Measurements techniques and technologies for high temperature laboratory plasmas

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EUROfusion

JET

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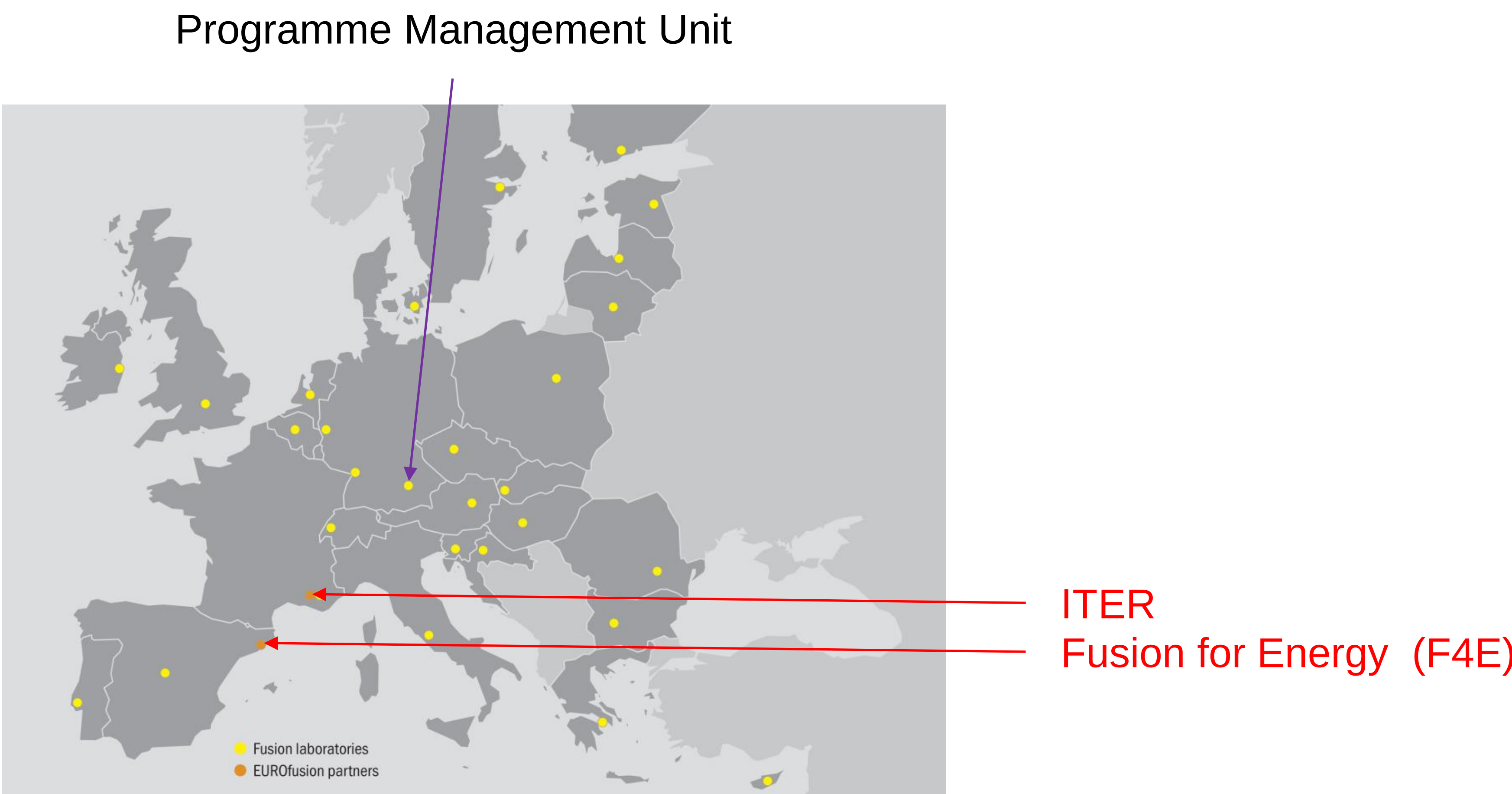
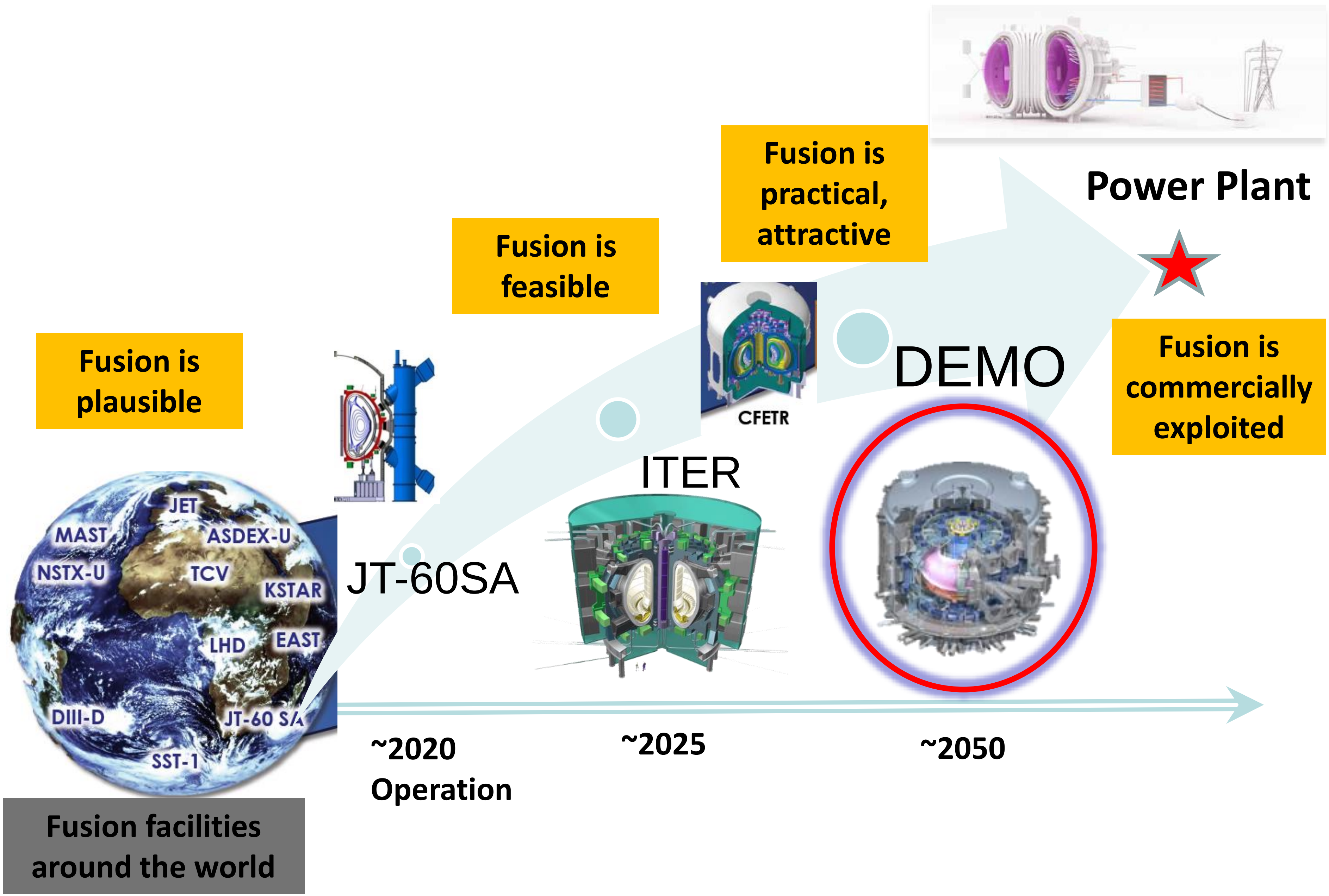
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

EUROfusion



All EU Member States plus Switzerland have joined the EUROfusion agreement involving 29 fusion laboratories and numerous Third Parties. Their combined effort will achieve the ultimate goal: fusion electricity by 2050s.


