ion and hence does not disturb the ion velocity distribution.
- **the number of C^{6+}**

Temperature, velocity and impurity measurements

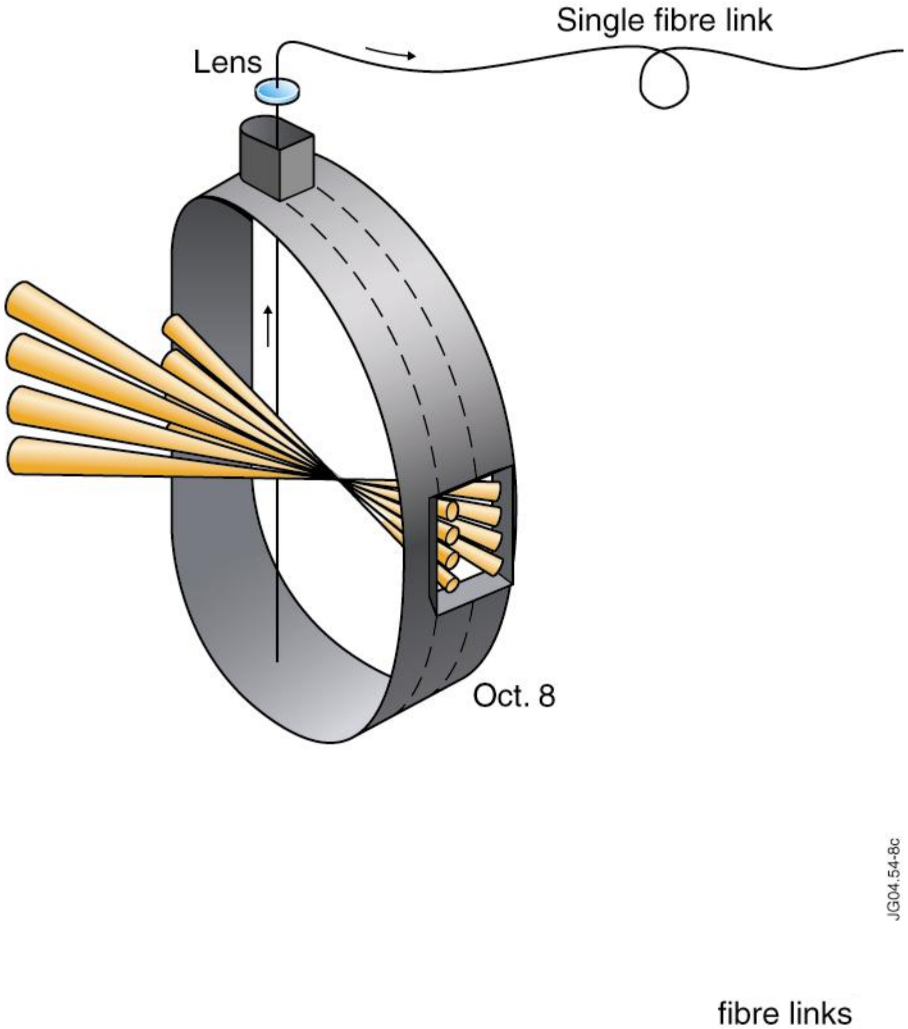
- Broadening dominated by Doppler width.

- Velocity can be measured from Doppler shift

- The density of the impurities can be determined from the absolute intensity of the line



Core CXRS diagnostic at JET



- **Spatial resolution:** limited by crossing between beam and los. Order of few cm
- **Time resolution:** limited by the detector ~10ms.

In terms of detectors, spectroscopy in fusion requires development mainly of spectrometers.

Measuring the parameters of the Fusion Products

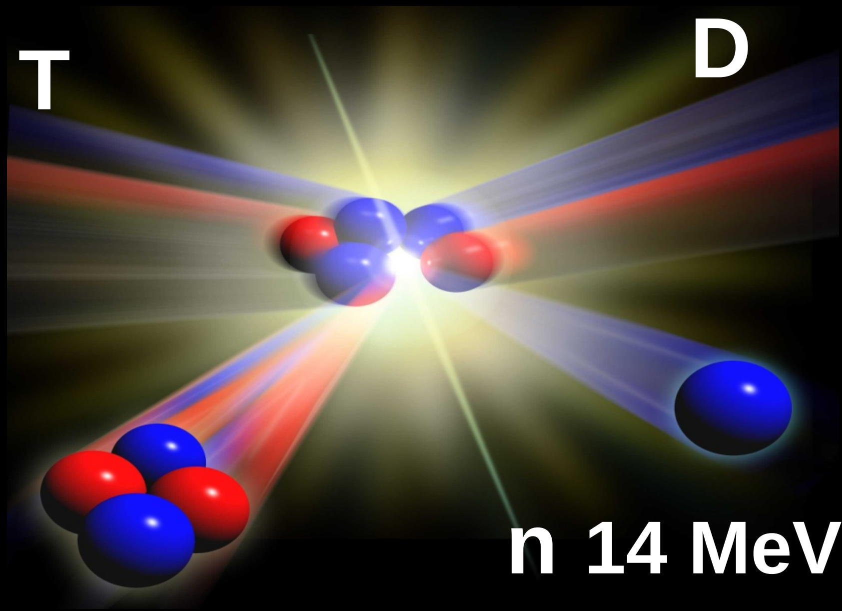
"Burning Plasma" Diagnostics: fusion products

In a "Burning Plasma" additional quantities have to be measured

The "fuel mixture" or "isotopic composition":

the maximum performance is expected at 50/50 D/T

He ash
thermalised alphas left in the plasma which dilute the main fuel



Tritium retention:
unburned tritium left in the machine (during TTE 10% T in the plasma 90 % in the wall in case of puffing)

α 3.5 MeV

The 3.5 MeV αs
which are meant to heat the plasma and sustain the discharge

The 14 MeV neutrons which are supposed to transfer the heat outside the vacuum chamber

Principles of Neutron Detection

Since its discovery in 1932 by Chadwick, the neutron is well known for being an elusive particle.

The main method to detect neutrons consists of <u>"transforming"</u> them (via nuclear processes:strong interactions) to <u>charged particles</u>, which then interact with matter through Coulomb collisions.

Target nucleus + neutron →
- **Recoil nucleus (proton, elastic)**
- **Proton**
- **Alpha particle**
- **Fission fragments**

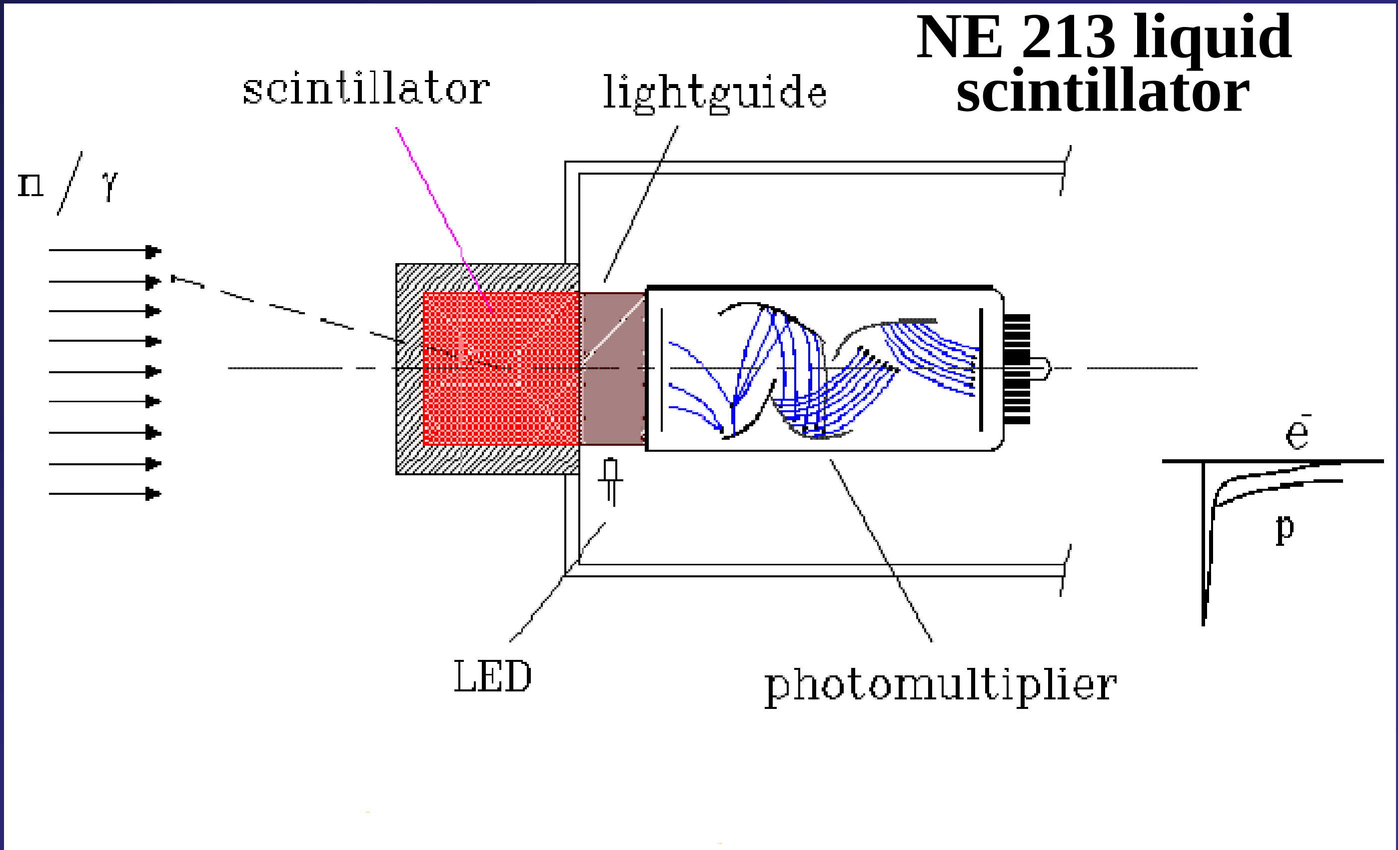
Proton, Alpha particle → Conversion reactions

In fusion fast neutrons (E > 100 keV) have to be detected and the main methods used rely on:

- **<u>Recoil protons</u>**
  scintillators: the recoil protons excite suitable materials which in turn emit light collected by a photomultiplier
- **<u>Conversion reactions producing αs</u> (n,α)**
  in semiconductors the reaction products create electron-hole pairs and the charge is collected (Si or Diamond detectors)
- **<u>Induced fission in materials</u> (n,fission) : fission chambers**

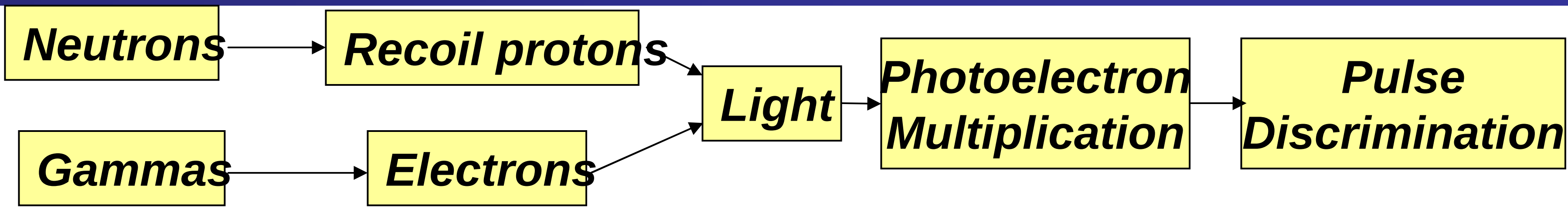
Principle of the Organic scintillator

These materials are plastics (solid or liquid) with a lot of H (to produce recoil protons) and scintillating molecules.

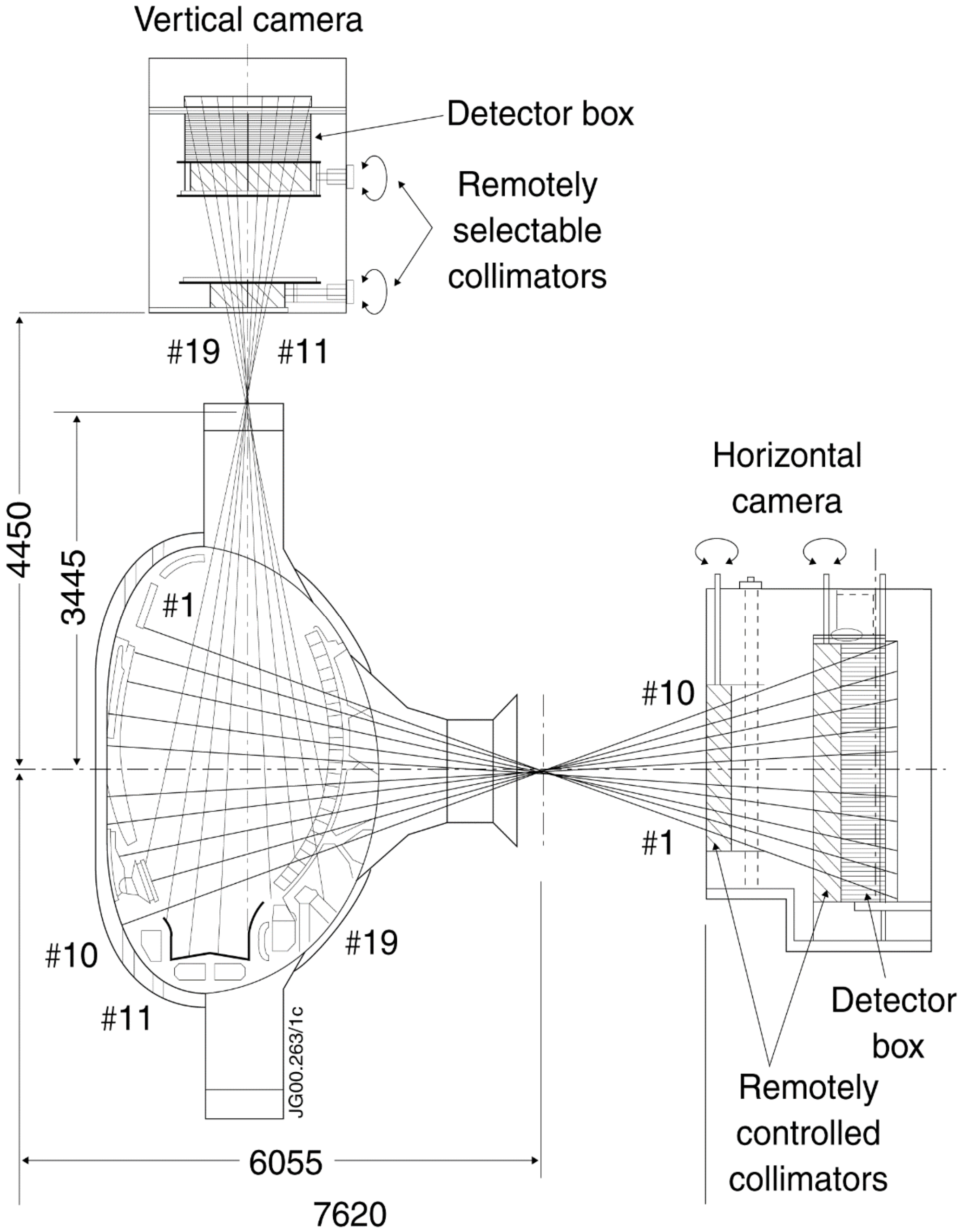


In a Tokamak the radiation field contains also γ-rays

The shape of the current pulse allows discriminating the neutrons from the γ s



JET Neutron Cameras



Vertical camera: 9 lines-of-sight

Horizontal camera: 10 lines-of-sight

Collimators: Ø10 and 21 mm

Space resolution: 15 cm in centre

Neutron Detectors:

- 19 Liquid scintillators NE213 (2.45 and 14 MeV) + PSD

- 19 Plastic Bicron 418 scintillators (14 MeV)

Detectors for γ-rays:

- 19 CsI(Tl) solid state

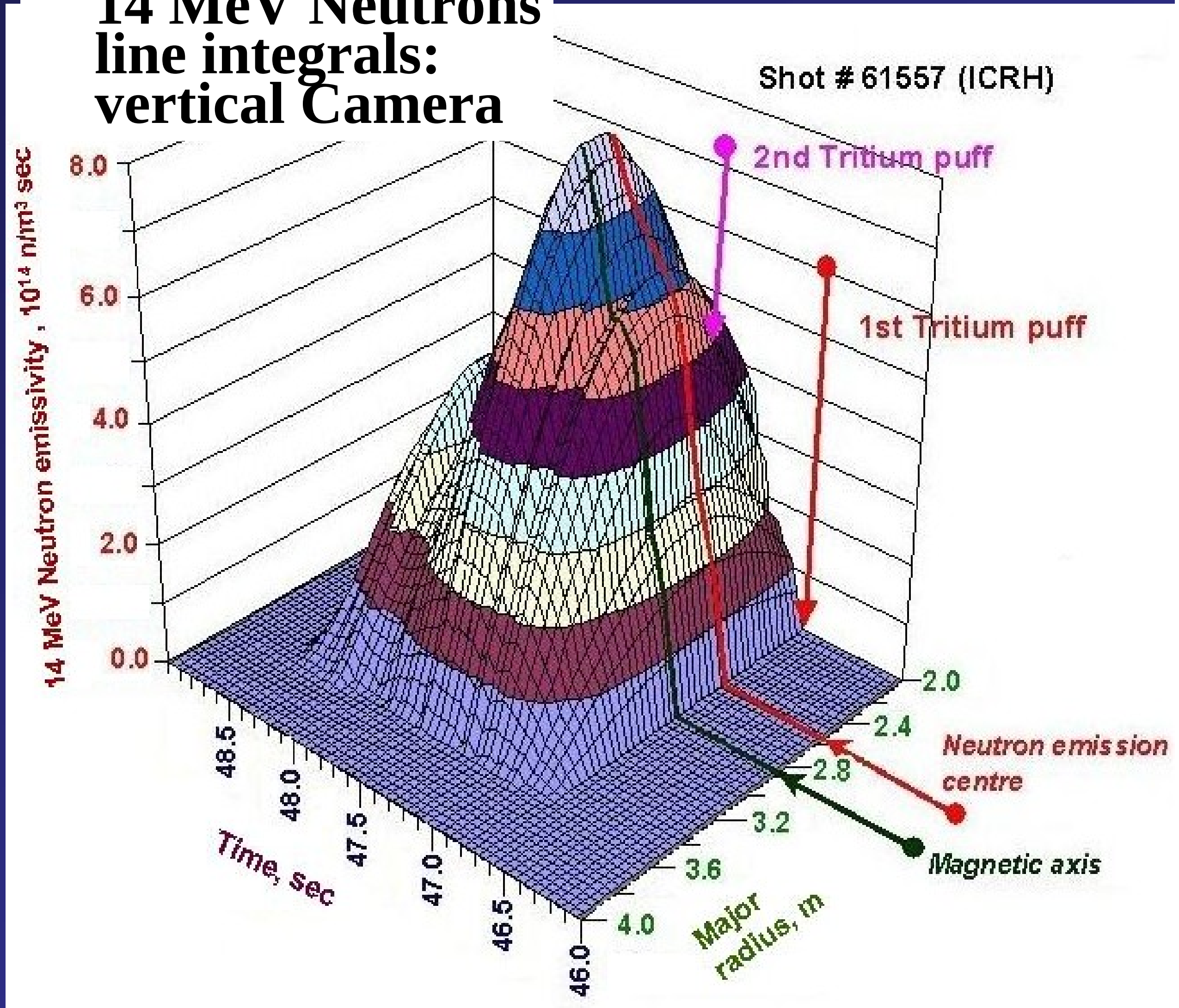
For every line of sight there is a collimator and a complete set of three detectors one of each category. Diagnostic calibrated absolutely.