Fusion is plausible
Fusion is feasible
Fusion is practical, attractive
Power Plant
Fusion is commercially exploited
JET
MAST
ASDEX-U
NSTX-U
TCV
KSTAR
LHD
EAST
DIII-D
JT-60 SA
SST-1
Fusion facilities around the world
JT-60SA
ITER
CFETR
DEMO
~2020
Operation
~2025
~2050

Fusion Roadmap

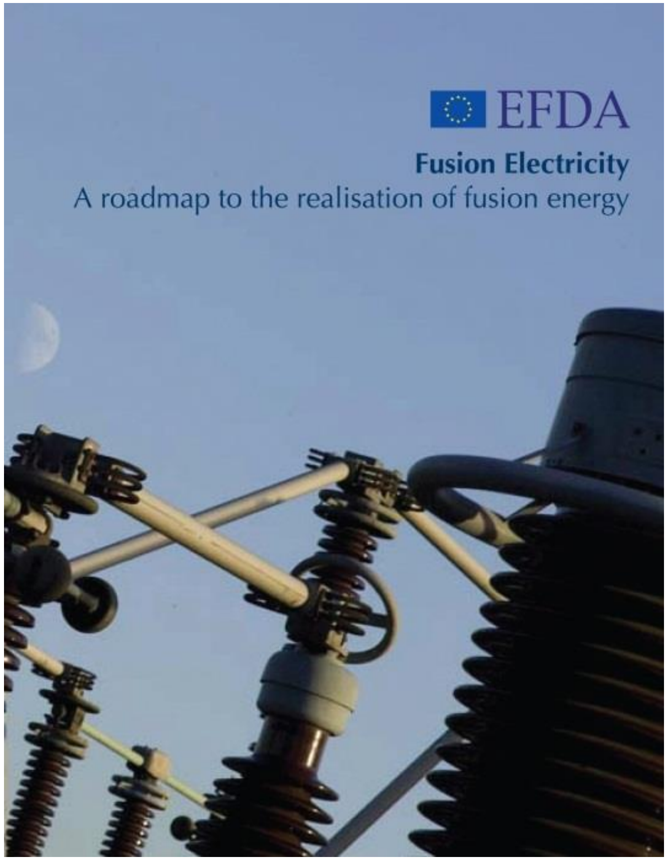
8 Strategic Missions to tackle the critical challenges for Fusion:

1. *Plasma Operation*
2. *Heat Exhaust*
3. *Neutron resistant Materials*
4. *Tritium-self sufficiency*
5. *Safety*
6. *Integrated DEMO Design*
7. *Competitive Cost of Electricity*
8. *Stellarator*

IPH

DEMO

IPH



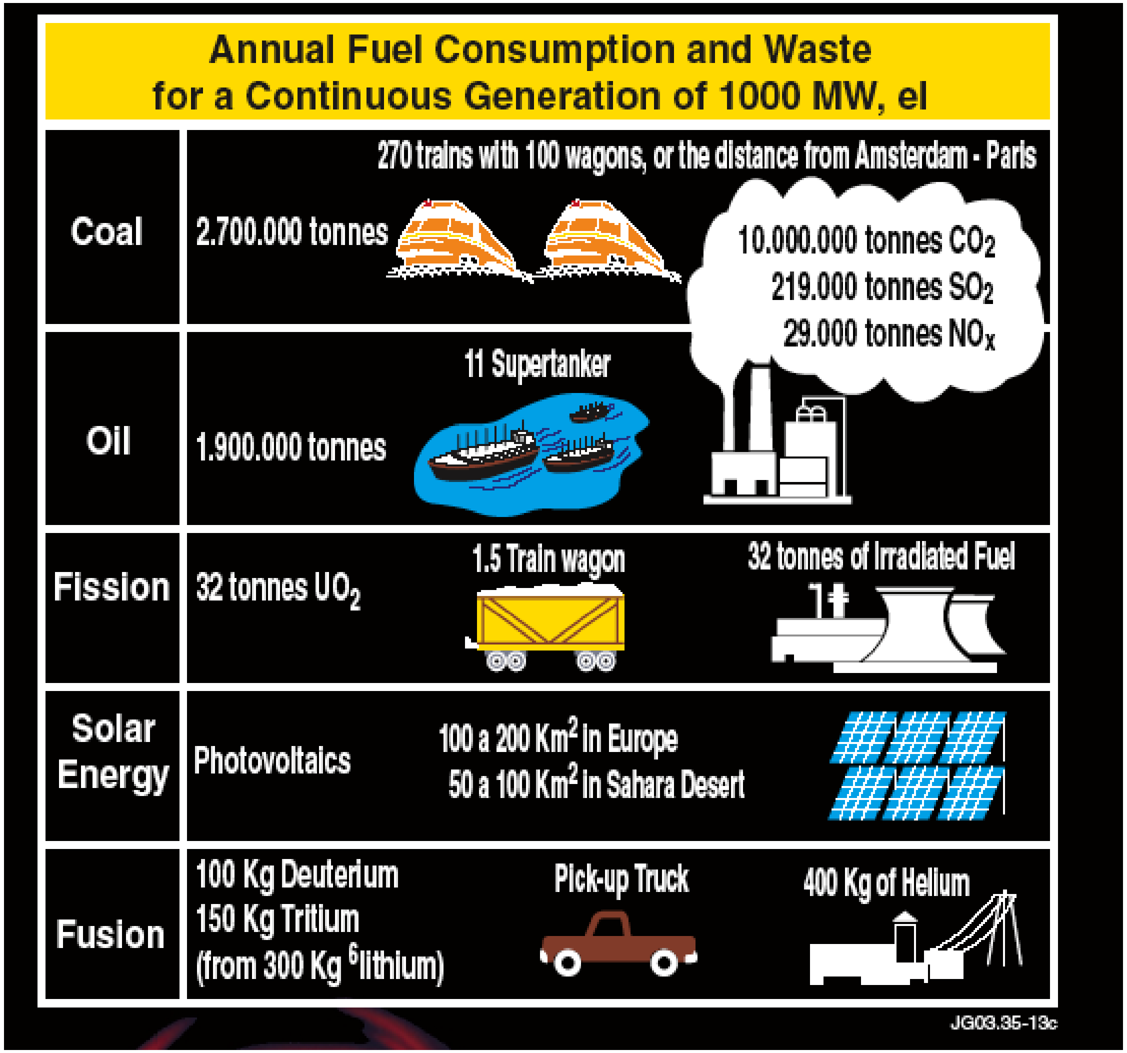
Emphasis on:

- Central role of ITER
- DEMO as a single step to commercial fusion power plants that produce electricity and have a closed fuel cycle
- DEMO construction starting early in the 2040s
- Pragmatic Approach: It should not be perfect but good enough and must come on time to make an impact

Comparison of Power Systems

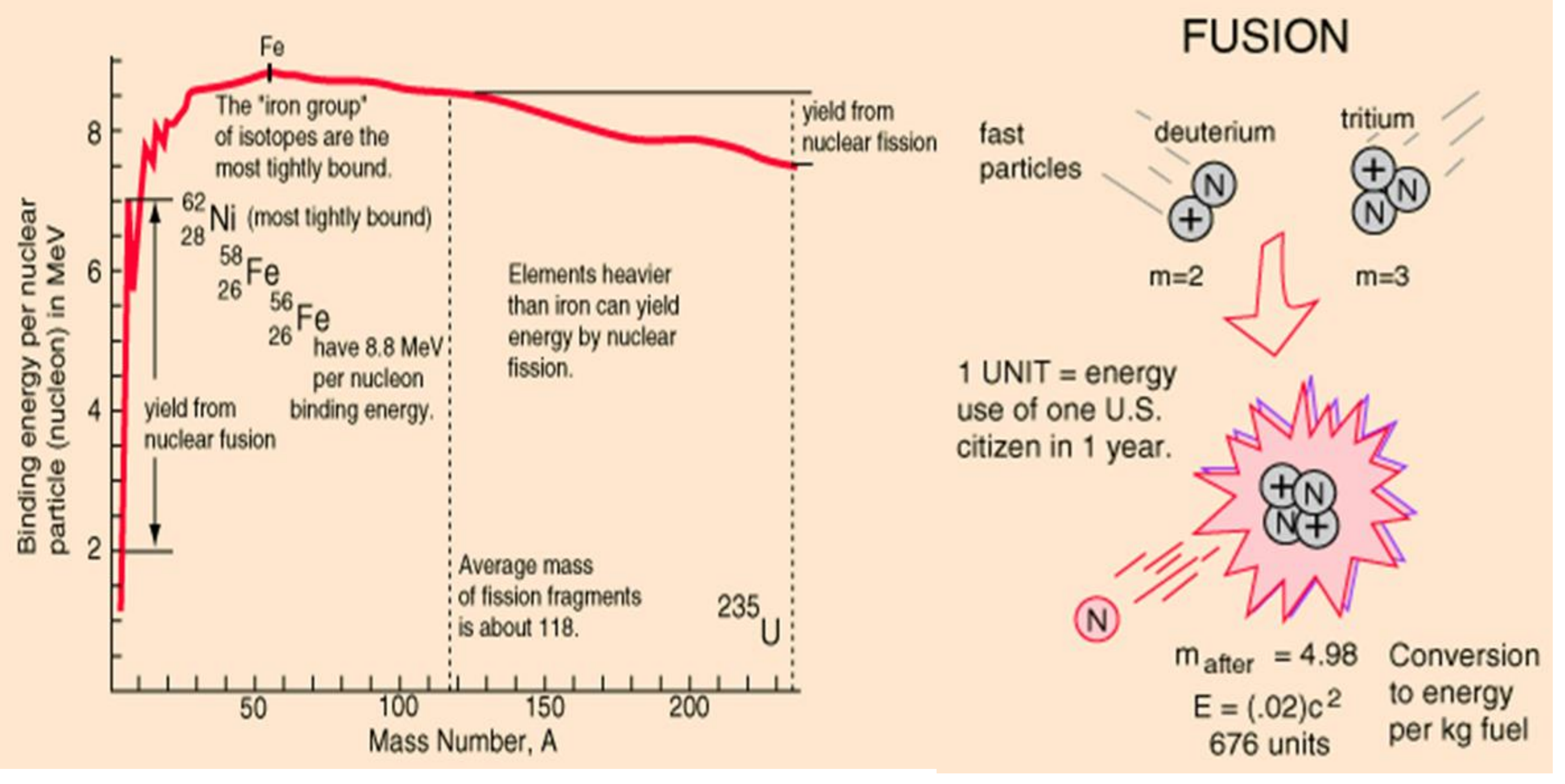
Why fusion?

- **Most exoenergetic reaction in the known universe**
- **Highest power density per Kg**
- **Lowest emission of greenhouse gases**
- **Technically safe**



The fusion process

Light nuclei fuse into heavier nuclei



Fusion products; 14.1 MeV neutron and 3.5 MeV alpha particle

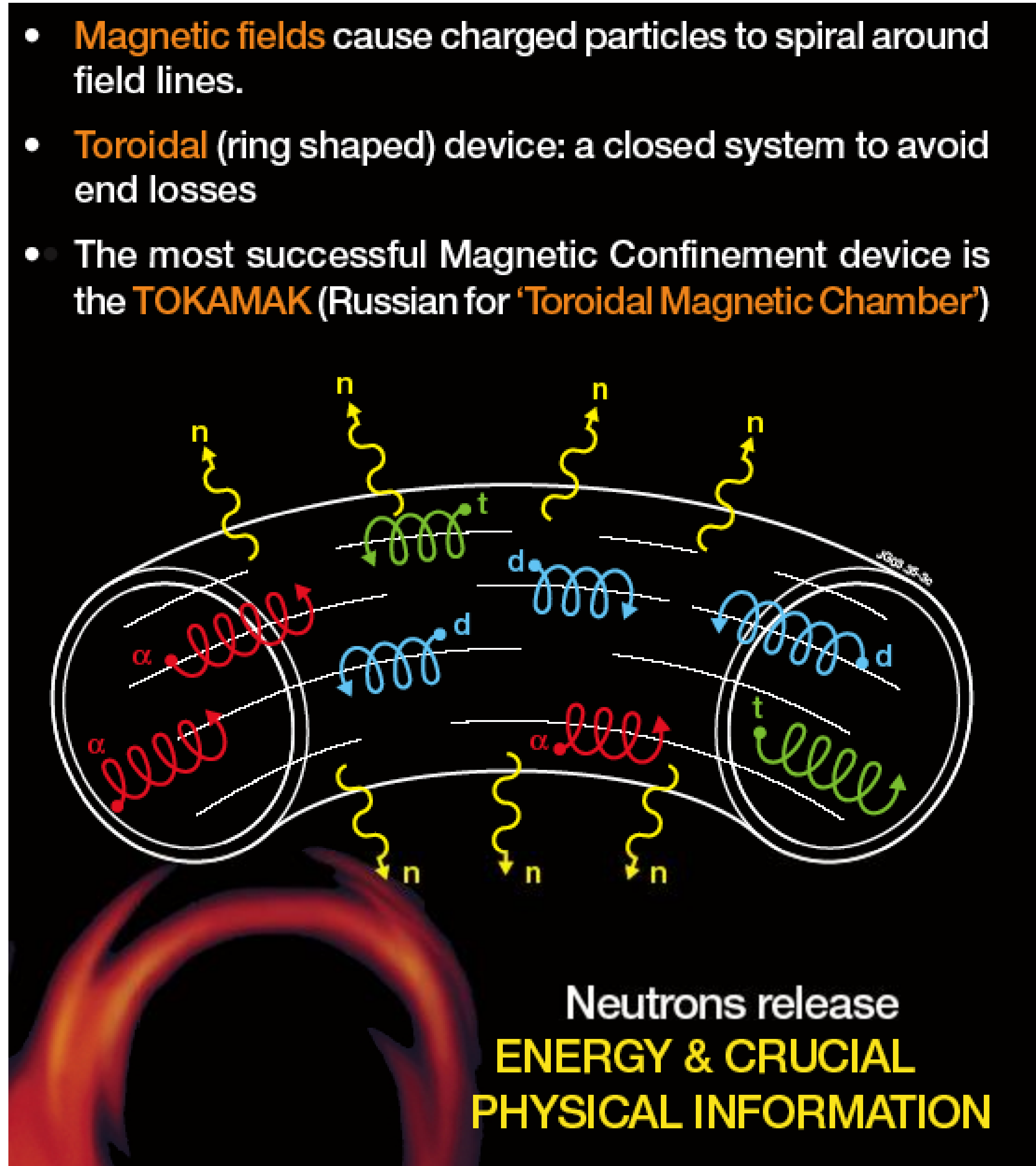
Principle of Energy Production with Magnetic Fusion