Effects of the ICRH heating on neutron emission

- **The spatial distribution of fast tritons heated by the ICRH system at the fundamental cyclotron frequency of tritium.**

- **The 14 MeV neutron emission profile <u>peaks off axis close to the T cyclotron</u> layer.**

14 MeV Neutrons line integrals: vertical Camera



This example shows a sort of de-coupling of the neutron emission from the magnetic topology.

Alpha Particles produce New Physics

- Up to now , fusion research was in sub-critical zone, $nT\tau < 8.3 \times 10^{20}$ m^{-3}keVs, without burn or with small burn (Q=0.61, JET where Q= Pfus/Pinput)

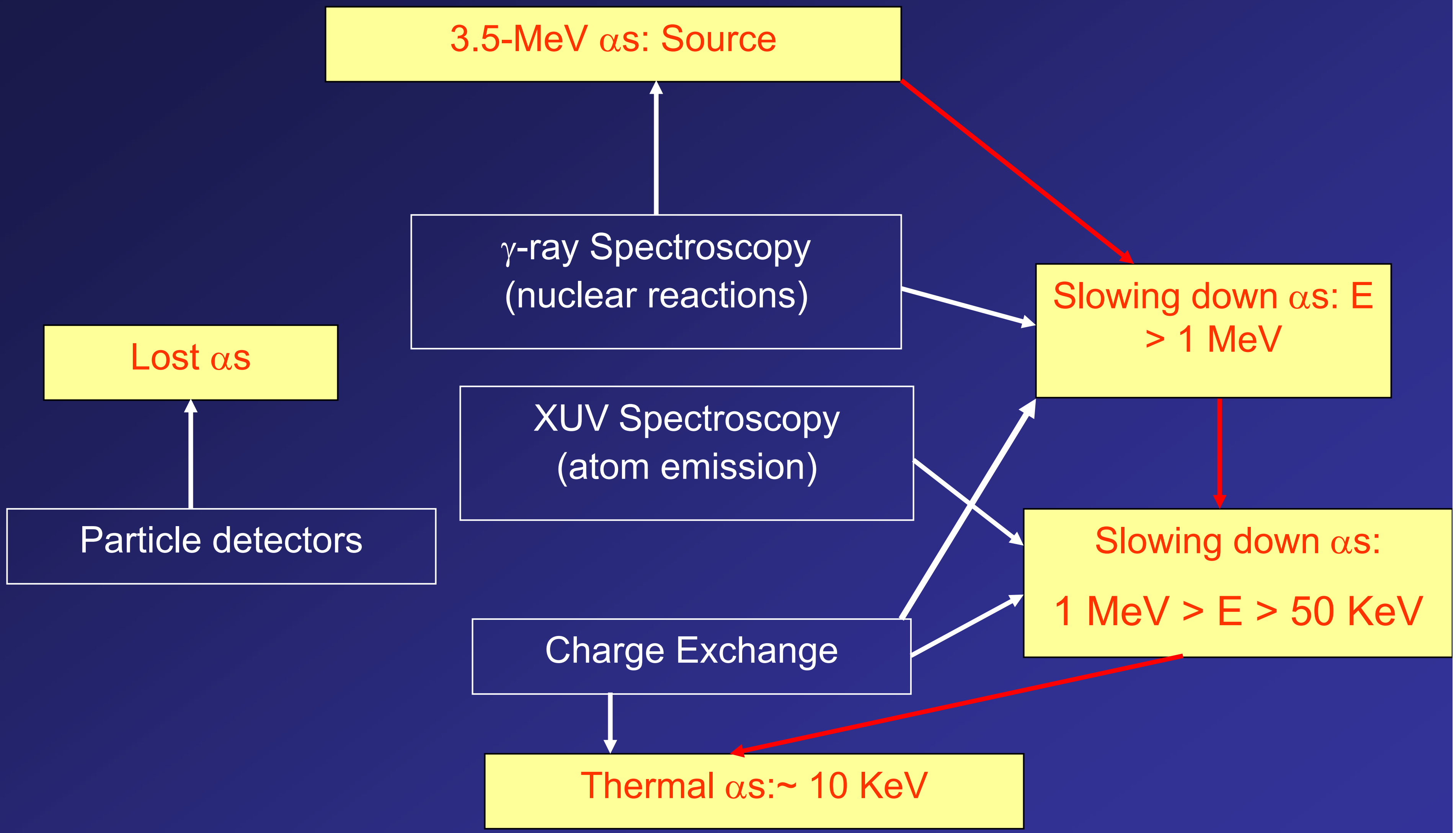
- Burning plasma - fundamentally new physics. New phenomena to be studied:

  10>Q>5 (f_α= 50-60%)
  α-effects on MHD stability and turbulence

  Q>10 (f_α>60%)
  strong non-linear coupling between α's and pressure driven current, turbulent transport, MHD stability, ignition transient phenomena

- It is likely, that JET will be the only opportunity before the "Next Step" to study *α's* with confidence at various Q's. <u>JET the only machine with the volume to confine the αs</u>.

Alpha Particles



Alphas and fast ions are difficult to detect because they are inside the plasma.

γ-ray Emission

γ -ray emission in a Tokamak is produced by

- fusion products: p(3 MeV, 15MeV), T (1 MeV), ^{3}He(0.8 MeV), α (3.5 MeV)
- ICRH-accelerated ions: H, D, T, ^{3}He, ^{4}He

due to nuclear reactions with fuel and main impurities (Be, C)

α-particle diagnosis at JET is based on the ^{9}Be(α,nγ)^{12}C reaction

Fast deuterons detection at JET is based on the ^{12}C(d,pγ)^{13}C reaction

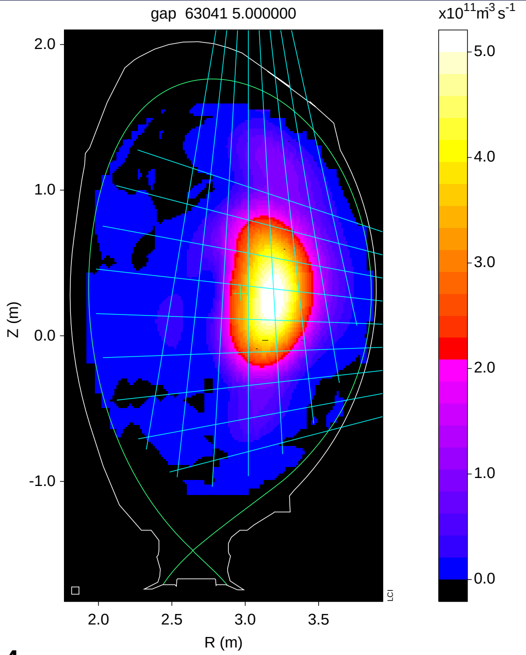
^{9}Be(α,nγ)^{12}C reaction

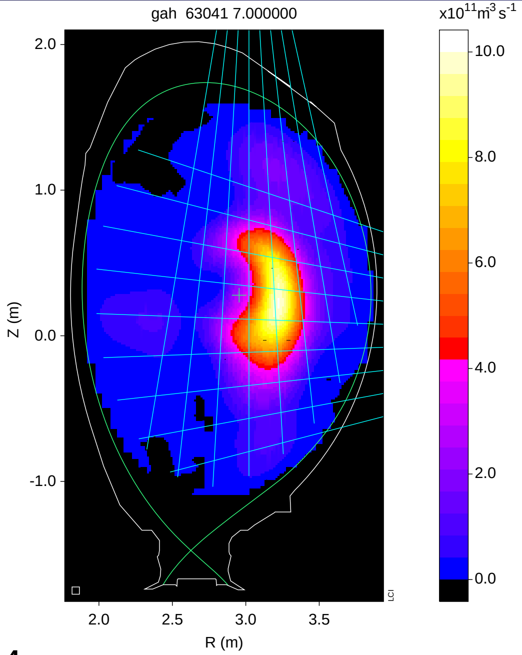
$$^{9}\text{Be} + \alpha \rightarrow {}^{13}\text{C}^{*} \xrightarrow{n} {}^{12}\text{C}^{*} \xrightarrow{\gamma} {}^{12}\text{C}$$

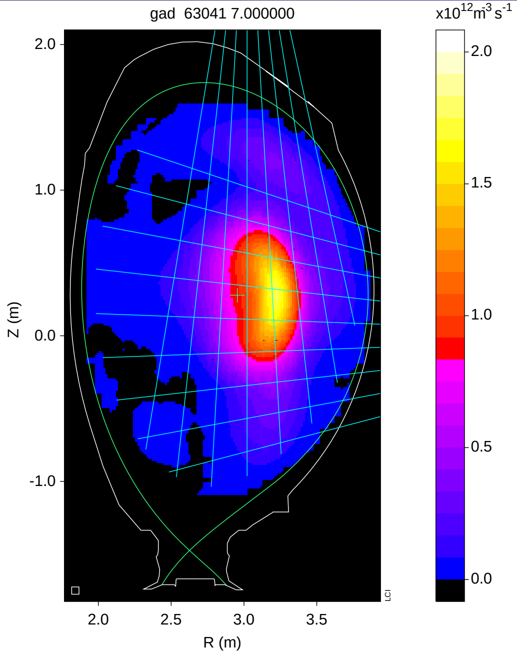
The nuclear reaction between fast alphas with E_α > 1.7 MeV and Be impurity leads to:

- **Excitation of high-energy levels in ^{13}C* nucleus**
- **De-excitation by emitting neutrons with population of low-lying levels in ^{12}C***
- **Further de-excitation by 3.1-MeV (D) and 4.44-MeV (α) gammas to ground state of ^{12}C nucleus**

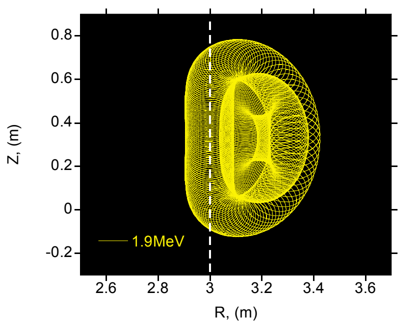
Visualization of Fast Particles

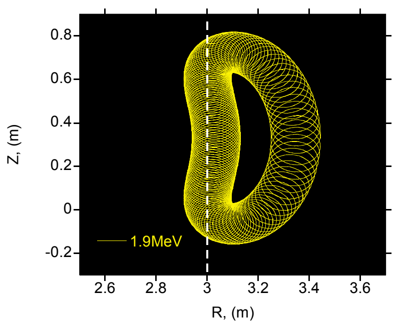


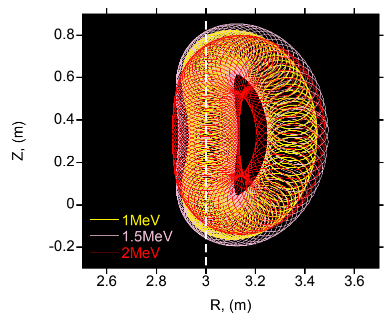




^{4}He in reversed-shear discharge **^{4}He in monotonic q(r)-plasma** **D in monotonic q(r)-discharge**

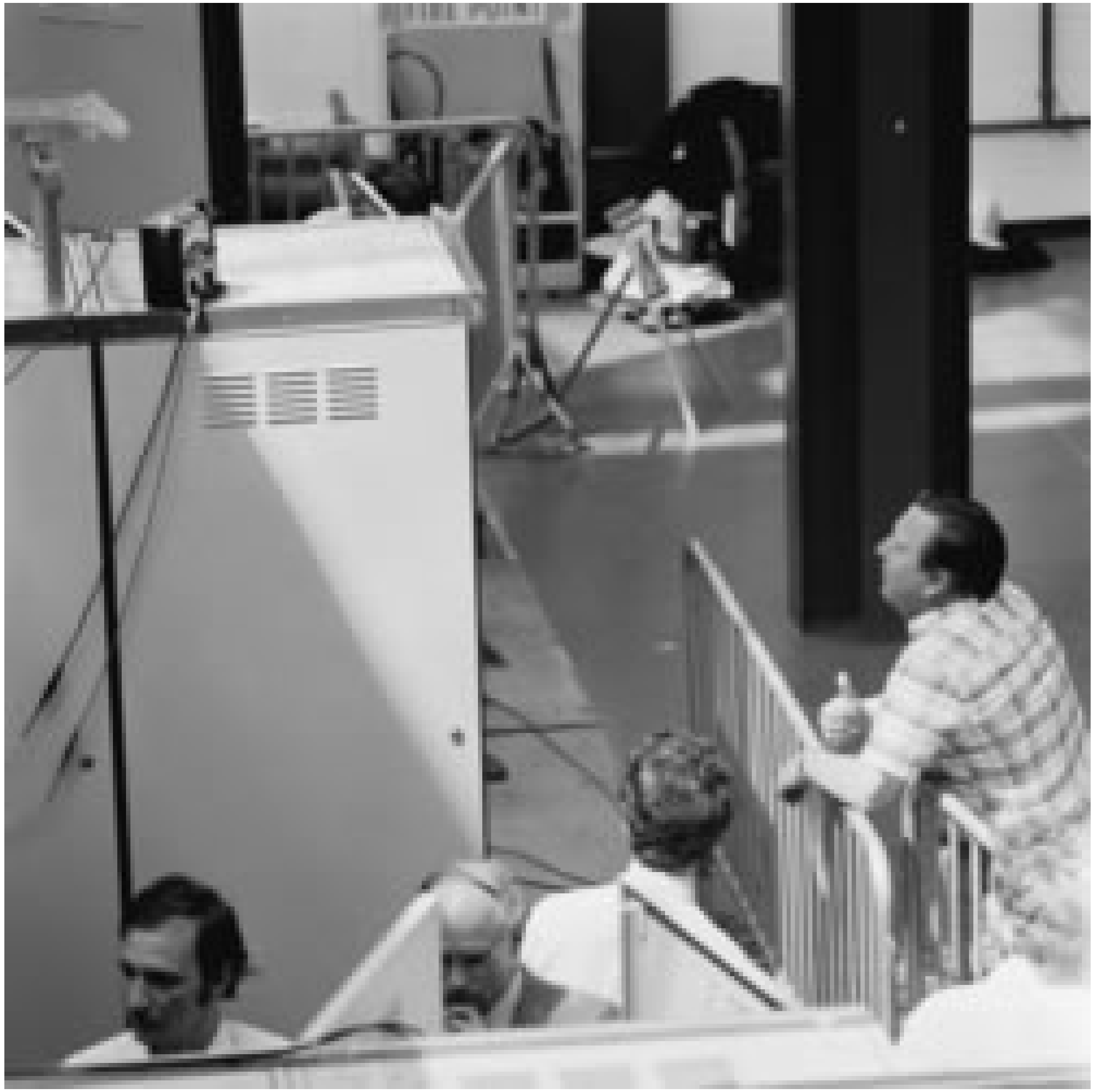






Results (tomography constrained by the equilibrium) are confirmed by simulations and can provide essential information on the effects of additional heating and magnetic topology on fast particles

Day 1- 25/06/1983



Data Growth

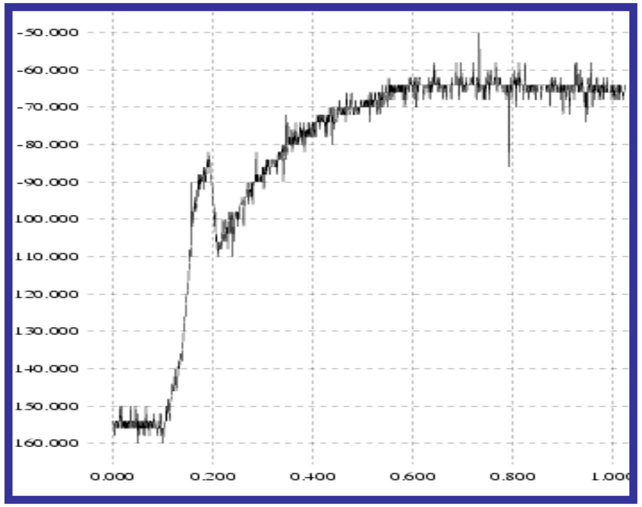
JET Pulses 25.6.83

240 000 databytes + GAPTree

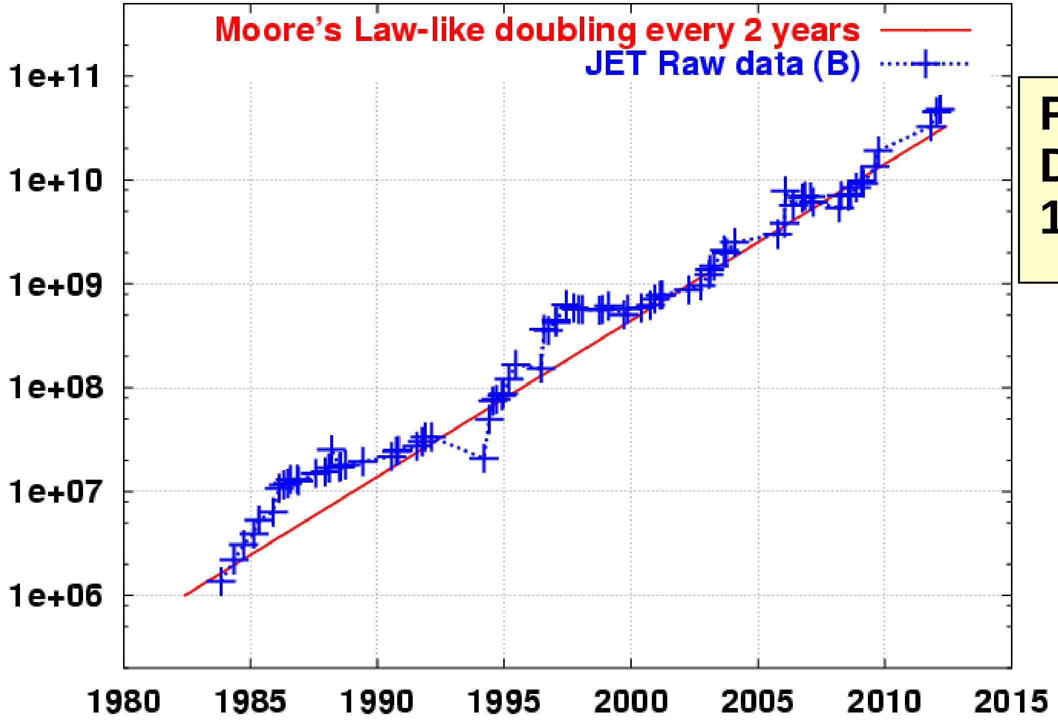
JPF Num	prepulse	module ini	postpulse	Remarks
70	58.22	3.64	92.94	164 Data Pages 243,260 bytes expected
71	68.22	8.58	90.26	
72	49.34	3.02	92.46	
Proper Test Pulses to check that everything is OK				
73	65.50	3.56	82.40	first Plasma
74				Puls aborted due to Comms error
75	61.08	3.96	67.56	no IPF, JPF partiall
76	52.28	3.04	84.38	TF trip, IPF,JPF OK
77	58.38	3.58	76.32	Pulse OK
78	71.30	4.14	93.40	Pulse OK