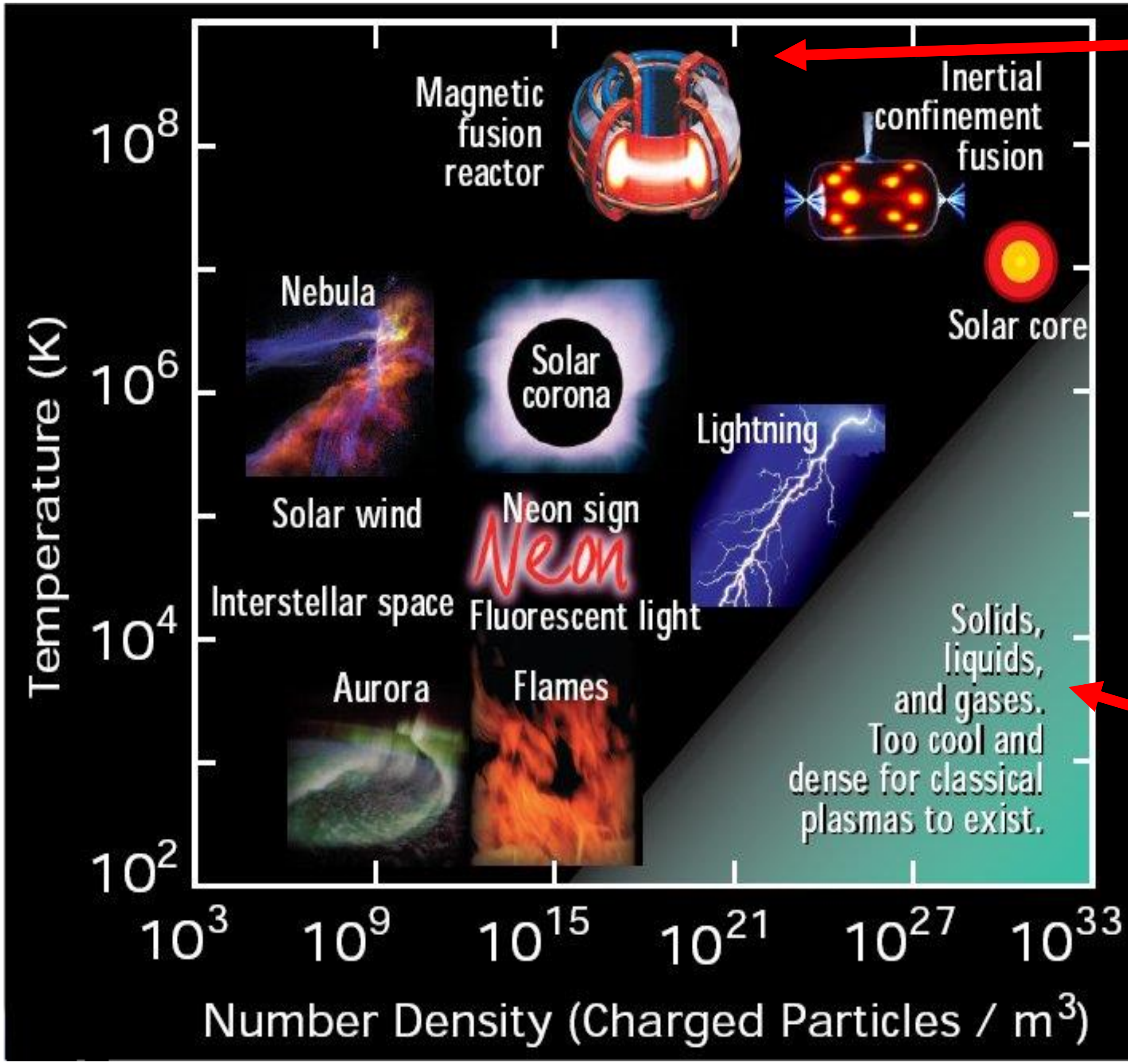
- For the nuclei to get close enough to fuse they have to overcome the Coulomb barrier.

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

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

- ➔”Magnetic bottle”

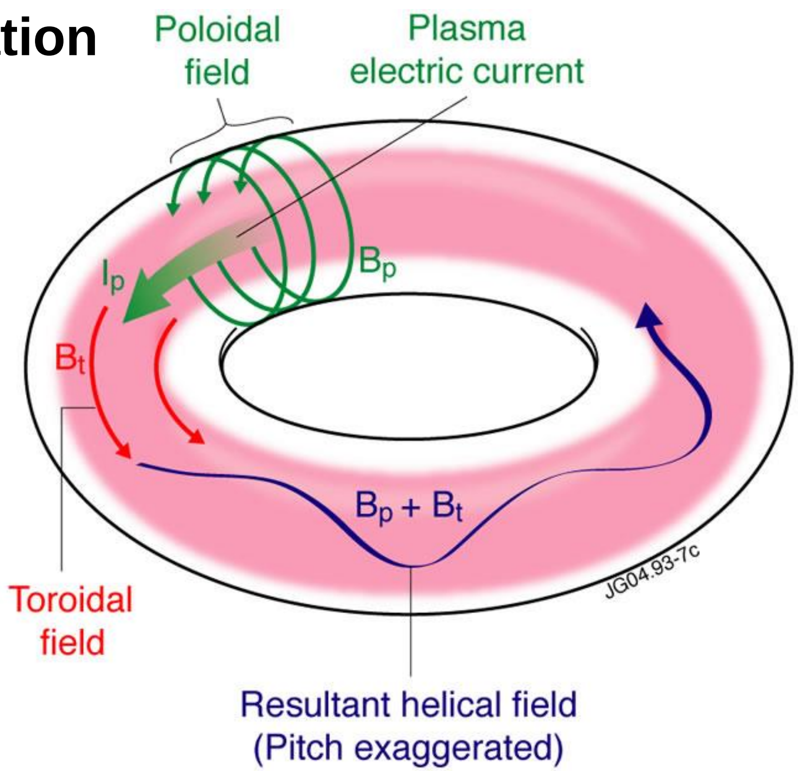




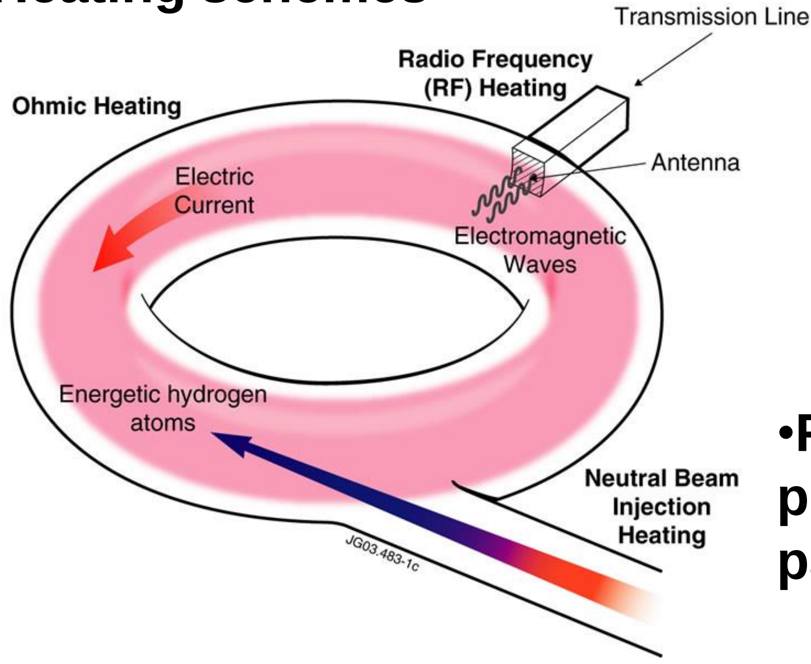
Magnetic fusion plasmas have temperature and pressure higher than the solar corona and temperature one order of magnitude higher than the Sun core