2.4e5 B

1st JET Plasma
25/06/1983

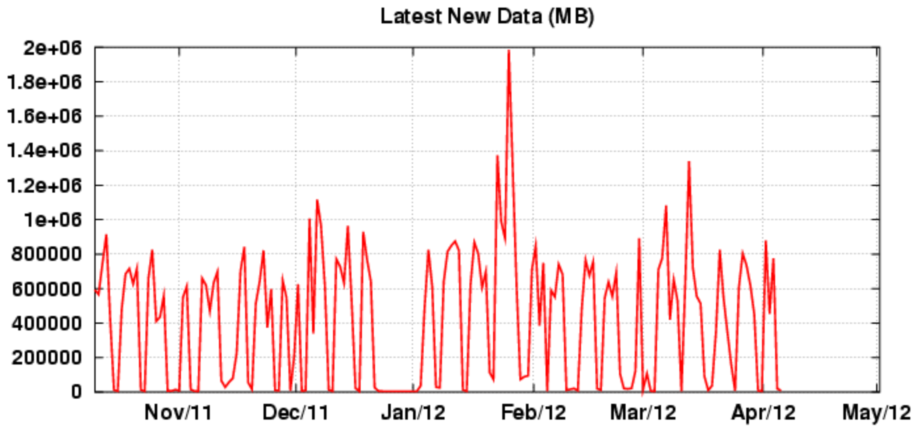


JET Raw Data Growth



Following Moore's Law Doubling every two years since 1983

~50GB per pulse
~800GB per day
~250TB total



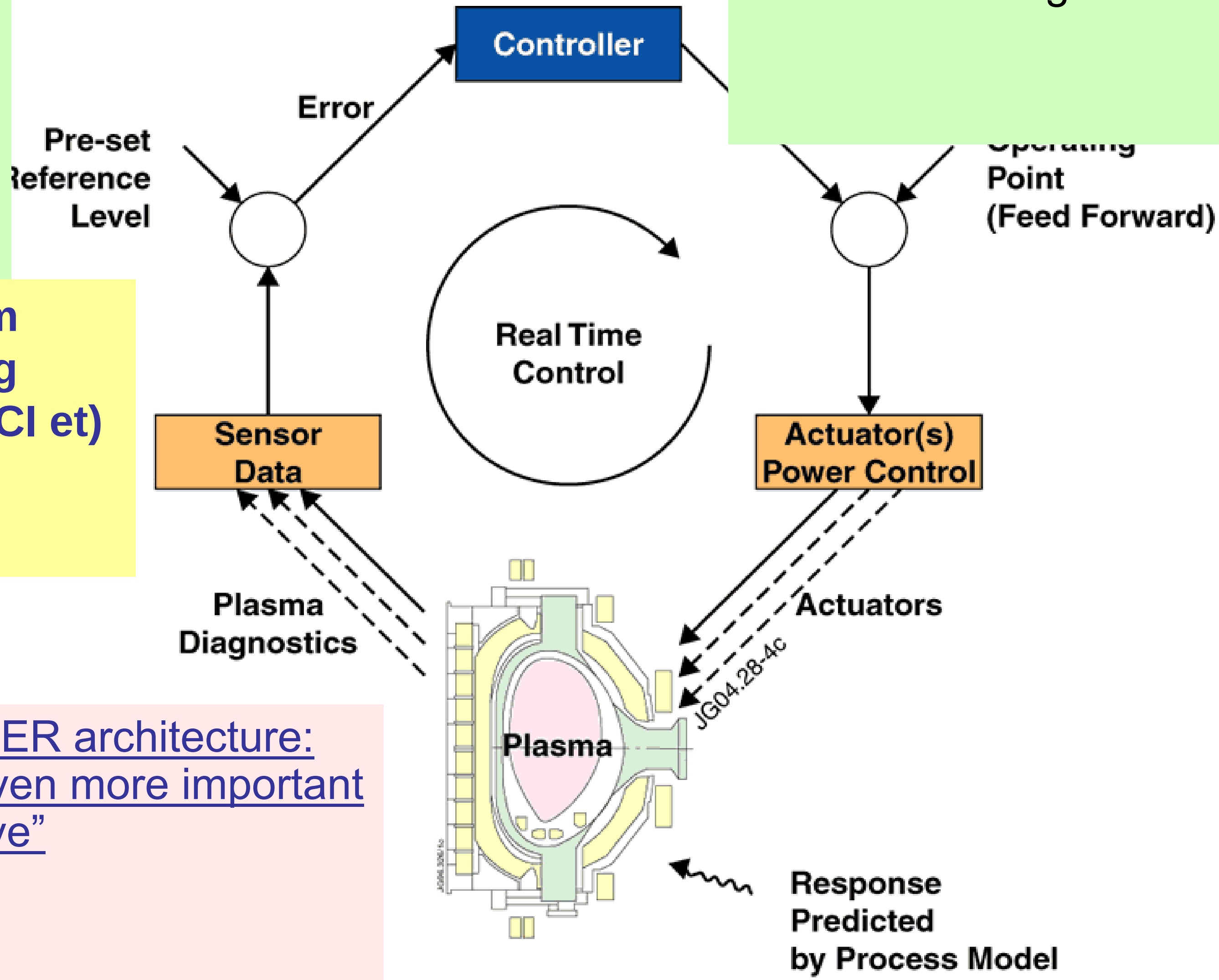
Data and knowledge derived from it are the real long term legacy of the experiments

Real time control system in JET

<u>Parameters to control</u>
Equilibrium
Profiles T_e, T_i, q, V_{rot}
neutrons, n_D, n_T

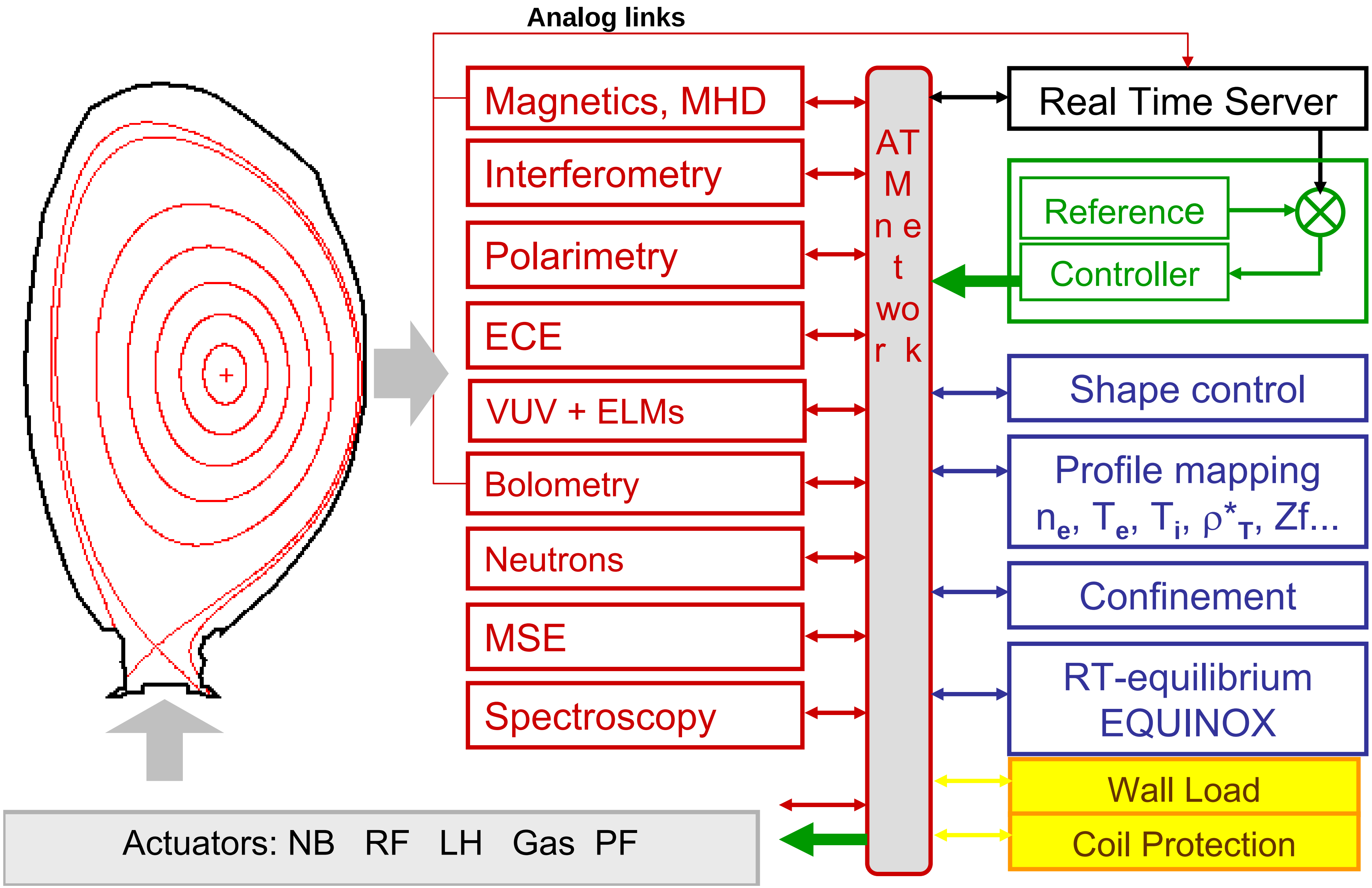
<u>Actuators</u>
PF coils & saddles coils
Heating: LHCD, ICRH, NBI
Fuelling

Distributed system
Parallel computing
Multiplatform (VME, PCI et)



<u>Good candidate for ITER architecture:</u>
<u>Flexible, efficient and even more important</u>
<u>“Adaptive”</u>

Real Time Measurements and Control network in JET

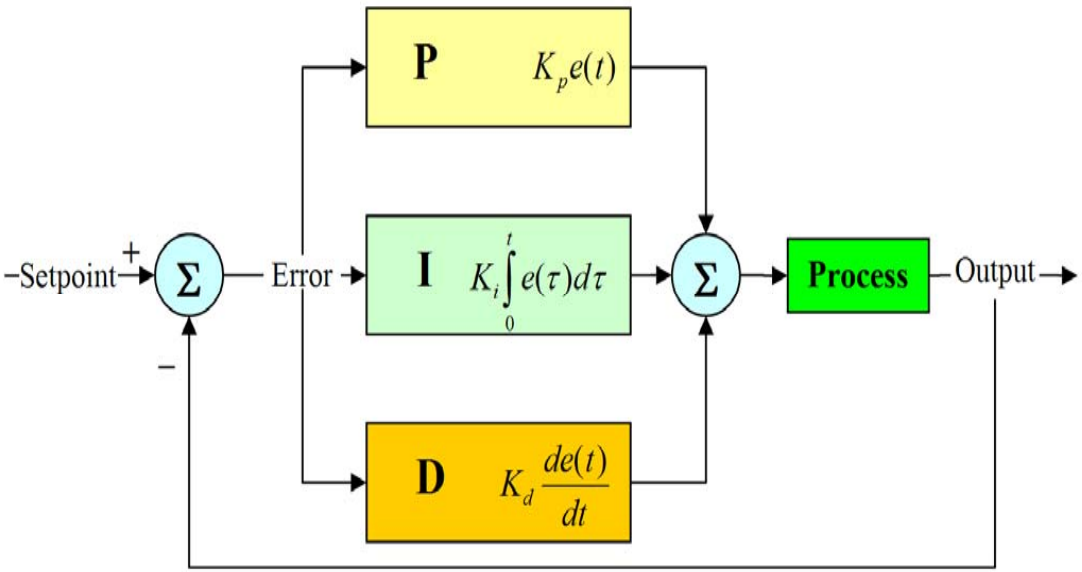


Typical closed-loop controller architecture: the PID controller

y(s) = k x(s) SISO CONTROL

Y(s) = K X(s) MIMO CONTROL

The K matrix might be diagonal (separate control) or not (coupling control)

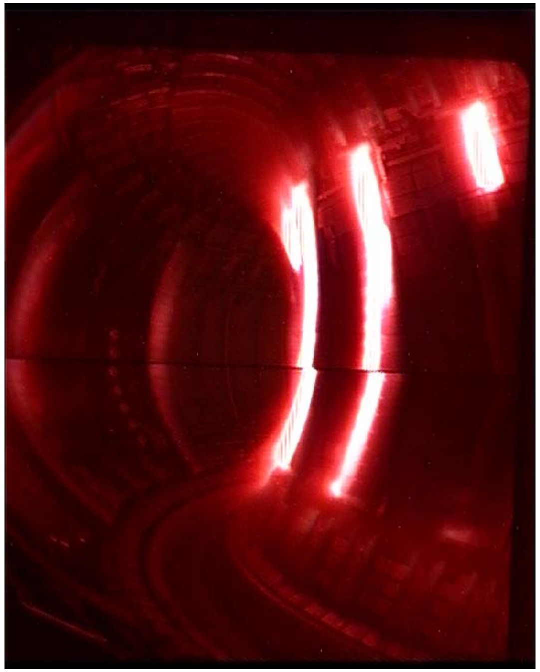


Two main difficulties:

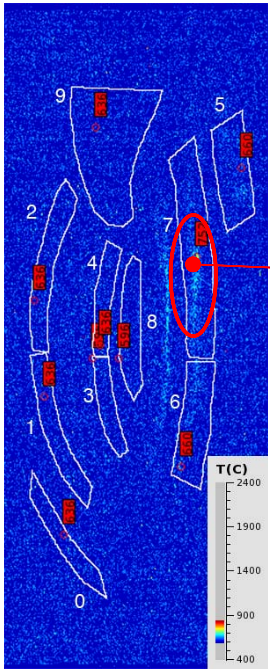
a) Determination of the model K → deducted from experimental data (open loop or neural network from database) or from physics equations

b) identification of the system (plasma) during the experiments

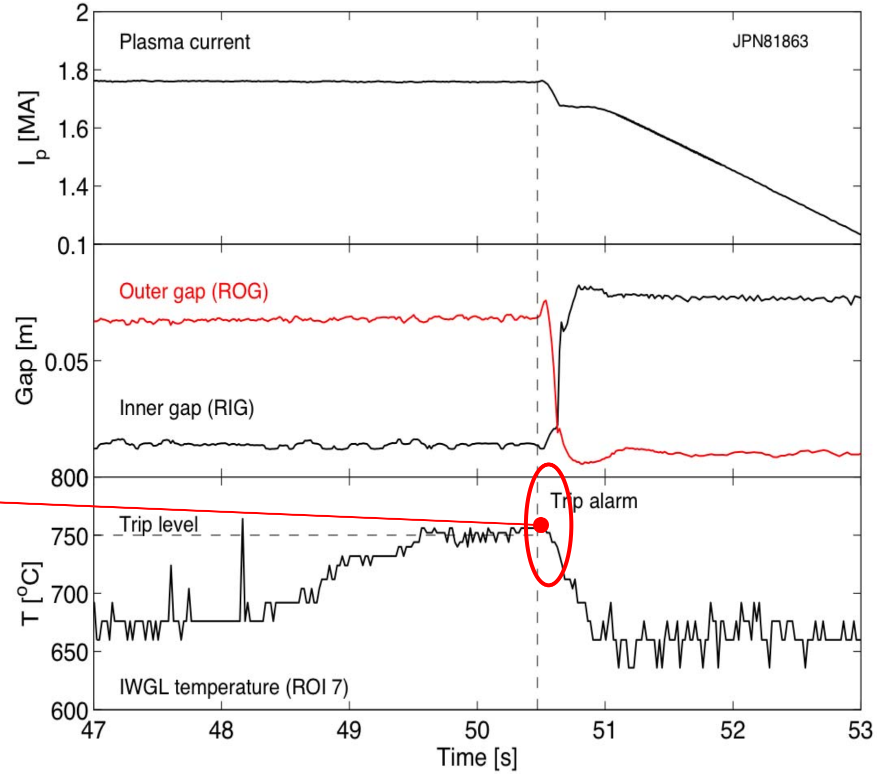
About 30 cameras operational on JET and 12 explicitly devoted to protection



Colour camera



Protection camera

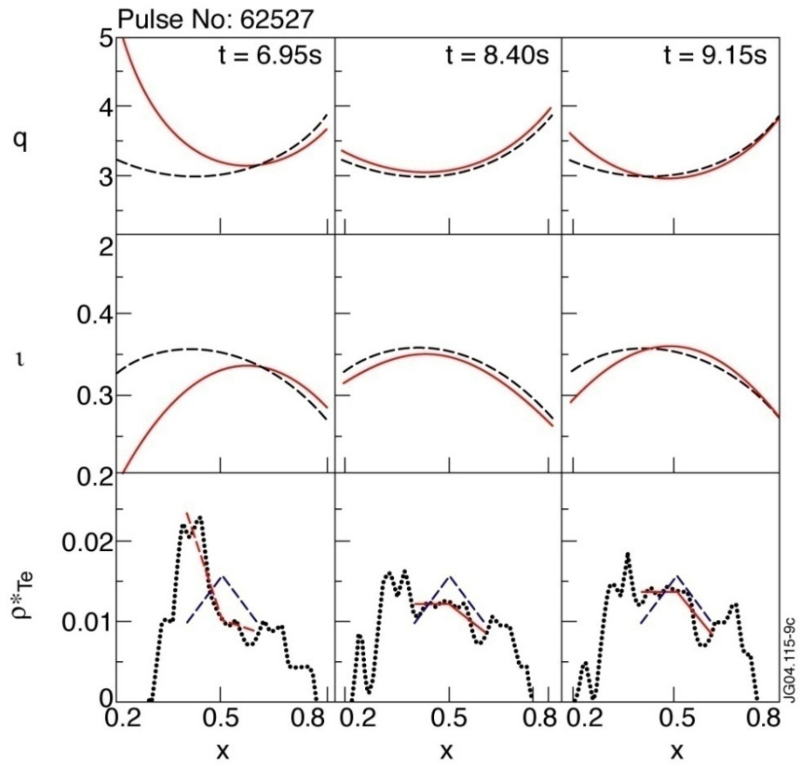


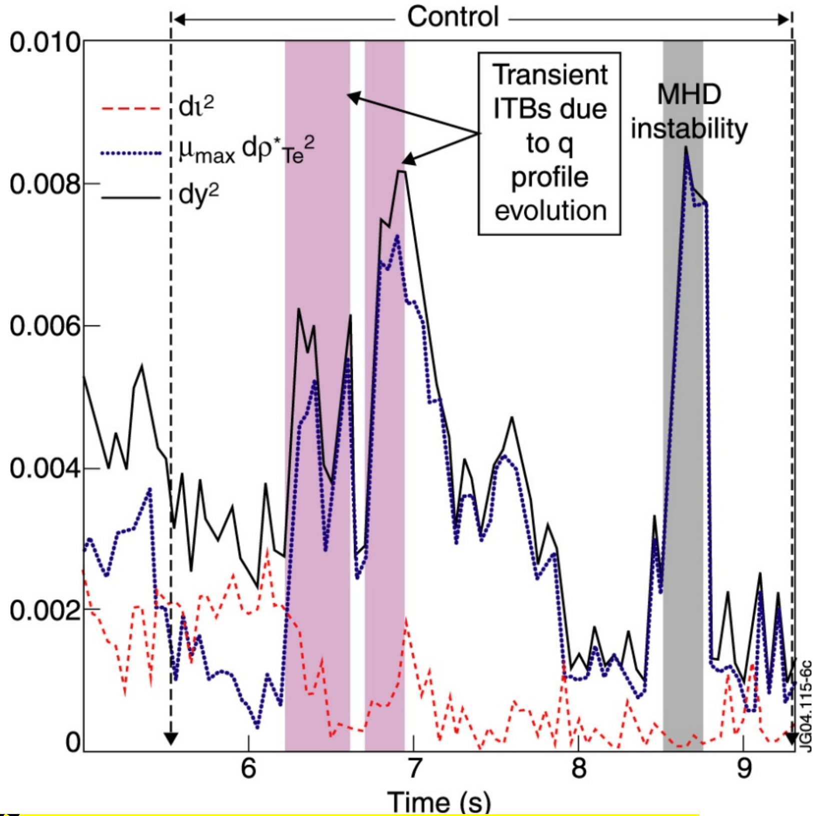
Main chamber hot spot (T > 750°C) initiates current ramp down and configuration change (from inner limiter to outer limiter configuration)