Region of Quantum plasmas

Magnetic field configuration



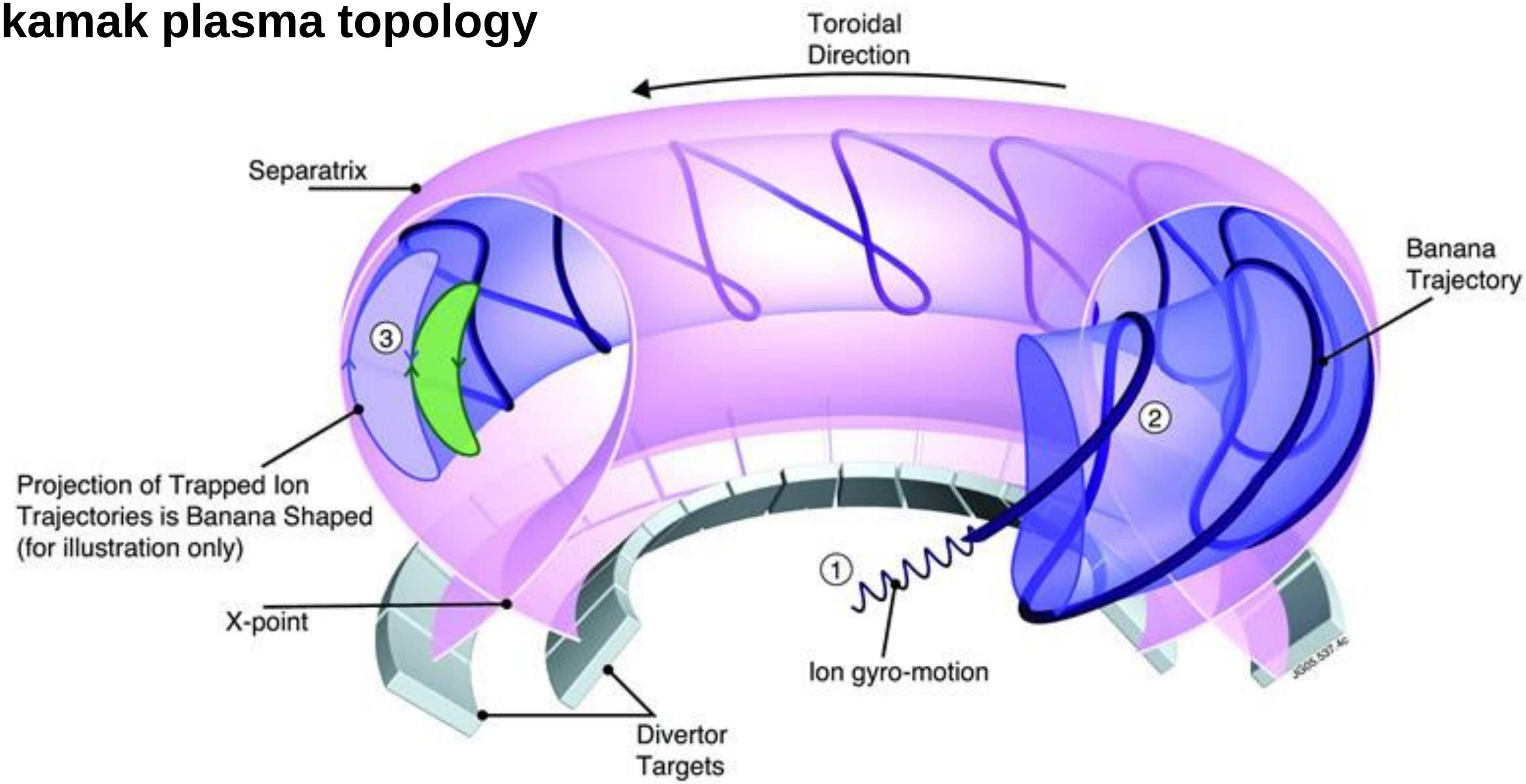
Heating schemes



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

Tokamak Plasma Overview

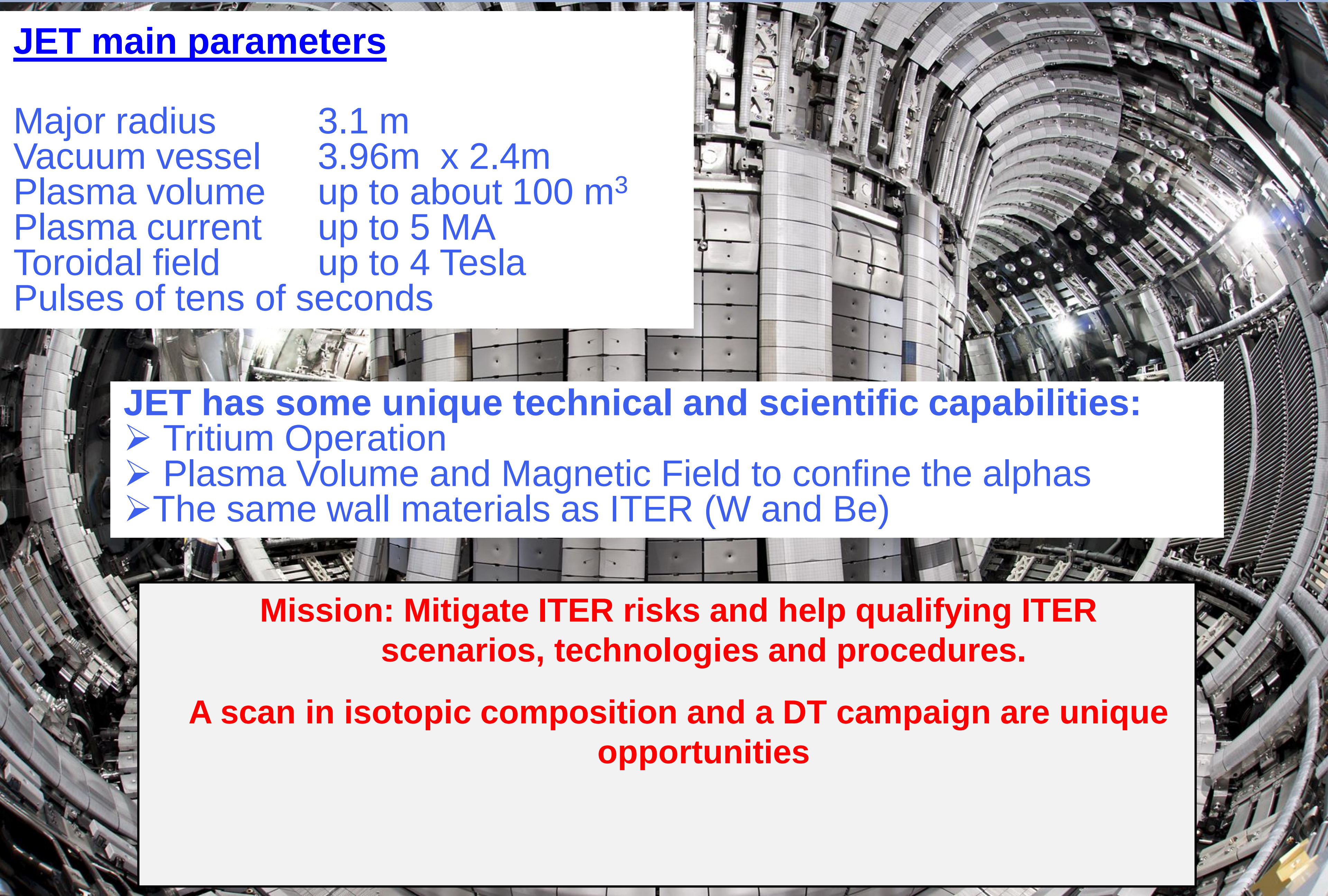
Tokamak plasma topology



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.

P_{fusion}/P_{add}	Q ~ 0	Q ~ 1	Q ~ 0	Q ~ 10	Q ~ 30
duration	~400s	2s	~100s	400-3600s	Continuous

JET ILW–Be main Wall, W in the divertor



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:

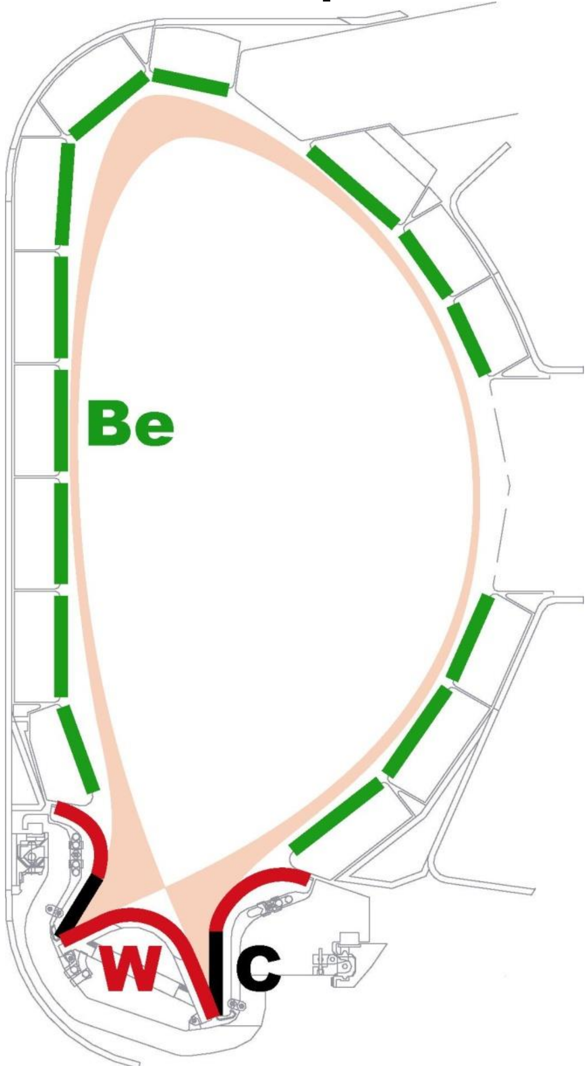
- Tritium Operation
- Plasma Volume and Magnetic Field to confine the alphas
- The same wall materials as ITER (W and Be)

Mission: Mitigate ITER risks and help qualifying ITER scenarios, technologies and procedures.

A scan in isotopic composition and a DT campaign are unique opportunities

Fusion Plasmas as Open Systems

A Tokamak plasma is an open system, kept out of equilibrium, fuelled by injection of both energy and mass and therefore presents all the problems of control of a typical open system.



Input of energy and matter: <u>fuelling and additional heating systems</u>

Internal Transformations: <u>optimization of the plasma configuration</u> to maintain the internal structure and maximise energy production.

Elimination of the waste: <u>power and particle exhaust</u>.

Contamination: <u>Helium Ash</u>

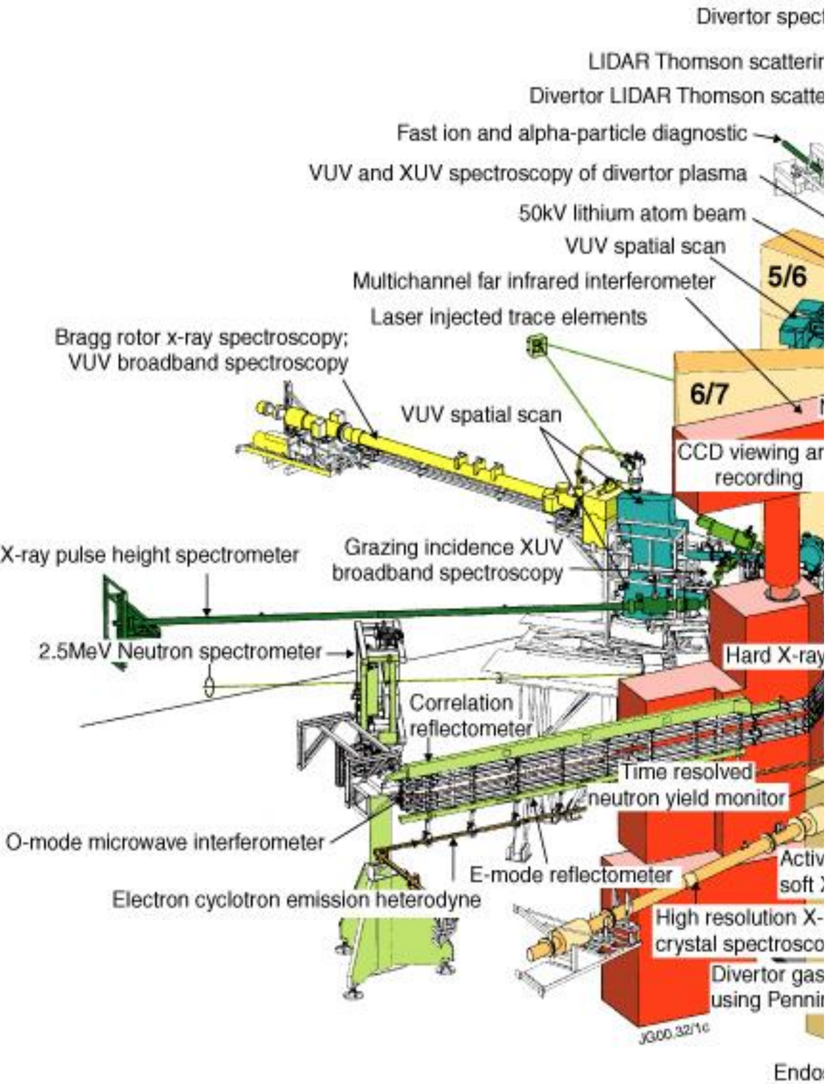
Goals of Diagnostics

- 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

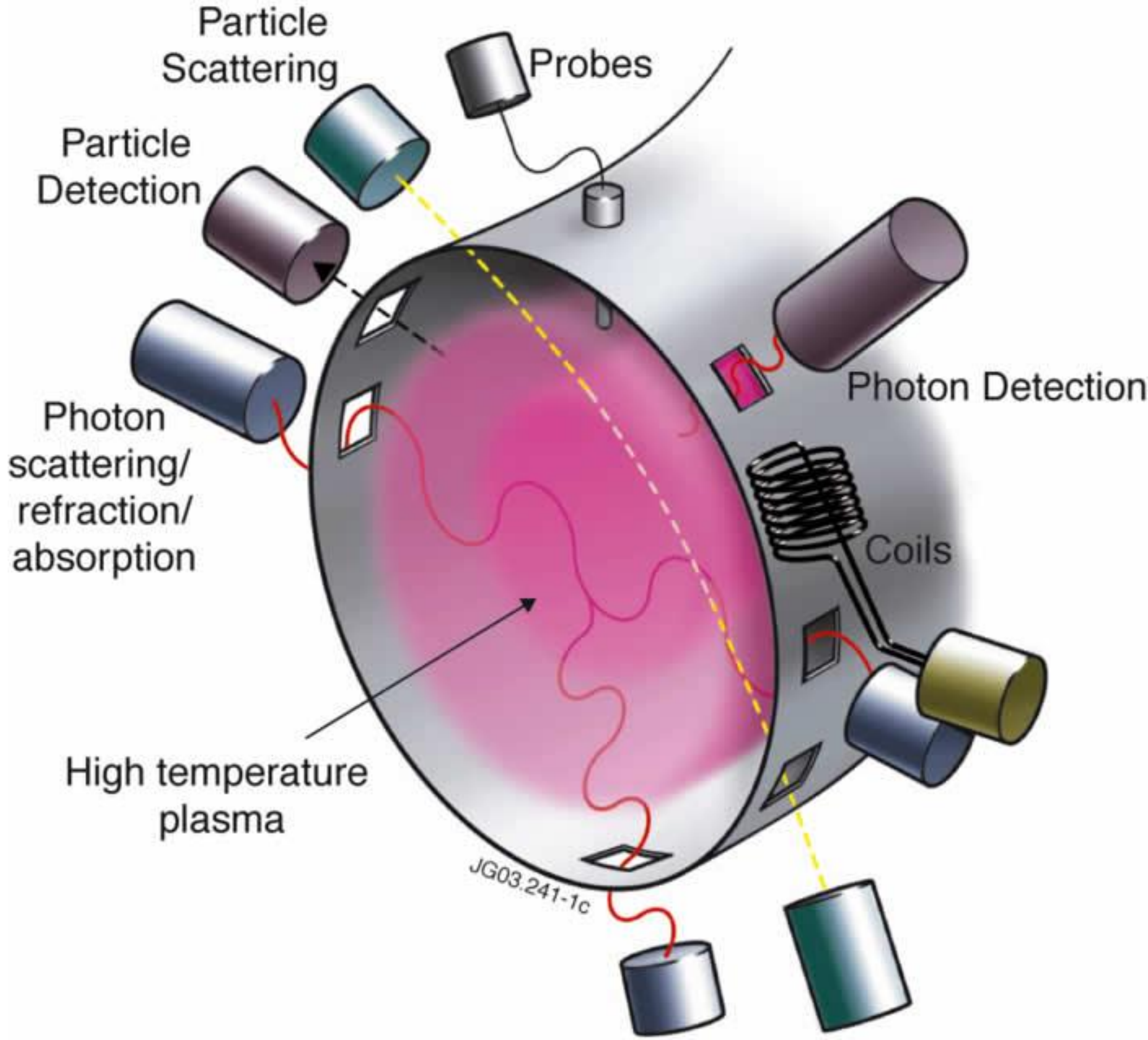