Towards simultaneous control of current and pressure profiles

Static-model control of current (q,ι) and temperature ρ_{Te}^* profiles on JET

Static gain matrix ≈ OK but controller not fast enough



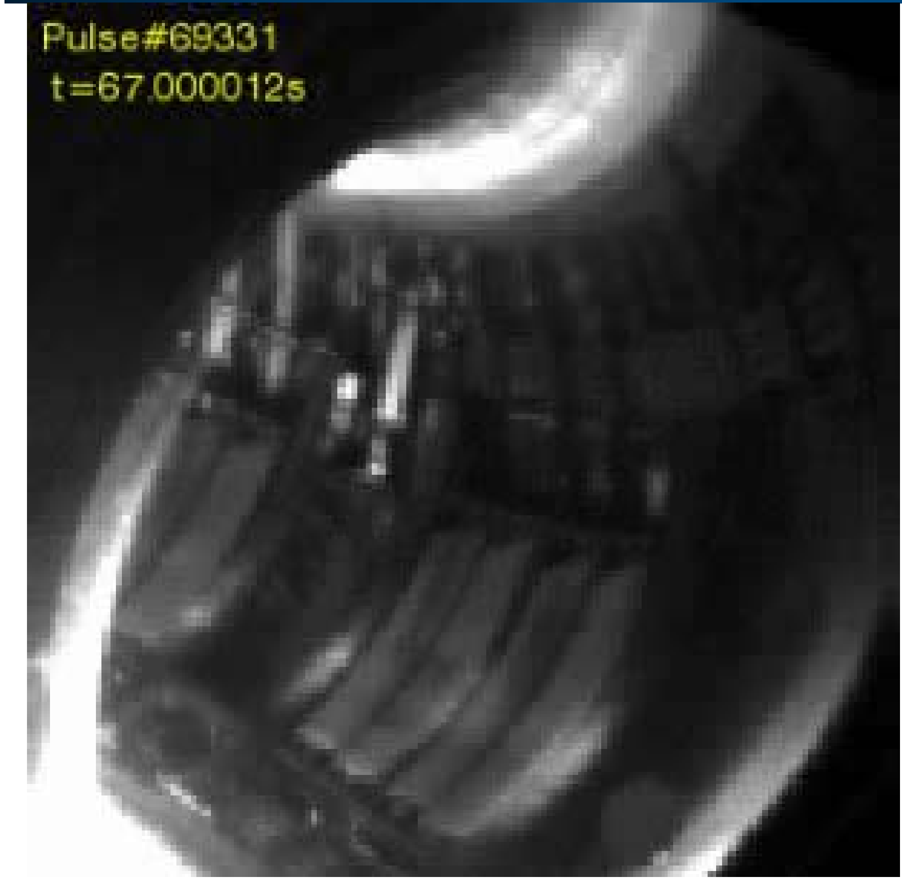


L. Labord

$$\int_0^1 \mu_1(x)\left[q(x) - q_{setpoint}(x)\right]^2 dx + \int_0^1 \mu_2(x)\left[\rho_T^*(x) - \rho_{T,setpoint}^*(x)\right]^2 dx$$

Control at different time scales required.

Disurptions

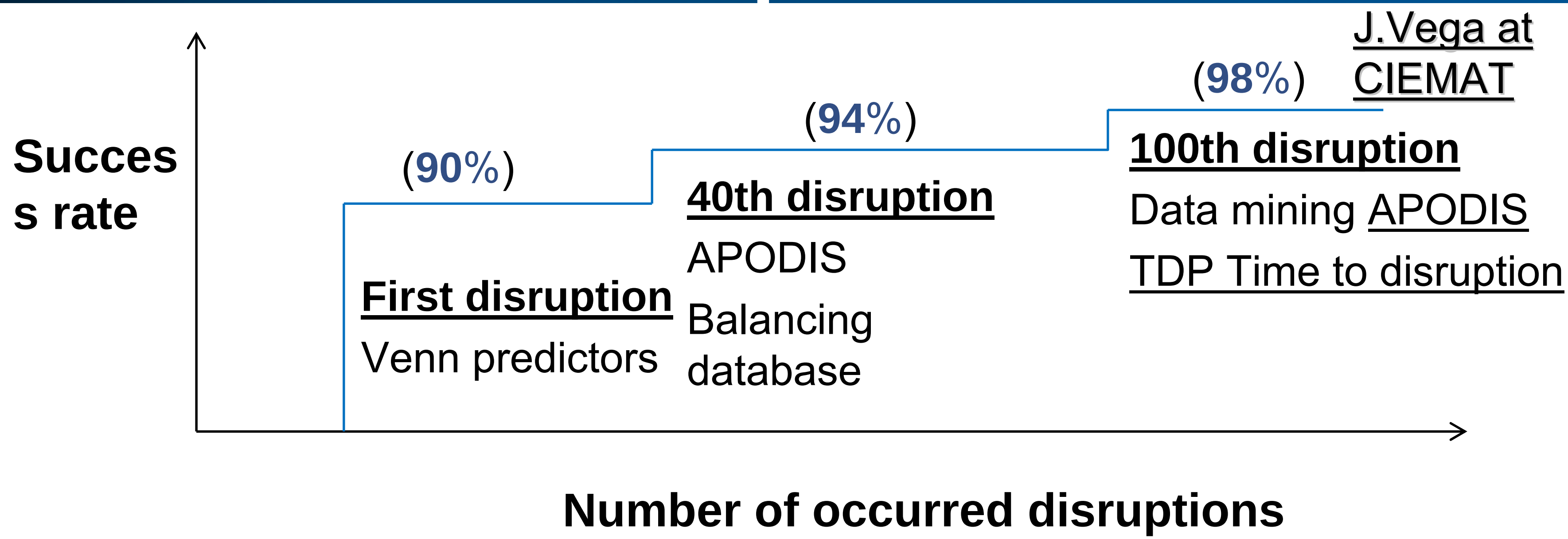


- *Disurptions: sudden losses of confinement and configuration*

- *Biggest problem for ITER*

•Data of a visible **Fast Camera: Photron APX-RS**
 1us minimum exposure time 2GB memory (210 kfps already demonstrated target 250 kfps)

Disruption Prediction



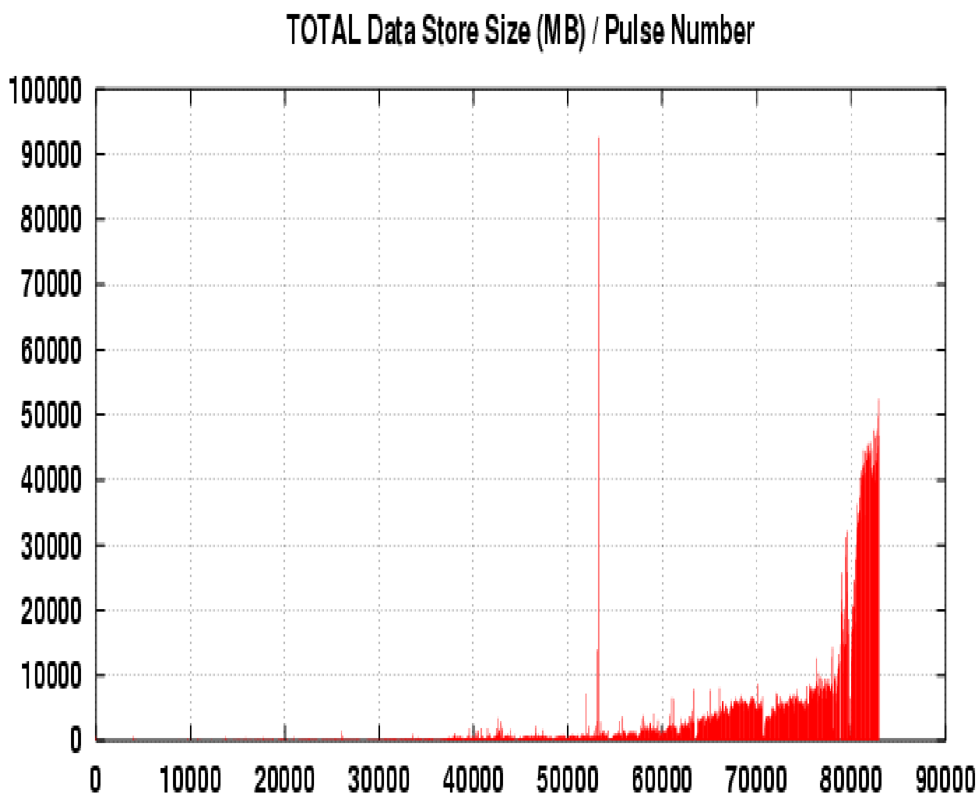
- The **APODIS** version installed to operate in real time in the ILW campaigns (C28-C30) has been trained with CFC wall data (C19-C22) and ***no retraining*** has been performed

	Safe	**False alarms**	**Successful prediction**	**Missed alarms**	**TOTAL**	**Intentional disruptions**
JET off-line classification	651	n/a	305	n/a	956	35
APODIS prediction (in real time)	645 (**99.08%**)	6 (**0.92%**)	300 (**98.36%**)	5 (**1.64%**)	956	n/a

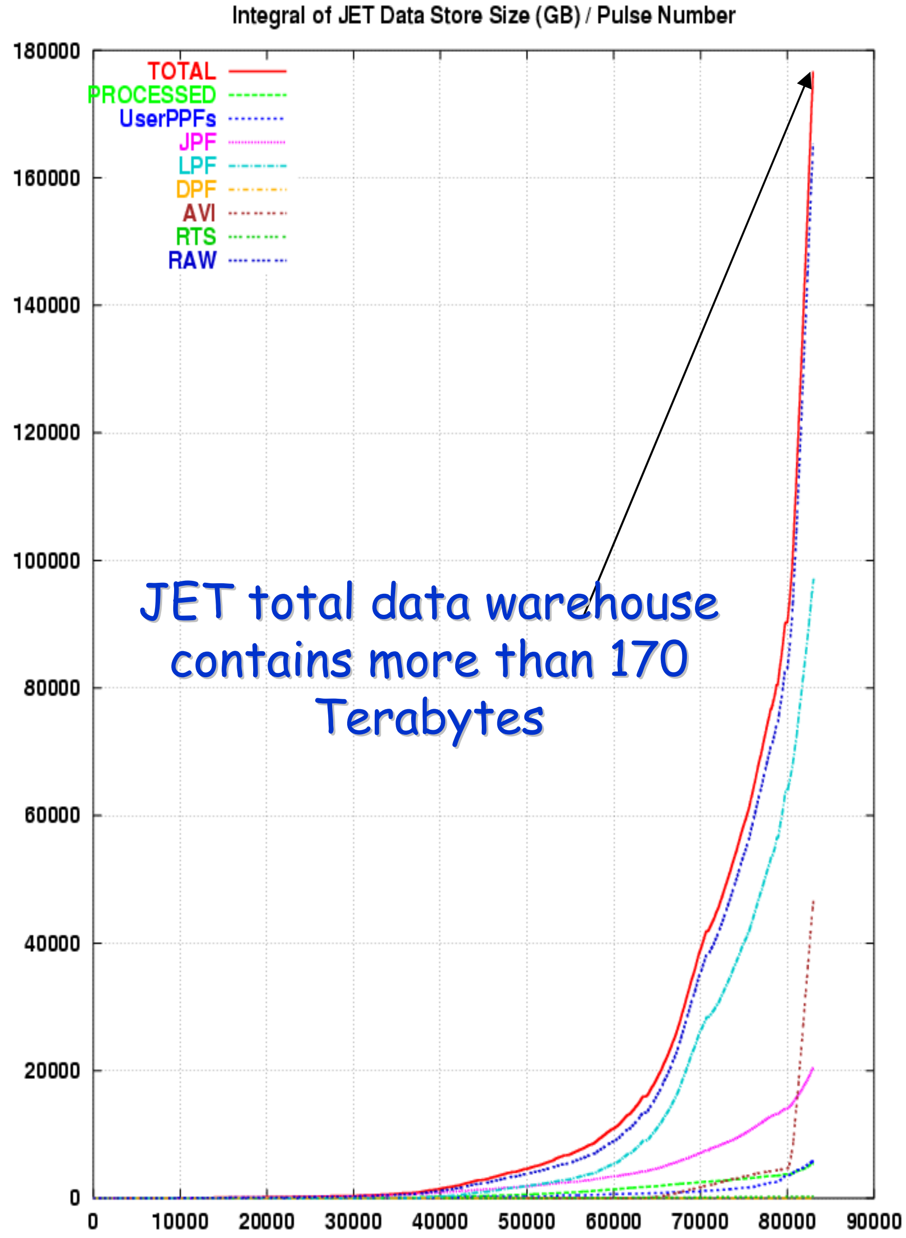
Conclusions

- Tokamak plasmas belong to the class of entities called "open or continuous systems" which are able to decrease their internal entropy at the expense of substances or free energy taken in from the environment
- They are therefore very difficult to control
- Particularly challenging is their identification
- In addition to better measurements also innovative data analysis and control methods are required

CODAS: warehouse statistics

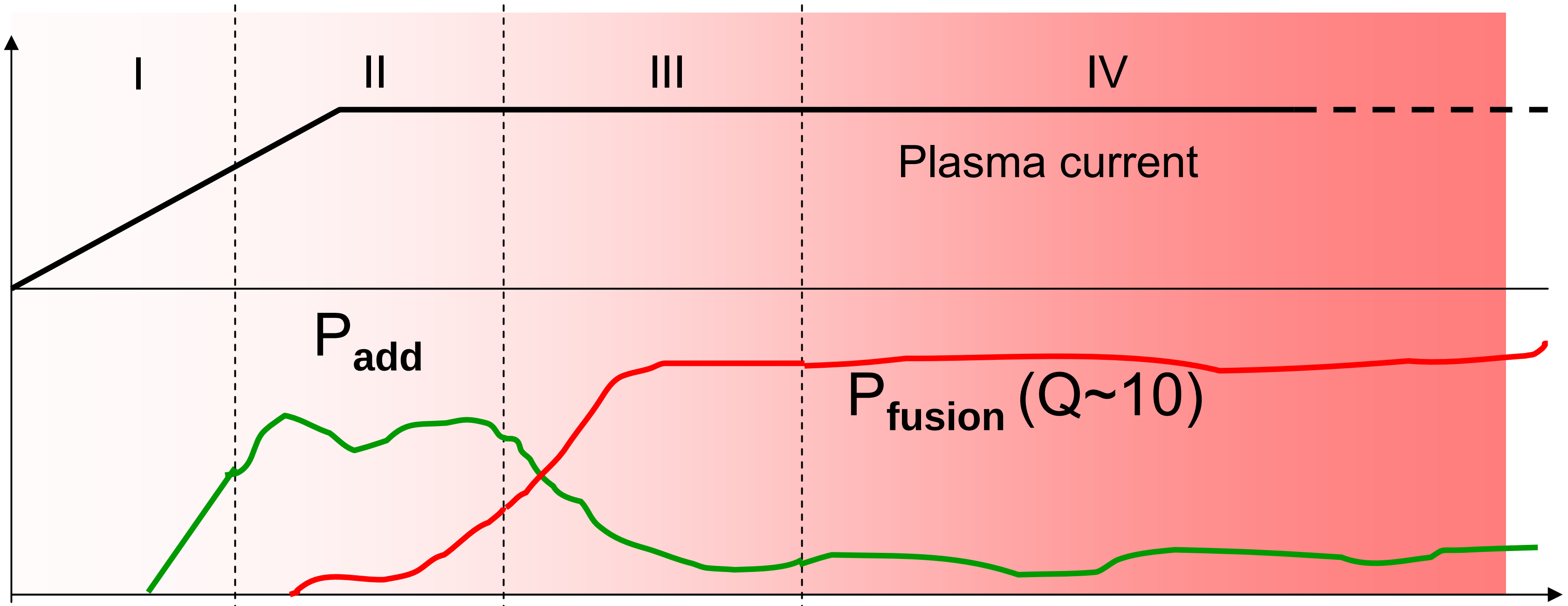


Total Raw data: a record of more than 45 Gbytes per shot has been reached



Motivations for real time control in ITER

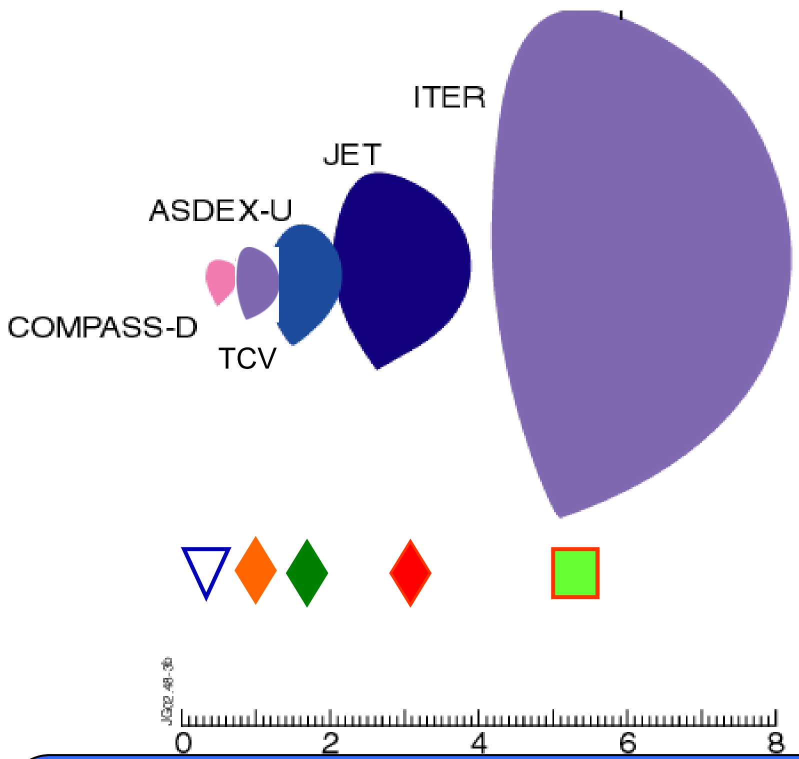
How might look a controlled advanced scenario on ITER?