JET diagnostics

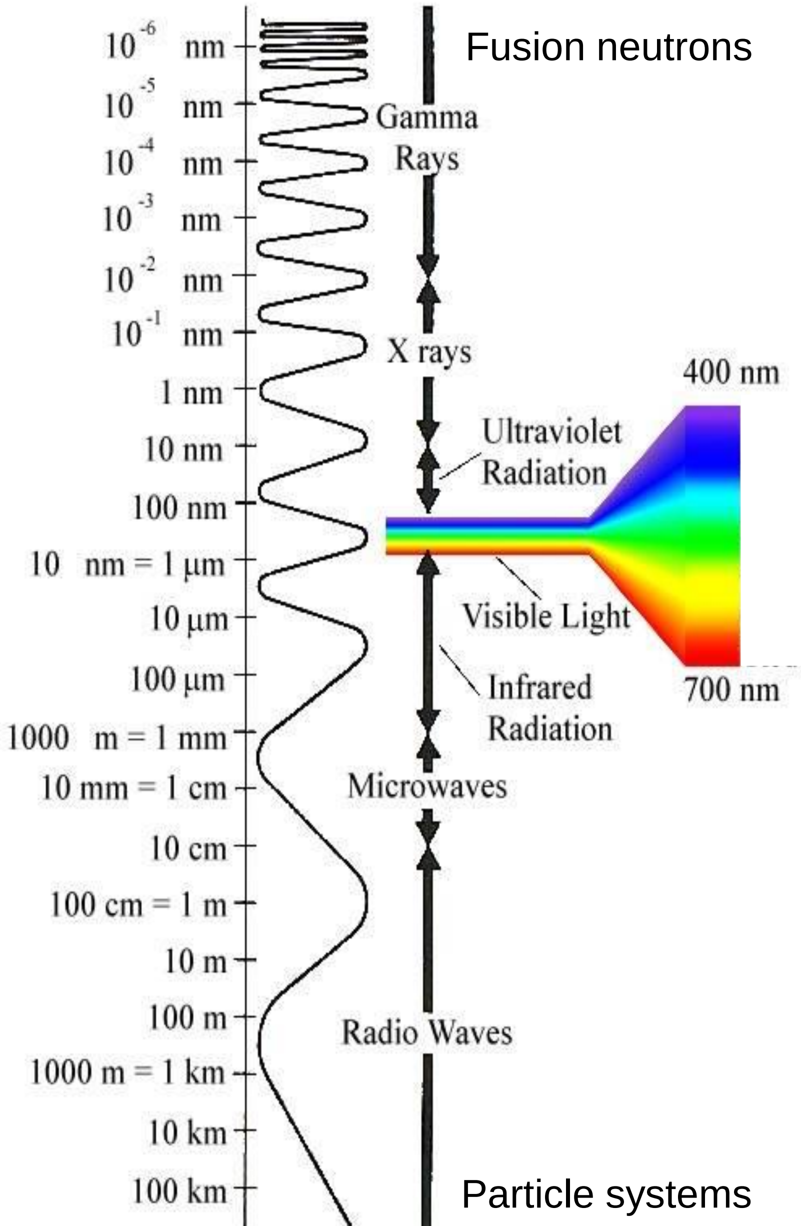


- **All major measurement techniques in physics are represented**
- **At JET about <u>100 diagnostics</u> operational and about 20 more in the design phase**
- **The measuring instruments are different but must be coordinated in a single experiments**
- **Already acquired <u>a maximum of more than 55 GBytes</u> of data per shot (equivalent to about a 5.5 hours digital movie). Database: <u>more than 90 Tbytes (comparable to US Congress library)</u>**
- **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





γ-ray and neutron diagnostics: based on nuclear physics

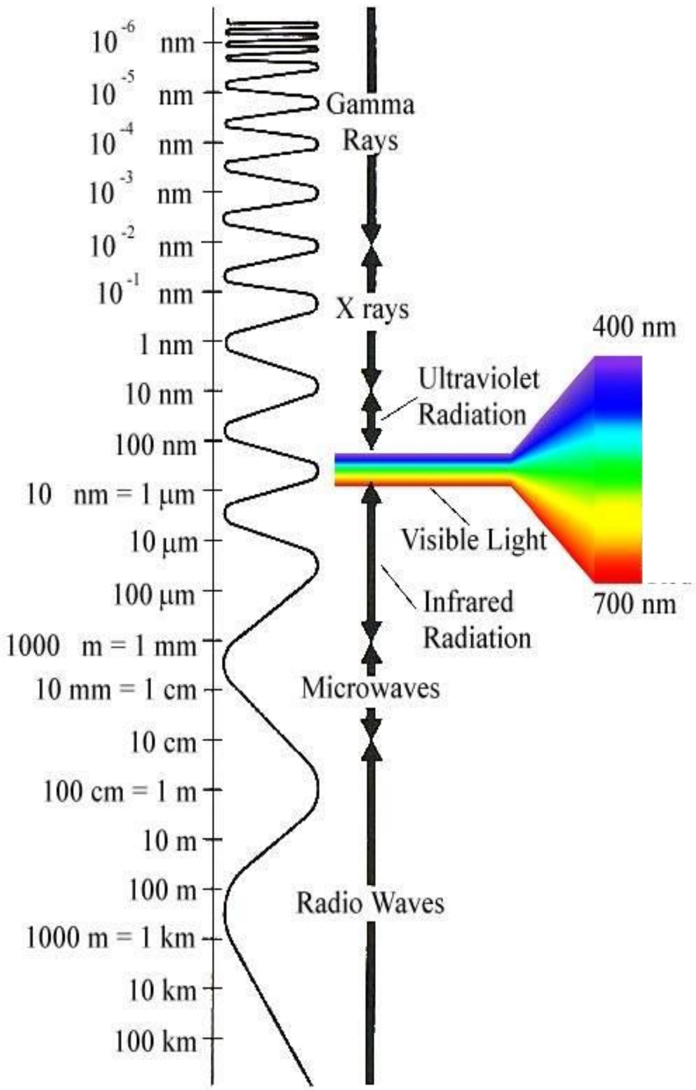
Spectroscopy (IR, visible, UV and SXR): based on atomic physics