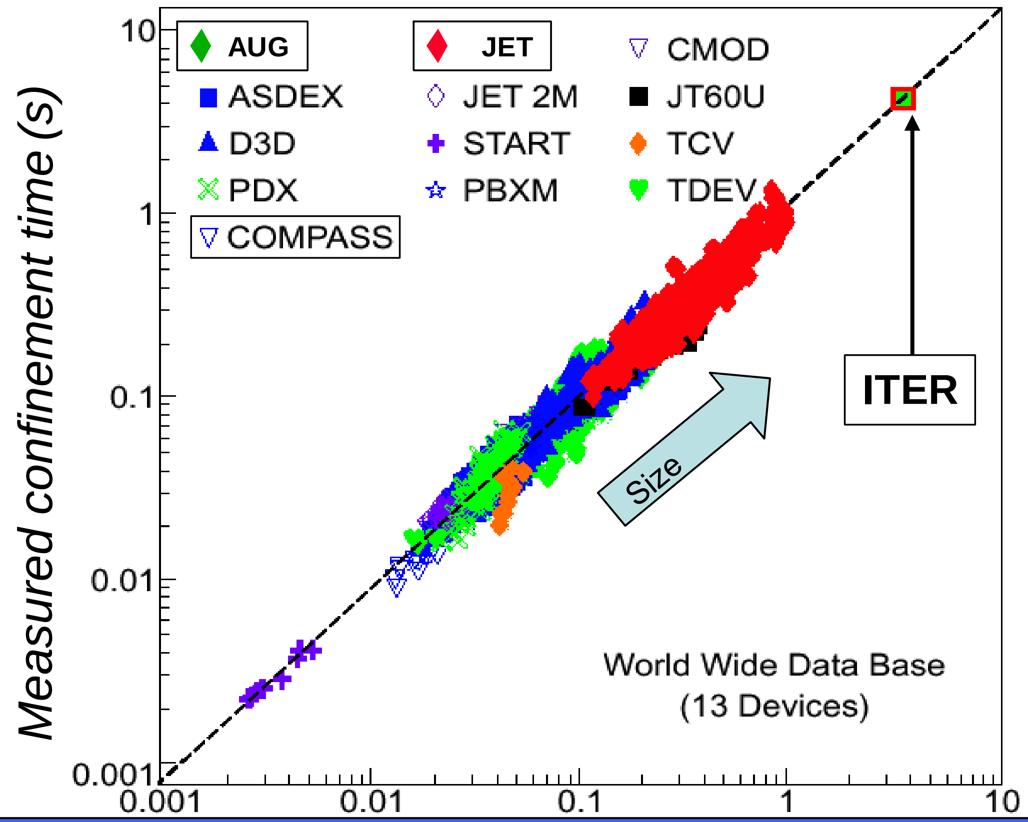


Configuration formation Assisted breakdown	Density and q profile formation + ITB triggering	Fuelling & non-inductive current optimisation	Steady state phase: • ELMs control • MHD control • Ashes + impurity exhaust • Disruption avoidance

D. Moreau et al., Nuc Fus 1999

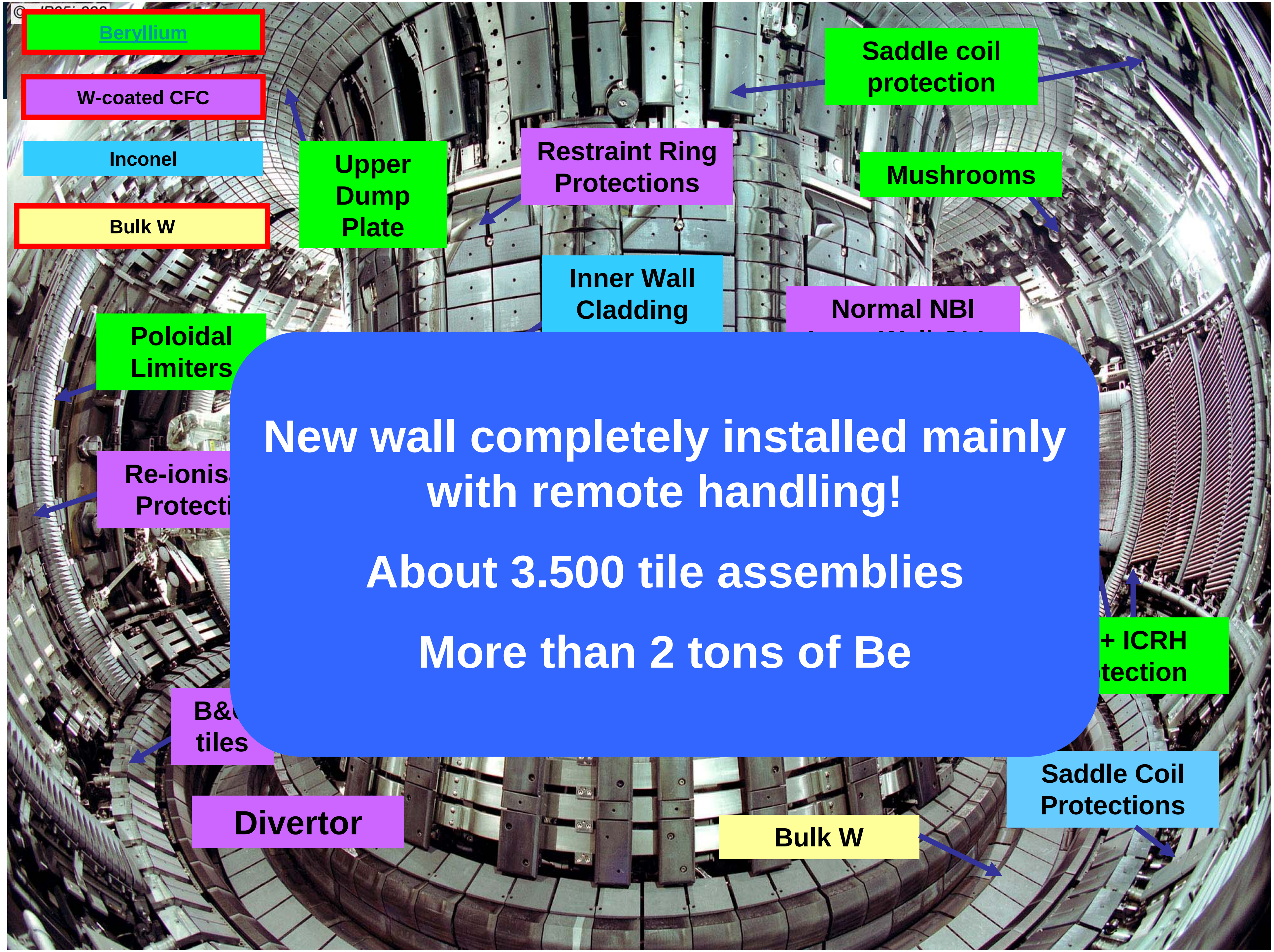
JET is the best performing magnetic fusion experiment





JET provides the point closest to ITER for the extrapolation of H-mode confinement

similar magnetic configuration

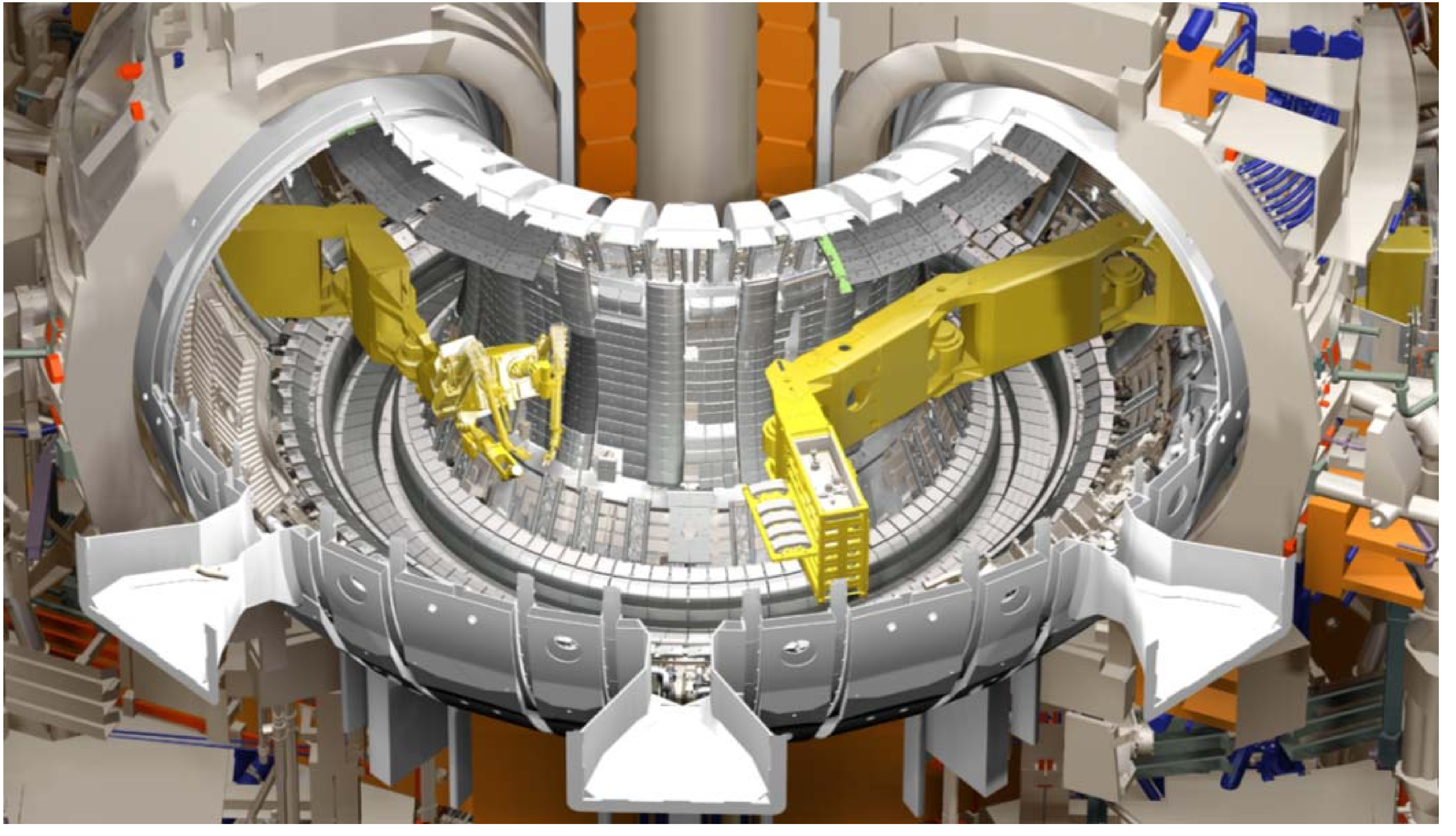


New wall completely installed mainly with remote handling!

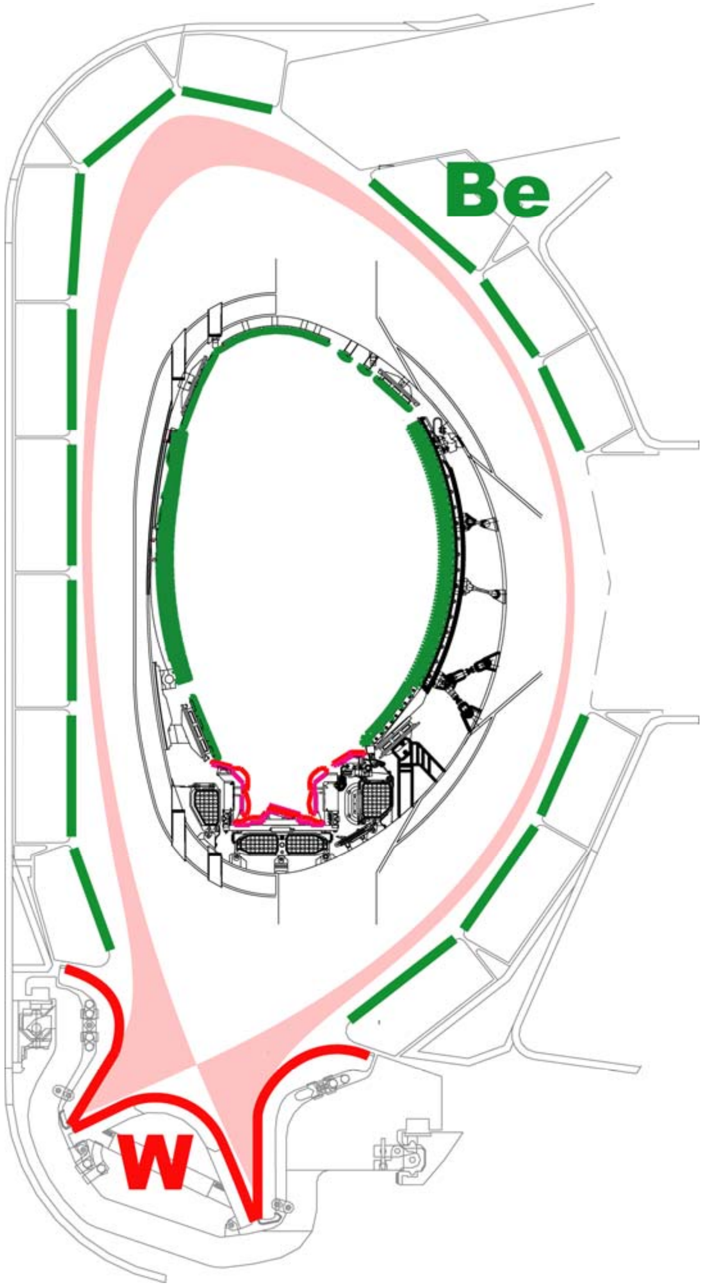
About 3.500 tile assemblies

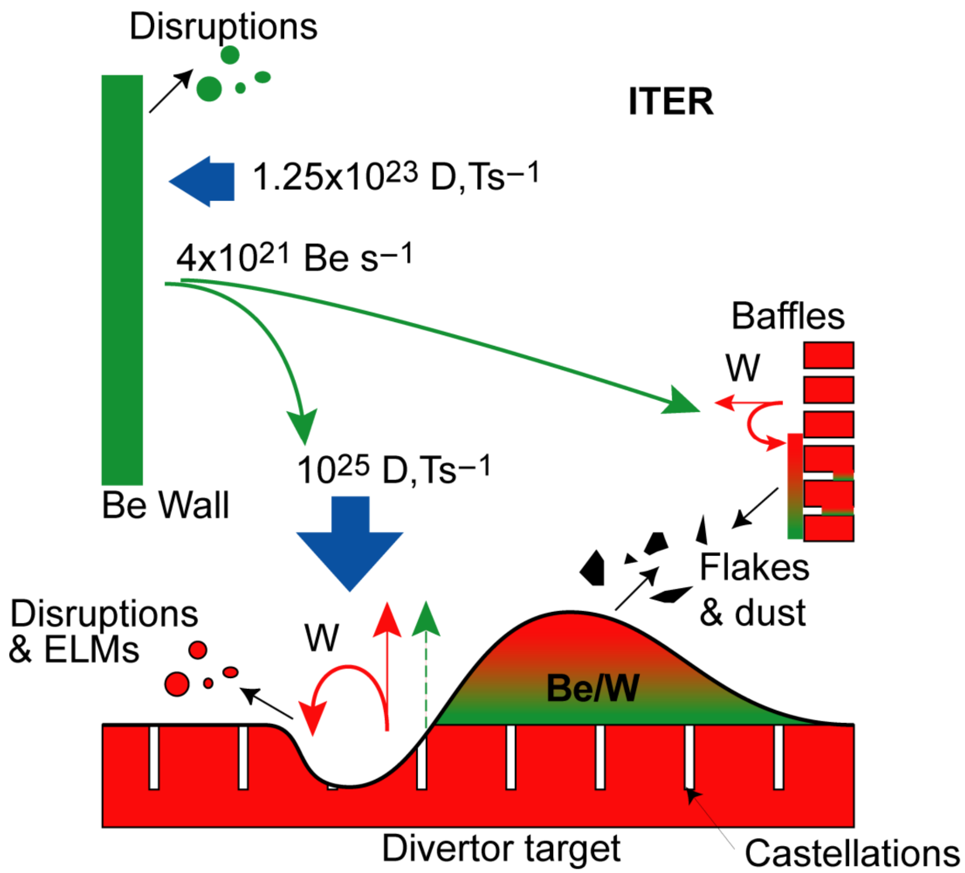
More than 2 tons of Be

Installation via Remote Handling Systems



JET ITER-like Wall

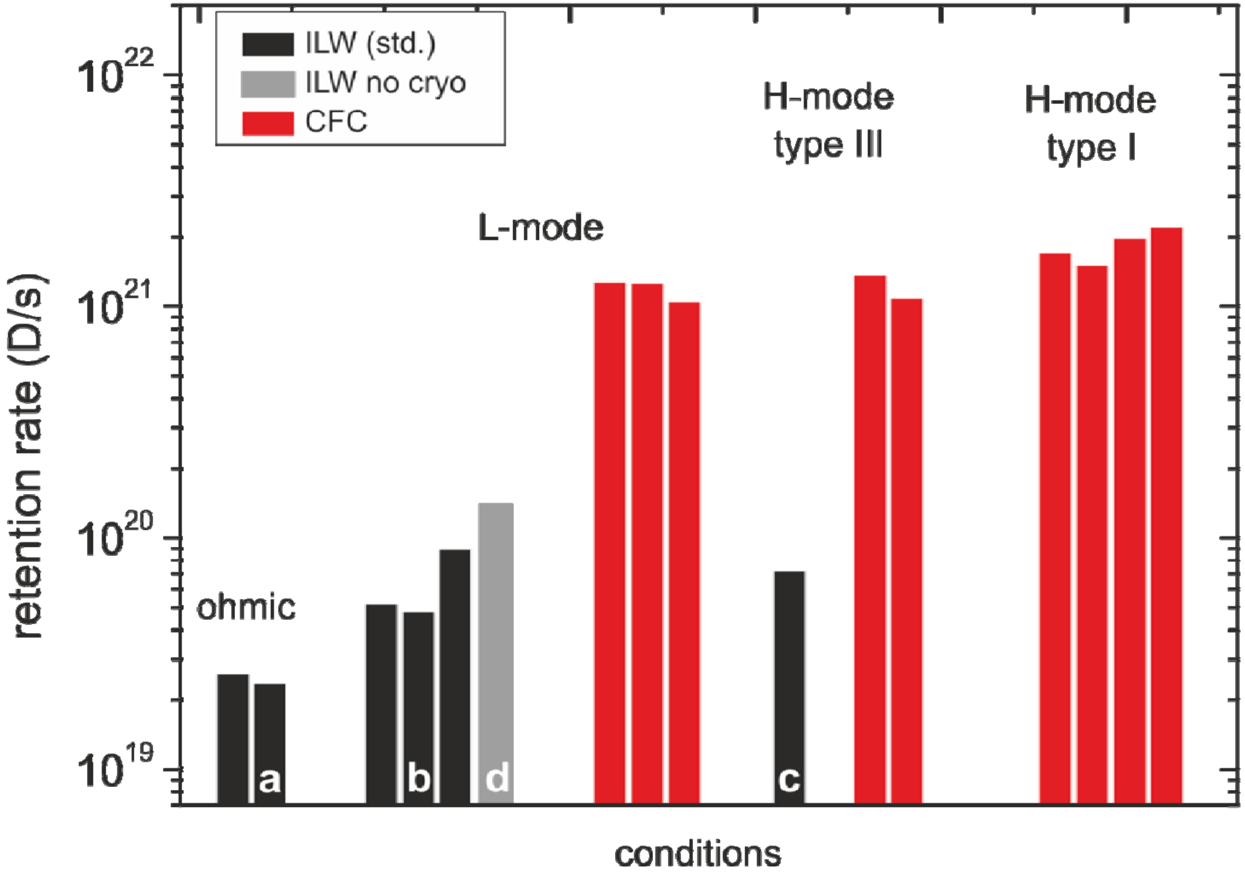




New JET Capability for EP2

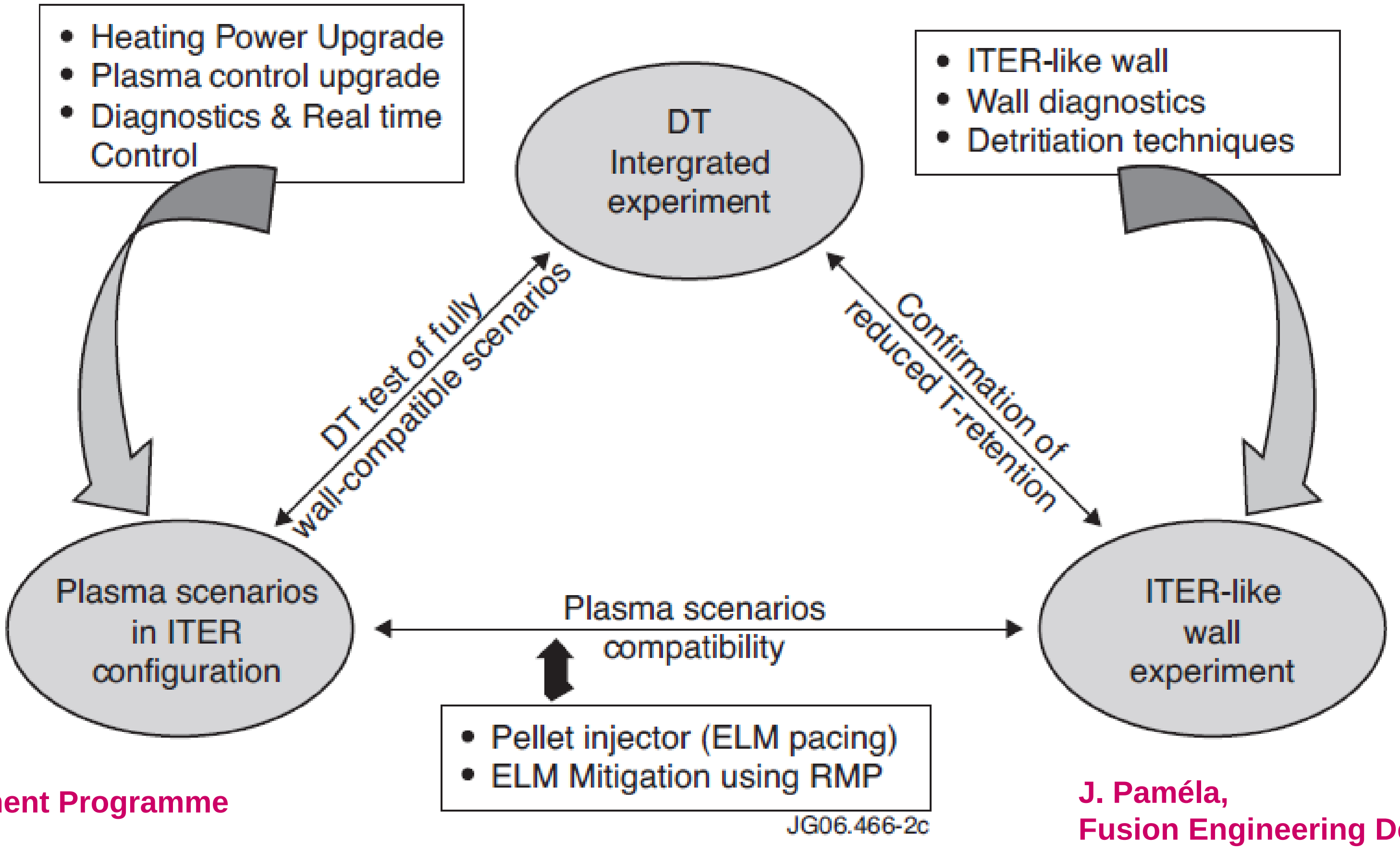
NBI:	~ 35MW
Pellets for ELM control:	50Hz
Enhanced spectroscopic coverage	

Reduction in Fuel Retention with the ILW in Comparison with the CFC Wall



- Robust and reproducible result from gas balance studies
- Reduction of fuel retention by at least one order of magnitude

Strategic Context for JET

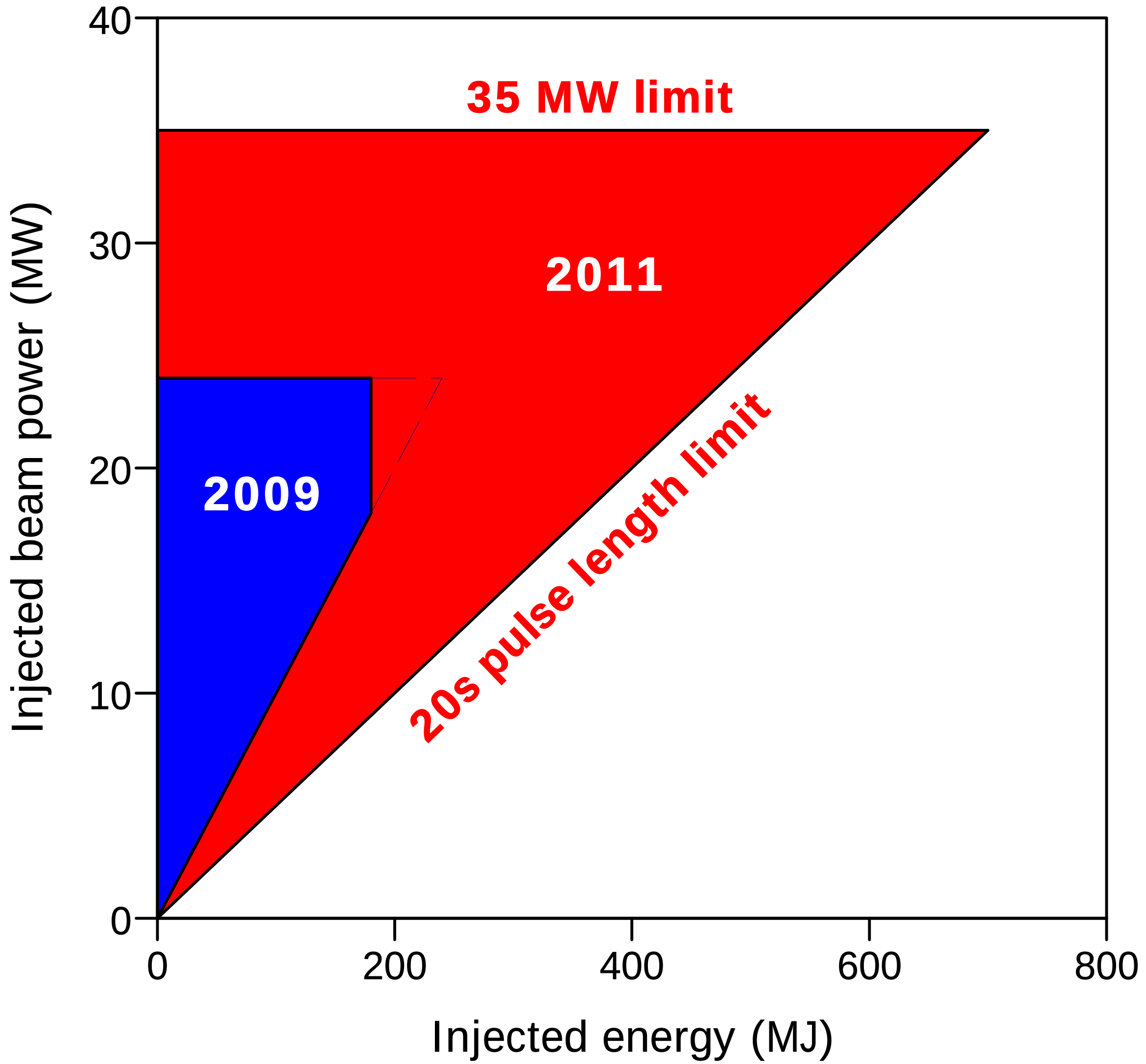


EP2 Enhancement Programme

J. Paméla,
Fusion Engineering Design, 2007

Coherent approach in a multi-annual "JET programme in support of ITER" based on the full exploitation of the ILW

Neutral Beam Enhancement

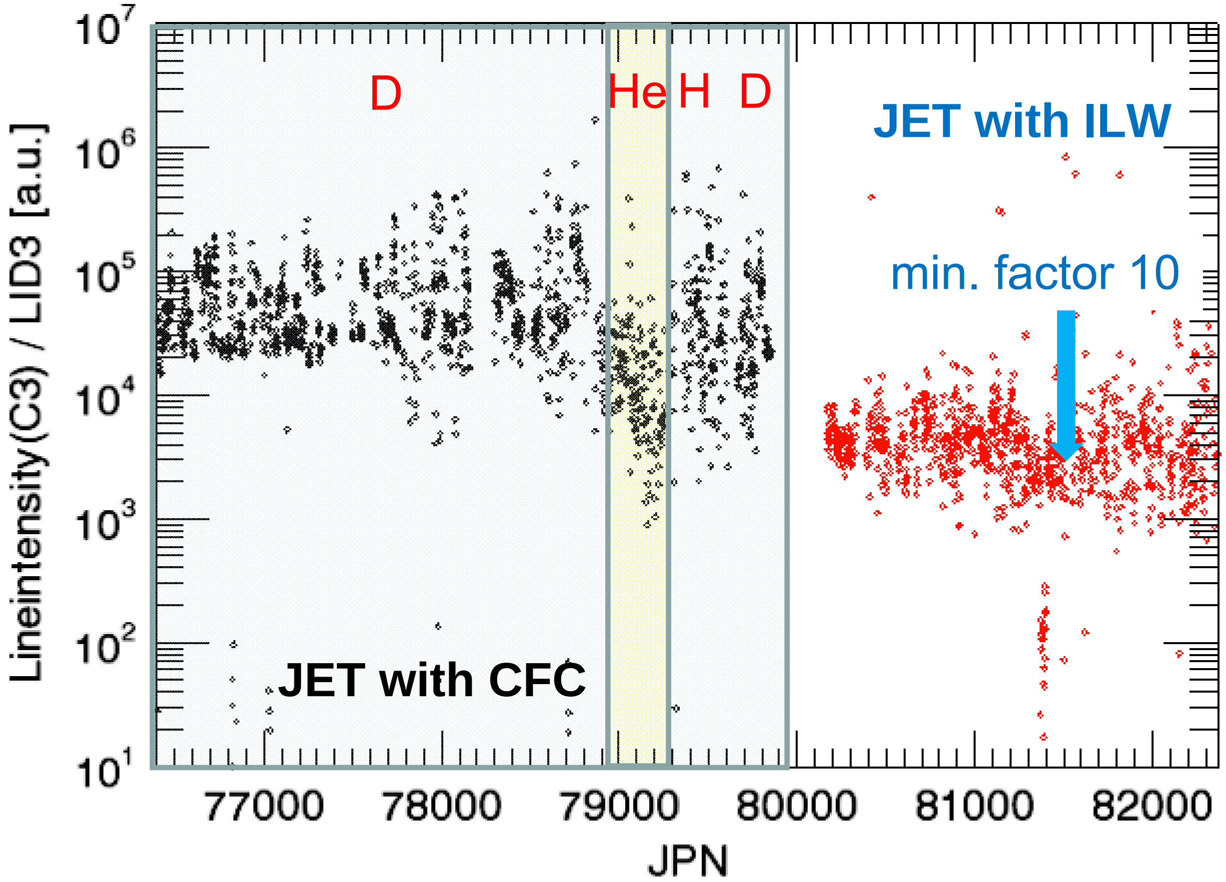


NB Operating Space (D_2)

New power supplies
Major reconfiguration
New PLC controllers
Reactive Power
Compensation

Reduction in impurity content with the ILW in Comparison with the CFC Wall

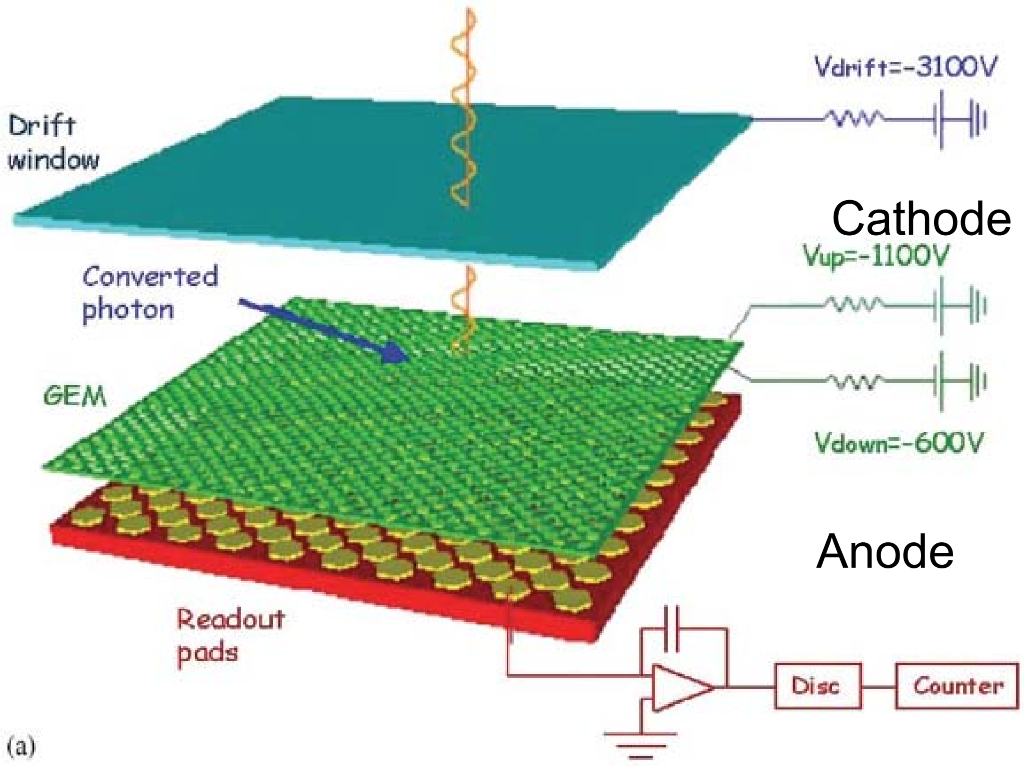
Evolution of carbon in the plasma edge (CIII at 97.7nm) during the last campaigns with CFC walls and the ILW



- Reduction of C content by at least one order of magnitude

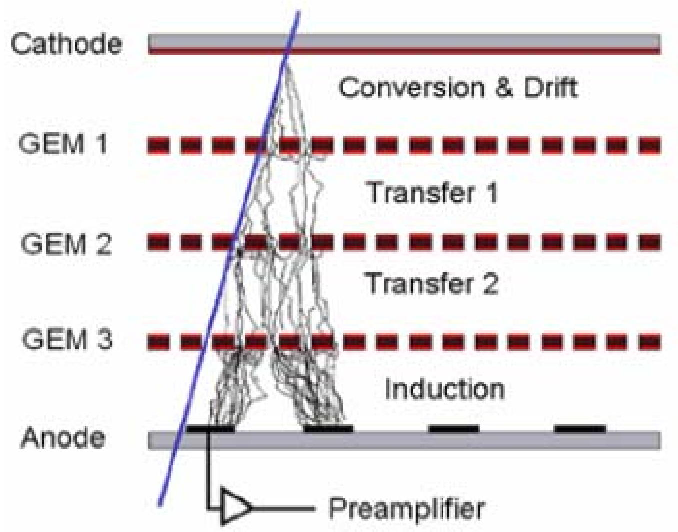
Plasma Boundary with SXR: the GEM Detector

- Pick-up coils have problems in a radiation hard environment (close to the plasma, integrators etc)
- The next generation of plasmas will be so hot that even the boundary will emit in the SXR
- Adapt Gas Electron Multipliers detectors



(a)

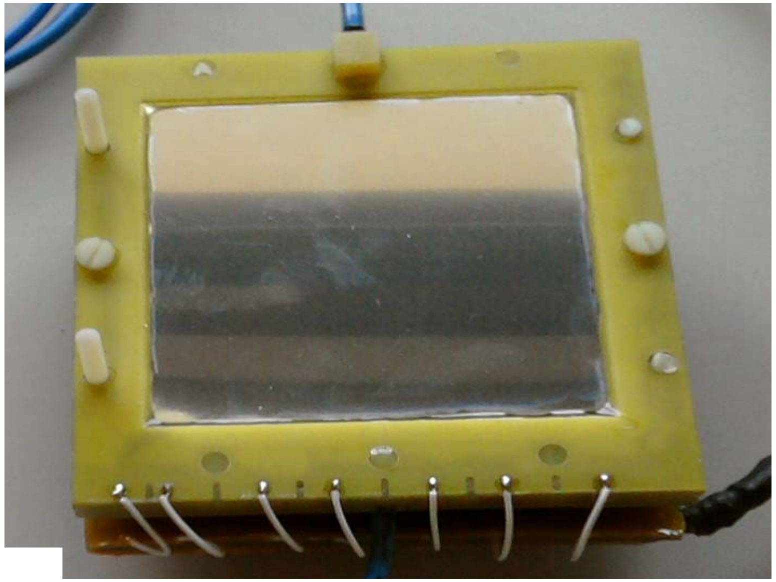
Current~few nA



The triple GEM Detector

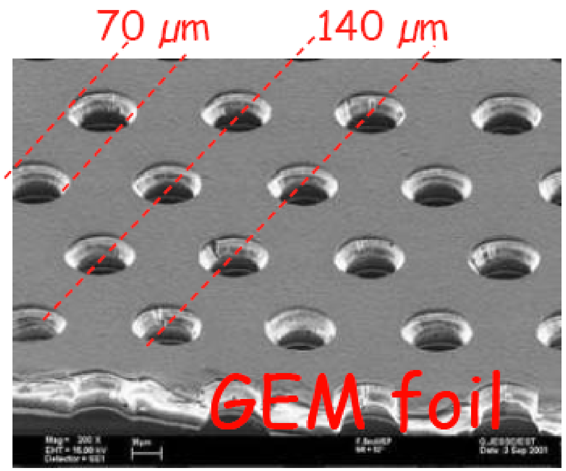
Main potential advantages:
- Flexible
- Radiation hard
- High count rate

Mylar foil with aluminium

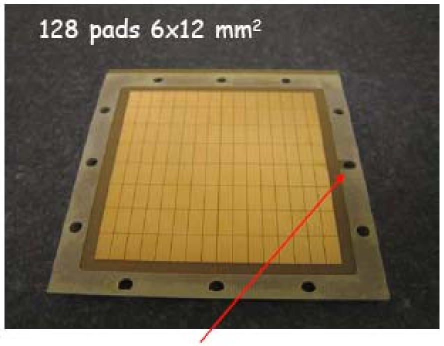


10cm*10cm

The capability of properly simulating these detectors has improved dramatically recently

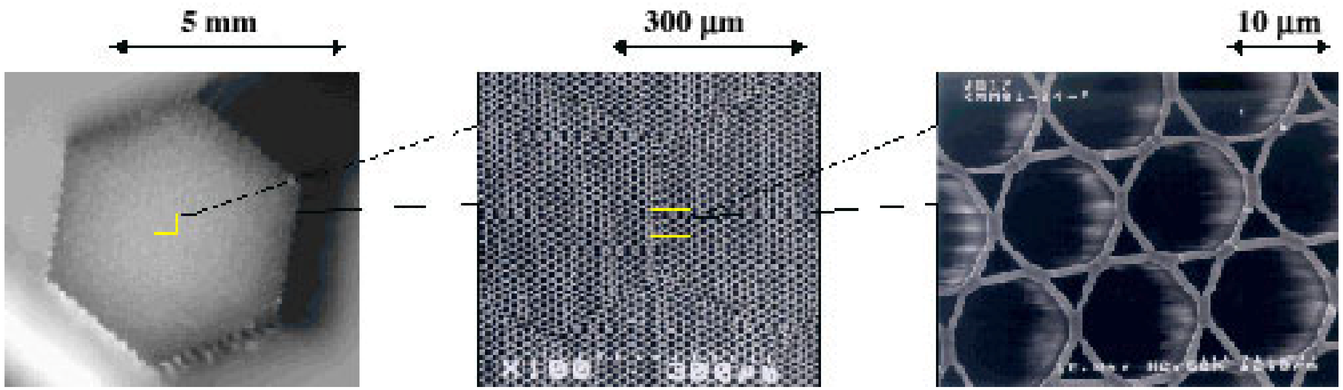


Width 50 μm (Kapton)



Basic principles of polycapillary optics

- Polycapillary lenses to locate the detectors far from the plasma
- Polycapillary optics are comprised of 10^4-10^6 hollow glass channels bundled together
- X-ray photons propagate in the hollow space of the capillary channels by the process of total reflection at the glass surface



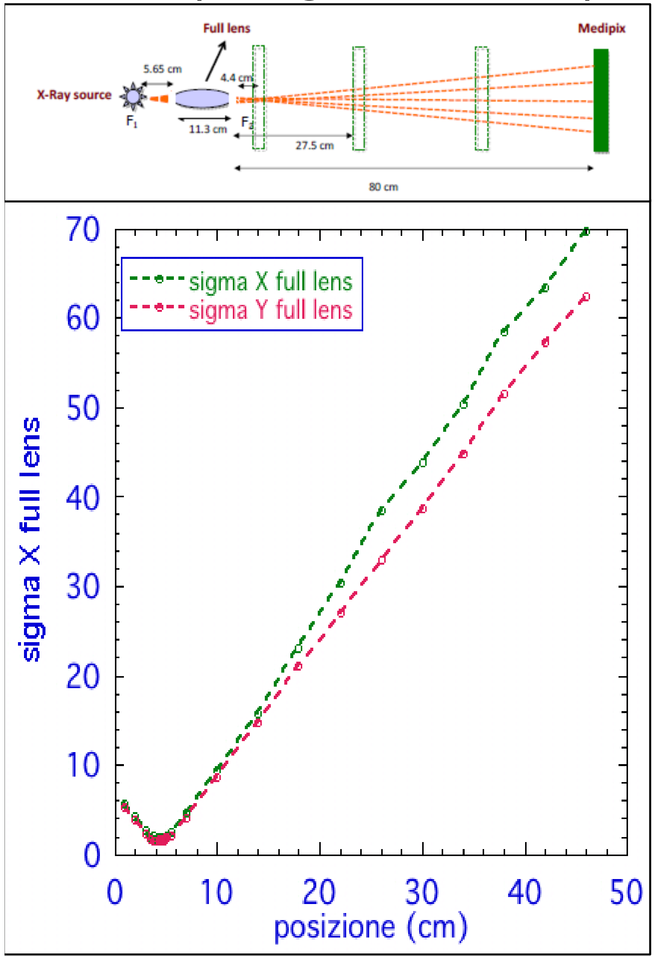
- Reflection of photon occurs at the boundary between media with different refractive indices
- Total external reflection of X-rays from a glass surface occurs when the incident beam strikes the glass surface at an angle ≤ the critical angle θ_c

$$\theta_c(mrad) \cong \frac{30}{PhotonEnergy(KeV)}$$

- e.g.: θ_c=3.8mrad(0.22o) for 8.0KeV(K_α Cu)

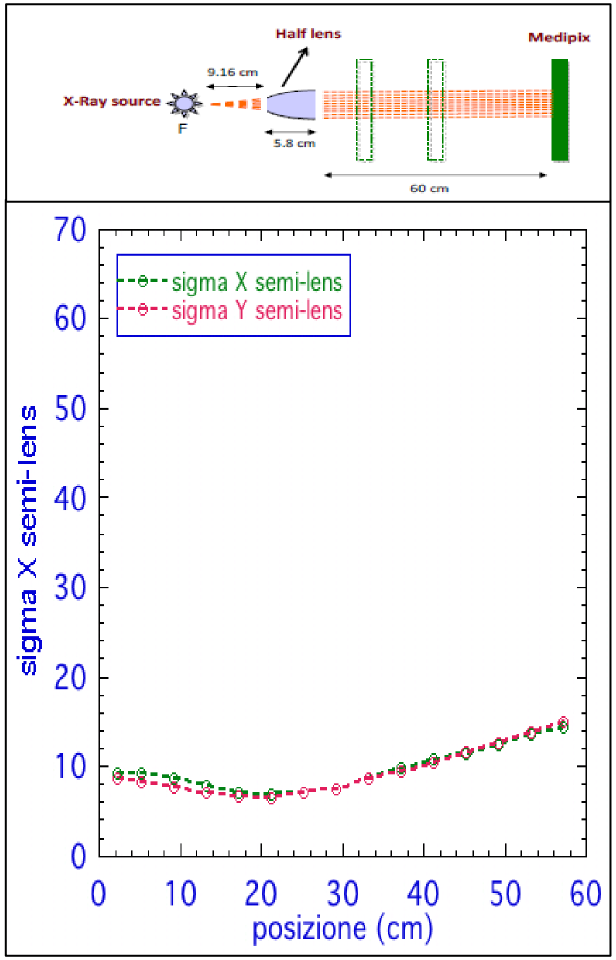
Preliminary tests on polycapillaries as SXR lenses

Full lens
Diverging beam
(magnification)

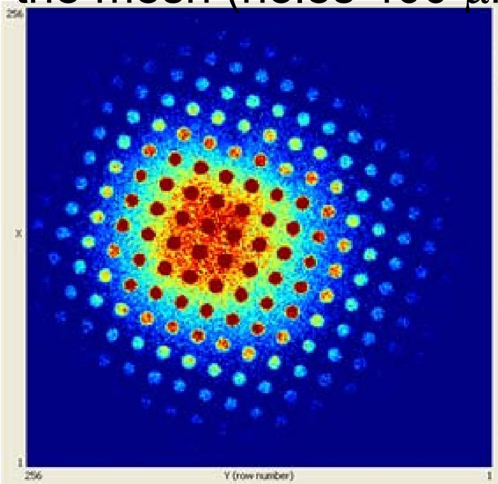


Half lens

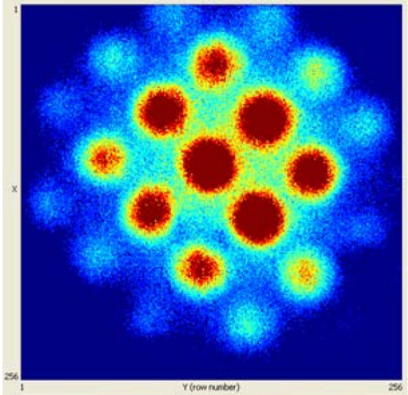
Parallel beam



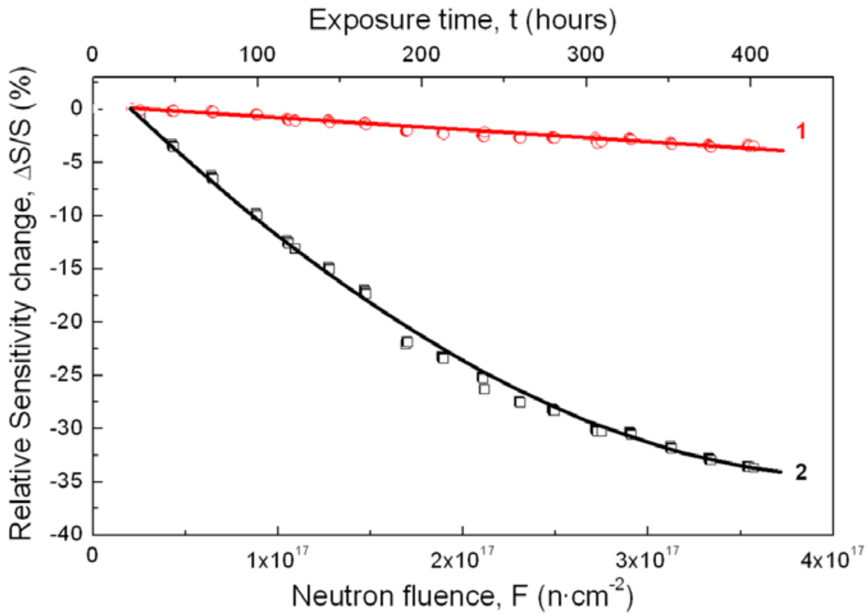
SXR radiography
of the mesh (holes 400 μm)



SXR image of the mesh with full lens (magnification ~6)



Hall sensors resistance in radiation environment



Sensors sensitivity change vs. neutron fluence:
1 – radiation-resistant sensor;
2 – conventional sensor

InSb-based sensors are operable up to neutron fluences $F = 5\cdot10^{18}$ cm^{-2}, which exceed maximum fluence in ex-vessel sensor locations at ITER

$F = 10^{15}$ cm$^{-2} \rightarrow \Delta S/S = 0.04\%$

$F = 10^{16}$ cm$^{-2} \rightarrow \Delta S/S = 0.08\%$

$F = 10^{17}$ cm$^{-2} \rightarrow \Delta S/S = 5\%$

$F = 10^{18}$ cm$^{-2} \rightarrow \Delta S/S = 10\%$

Nuclear reactors

Sensor testing in ITER-relevant neutron fluxes

IBR-2
Joint Institute of Nuclear Research, Dubna, Russia

WWR-M
Petersburg Nuclear Physics Institute, Russia

WWR-Ts
Institute of Physical Chemistry, Obninsk, Russia

LVR-15
Nuclear Research Institute, Řež, Czech Republic

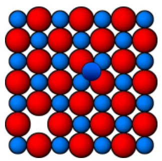
Radiation physical processes occurring in InSb-based Hall sensors under irradiation

Neutrons

Fast → **Semiconductor** ← **Thermal**

Radiation defects ⟷ **Mutual compensation** ⟷ **Nuclear doping**

Acceptors



Minimal sensor parameter drift

(subject to correction with dedicated electronic methods)

Donors

$$^{115}In(n,\gamma)^{116}In \xrightarrow[54\,\text{min}]{\beta} {}^{116}Sn$$

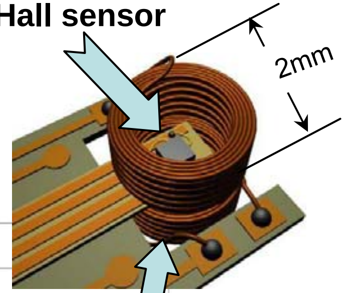
(97,5% of possible reactions)

Methods for stabilizing the semiconductor sensor parameters:

- Chemical doping of semiconductor materials (InSb, InAs) with the complex of doping impurities (donor, isovalent, rare-earth ones) up to optimal initial concentration of free charge carriers.
- Radiation modification – preliminary introduction of certain number of radiation defects.

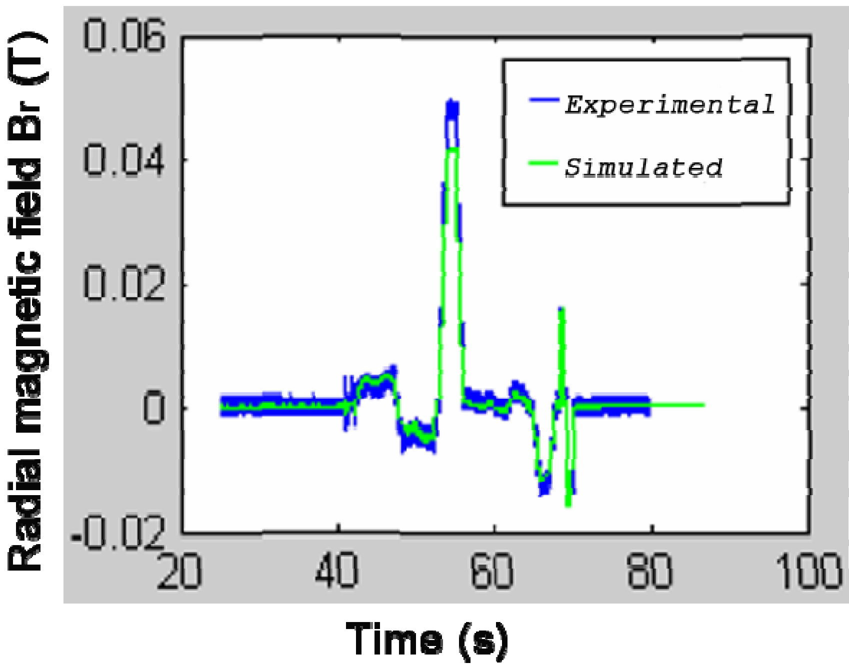
JET: Radiation-hard ex-vessel Hall Probe locations

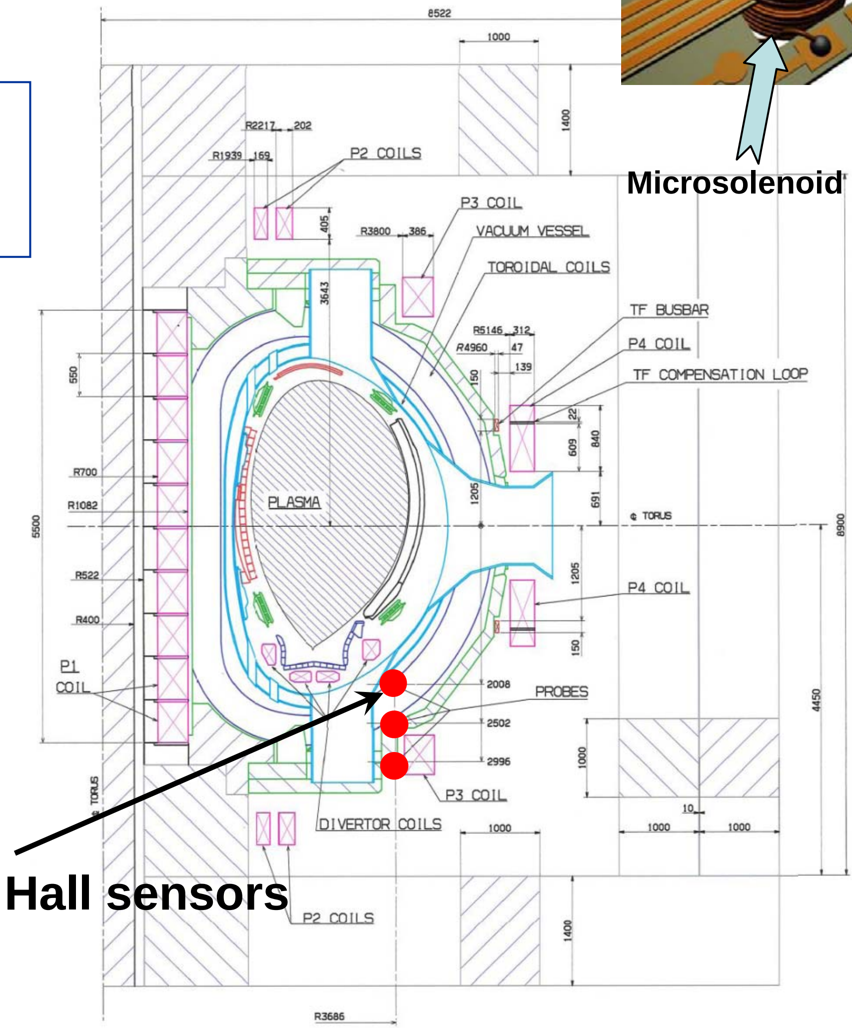
6 Hall Probes with
18 Hall Sensors and
18 microsolenoids
→ in Octants 5 & 8, Sector D, Ports



Prompt effects to be assessed in D-T

#79206.



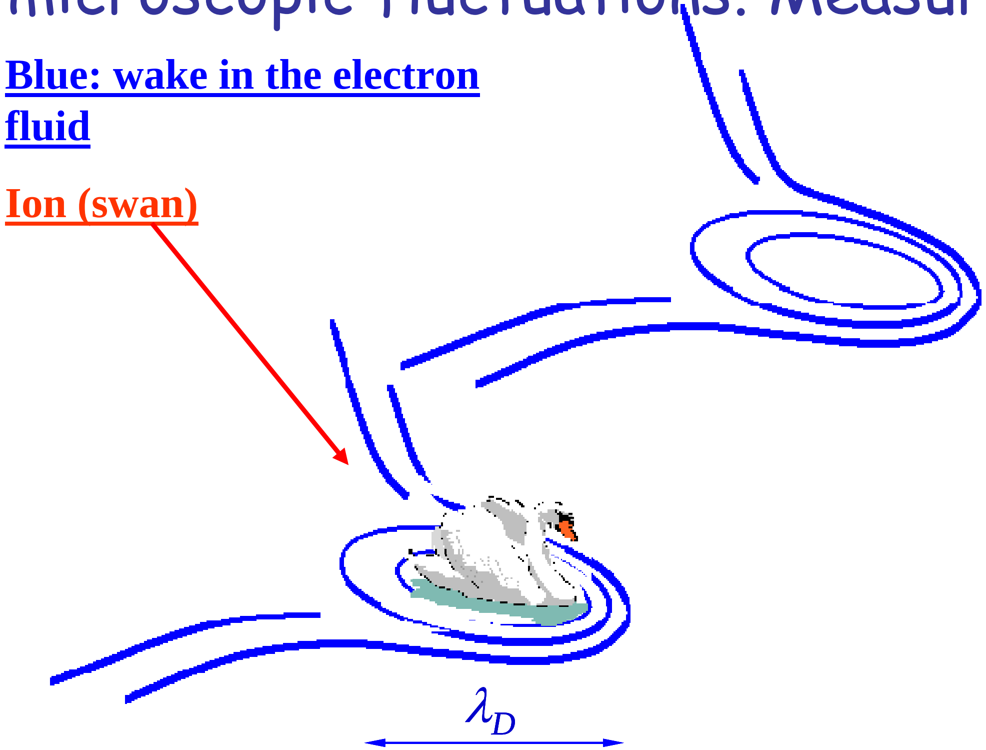


Collective Thomson Scattering

Contrary to high energy physics in Fusion the tendency is to use longer wavelengths to probe the ion fluid and to investigate collective effects.

Fast ions, being fully stripped, are nearly invisible but their wakes in the electron fluid give them away.

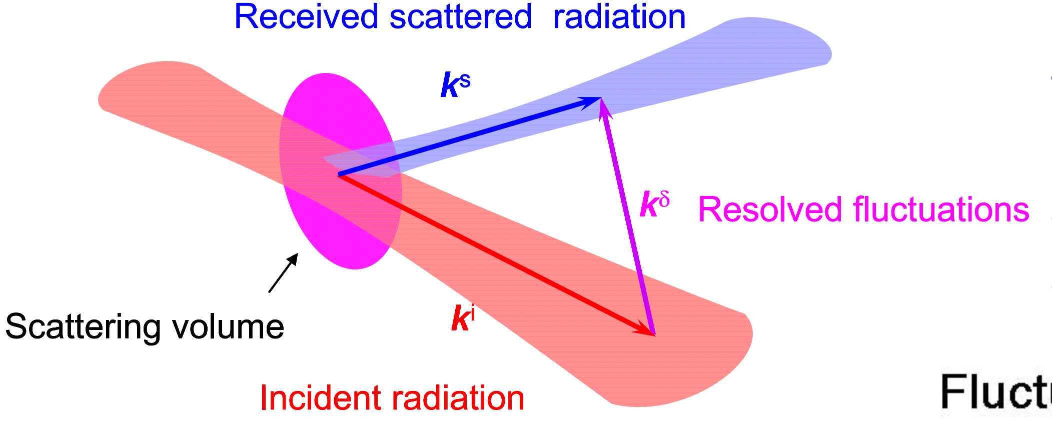
Fast ions draw a wake in the electron distribution, detectable by Collective Thomson Scattering (CTS). And at scales larger than the Debye length ion wakes are the dominant cause of microscopic fluctuations. Measurement of a collective effect.



Light scattered coherently from the electrons give information about the presence of the fats ions.

Contrary to the high energy physics longer laser wavelengths are required to detect this collective effect.

Collective Thomson Scattering

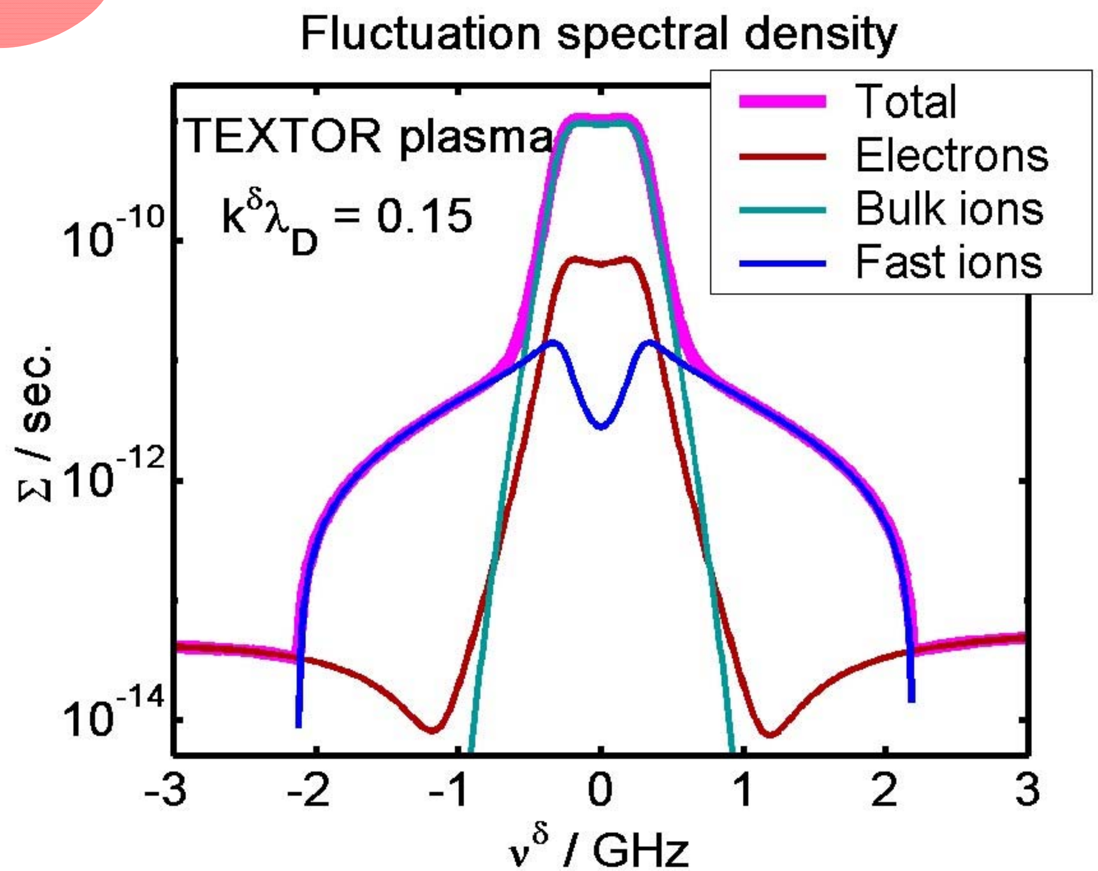


Forward scattering only viable alternative to measure the wake of the fast ions on the electron fluid

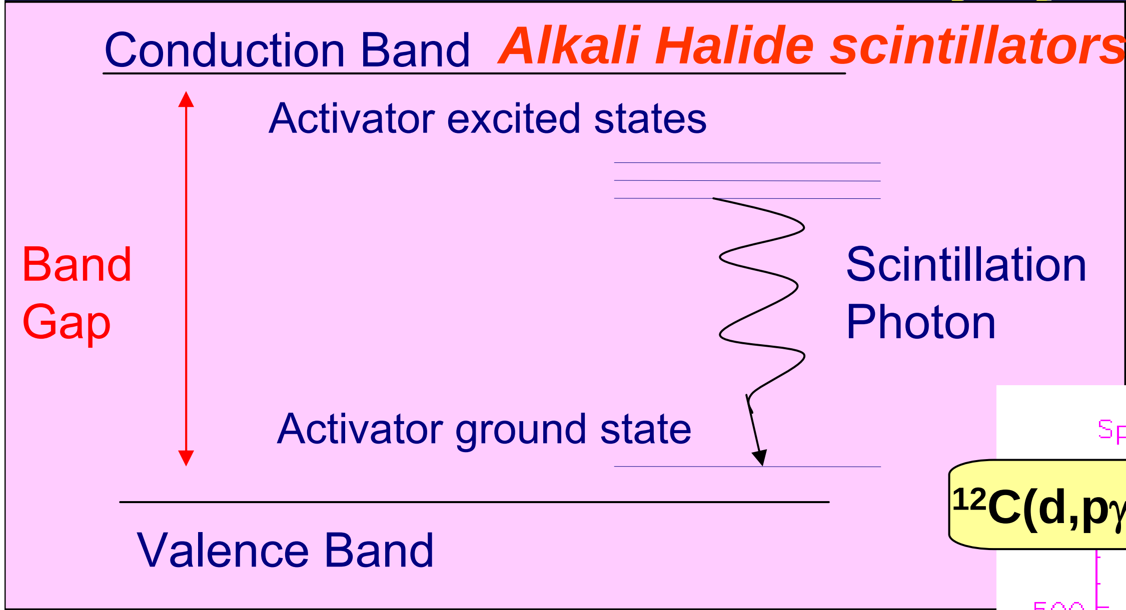
Theoretical CTS scattering function

Fast ions can be studied from

νδ= νs - νi ~ 1 GHz



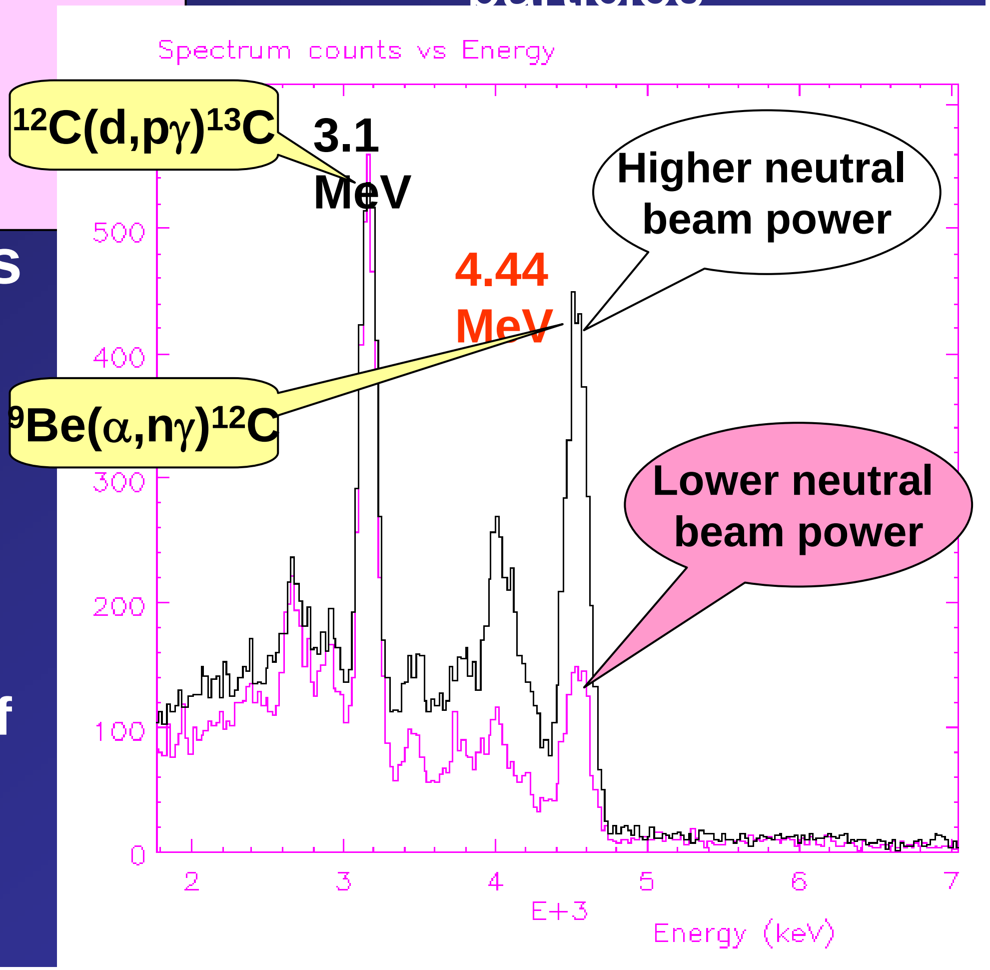
NaI(Tl)



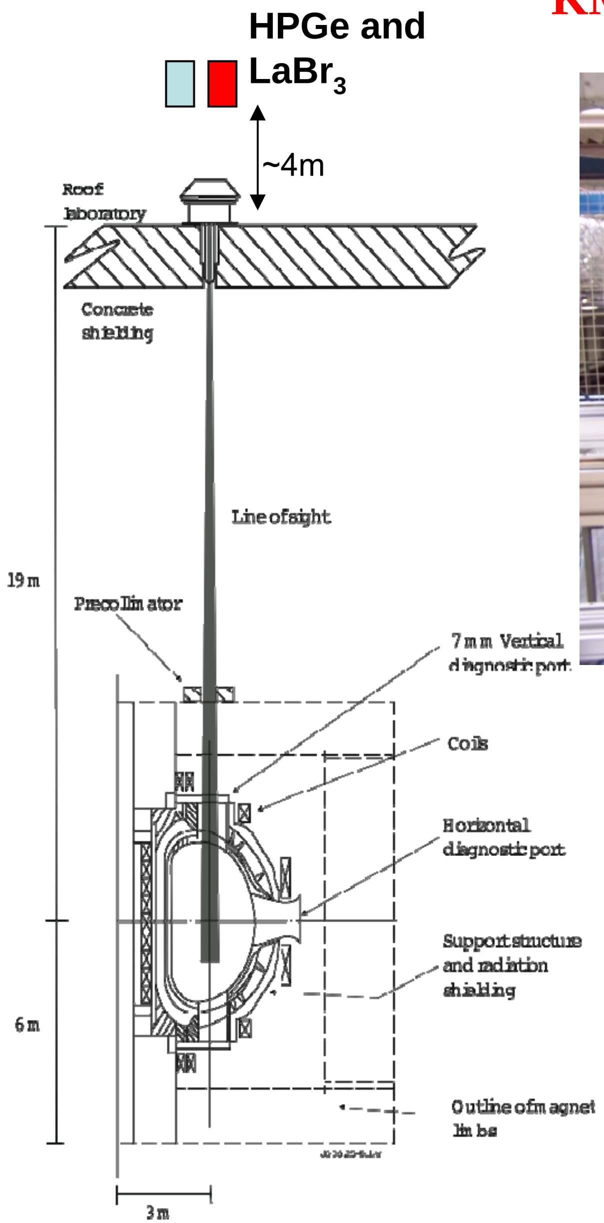
Measurements with high resolution spectrometers for two discharges with different neutral beam power input into the fast particles

An energetic photon creates electron -hole pairs.

- **The electrons and holes migrate to the activator sites (Tl).**
- **De-excitation of the activator atoms produces radiation more efficiently.**
- **The light is then detected with photomultipliers as in the case of organic scintillators.**
- **The properties of solid state scintill. depend on the crystal structure**



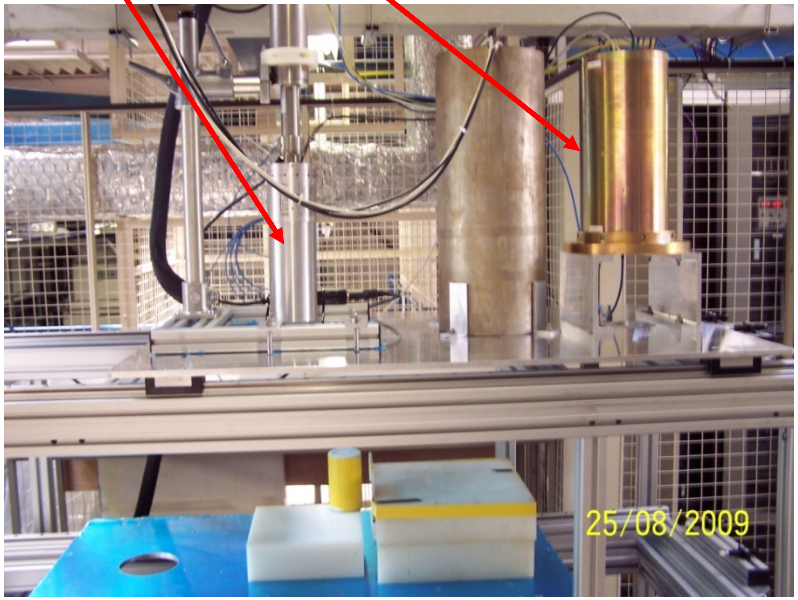
KM6G and KM6S installation in J1L

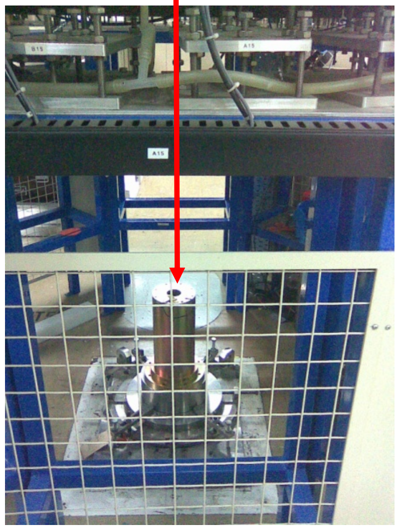


KM6G

KM6S1

KM6S2





Gammas & Neutrons

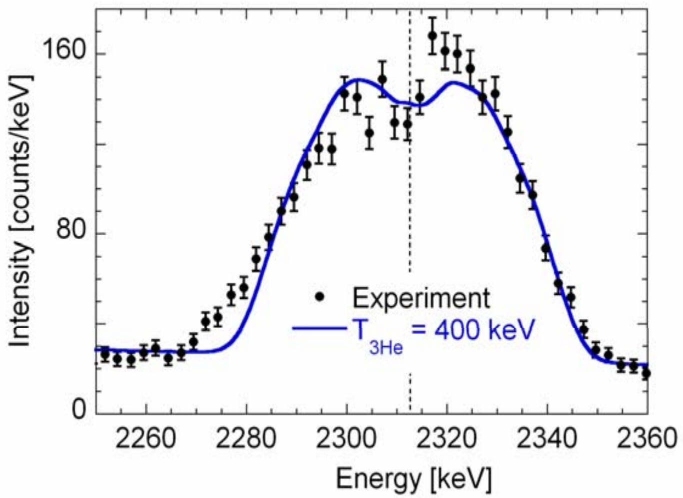
Gammas & Neutrons

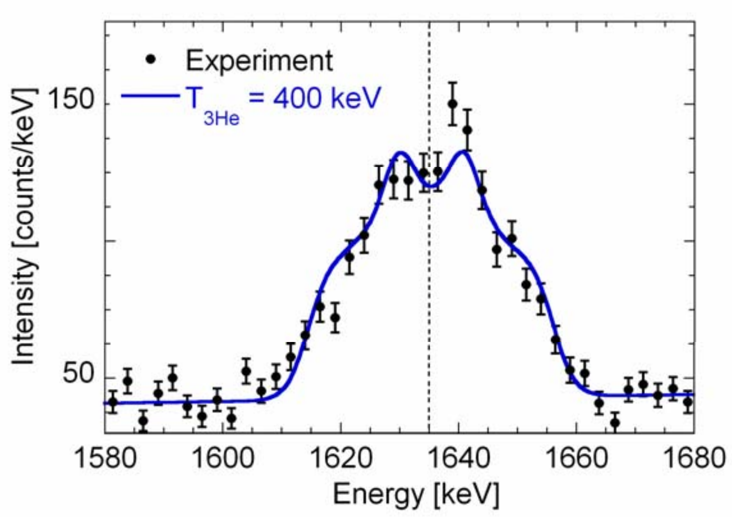
Detectors chosen to match plasma conditions:
efficiency, energy resolution, rate capability, neutron tolerance

HPGe Measurements with ICRH plasmas

Sum of 7 JET discharges: #73760-73770

(^{3}He)D, n_{3He} =1-5%, P_{ICRH}~5-6MW tuned at ω_{3He}, n_e=2-3 10^{19} m^{-3}





$^3He+^{12}C \rightarrow p+^{14}N^*$ (Q=4.8 MeV)

- **Good** description of the 1.63 MeV and 2.31 MeV peak for T_{3He}> 300 keV
- Some details are missing but can be ascribed to non flat background due to concurrent reactions
- A slight **asymmetry** (at the limit of statistical significance) is observed

Detailed modeling is required: T_{3He}~400 keV

M. Tardocchi et al, PRL 107 (2011) 205002