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

Fusion neutrons

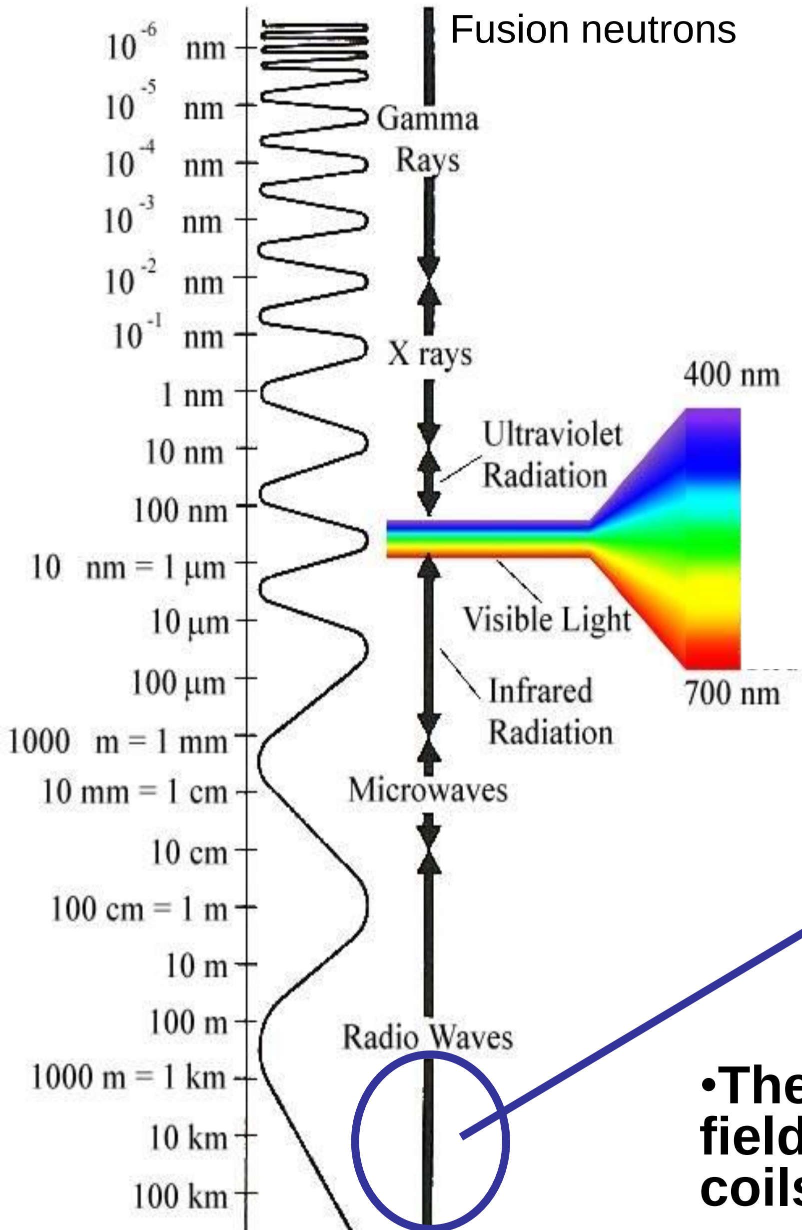


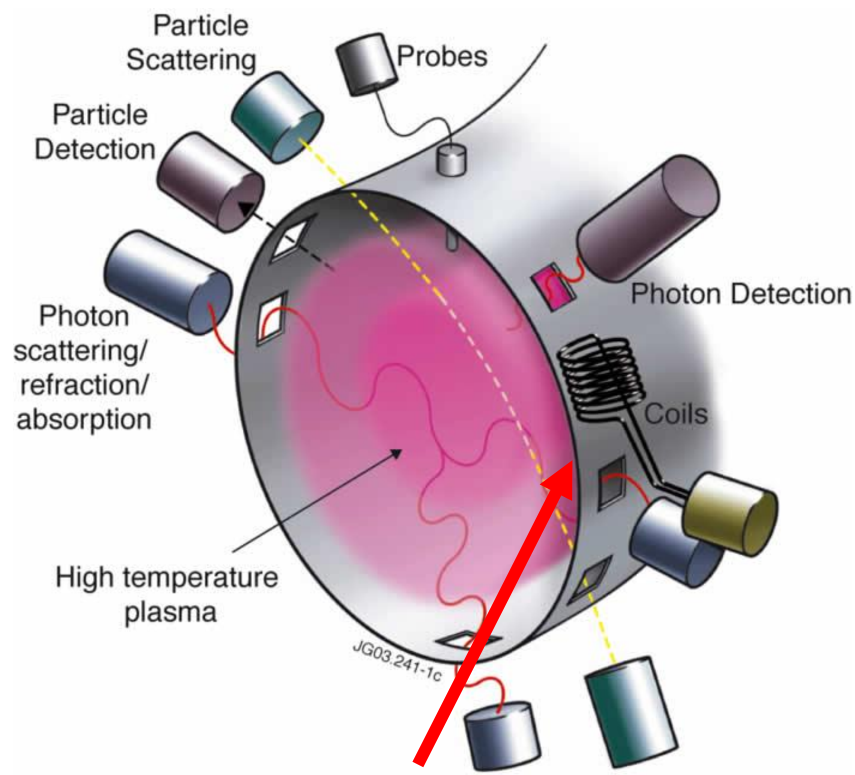
Particle systems

- •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

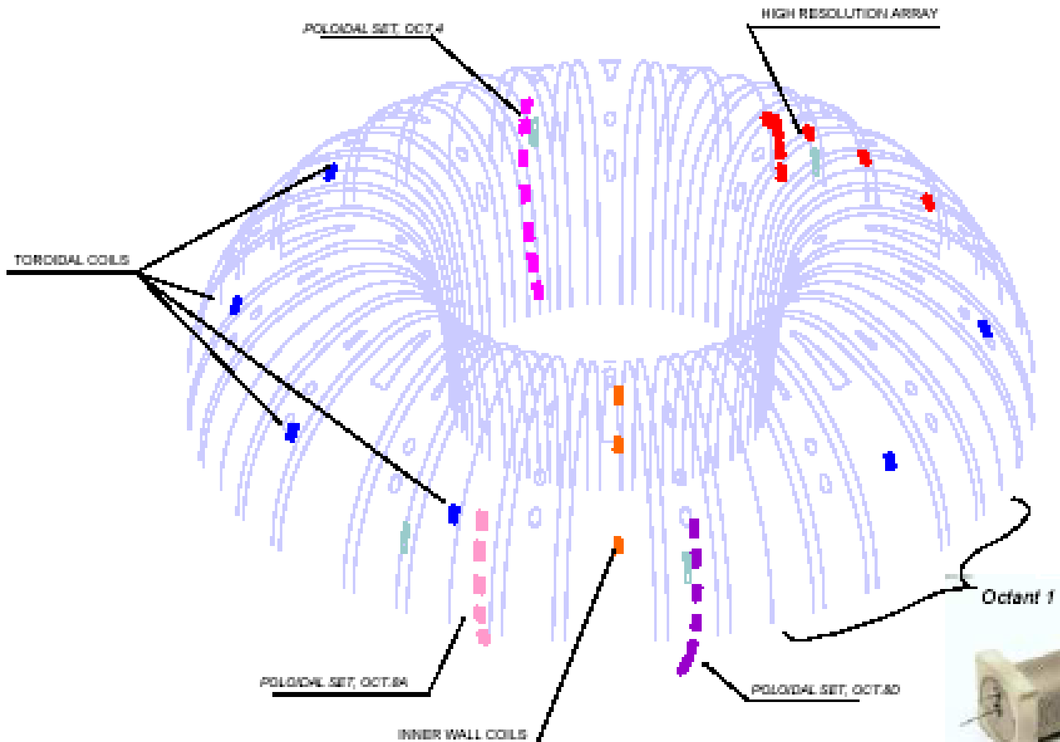
$$V = -\frac{d\phi}{dt}$$

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

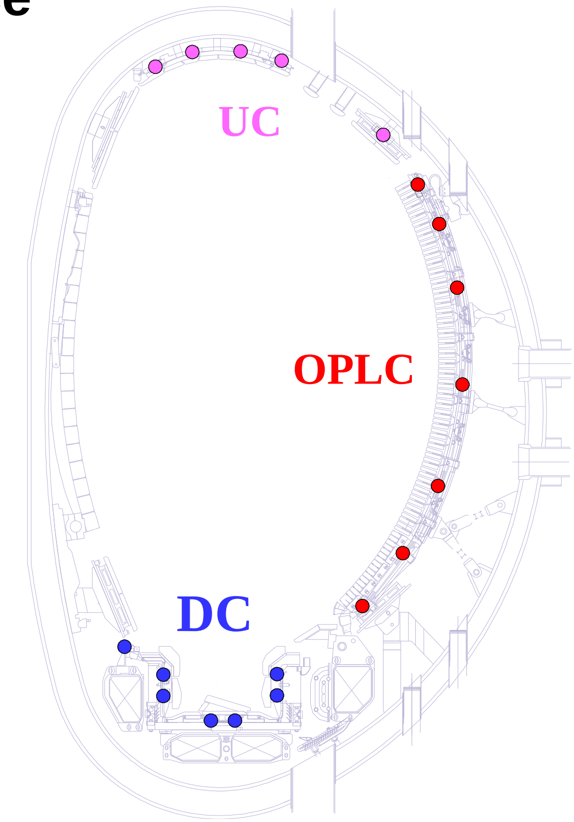
Location of the pick-up coils

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



High Resolution Magnetic Coils



Poloidal cross section

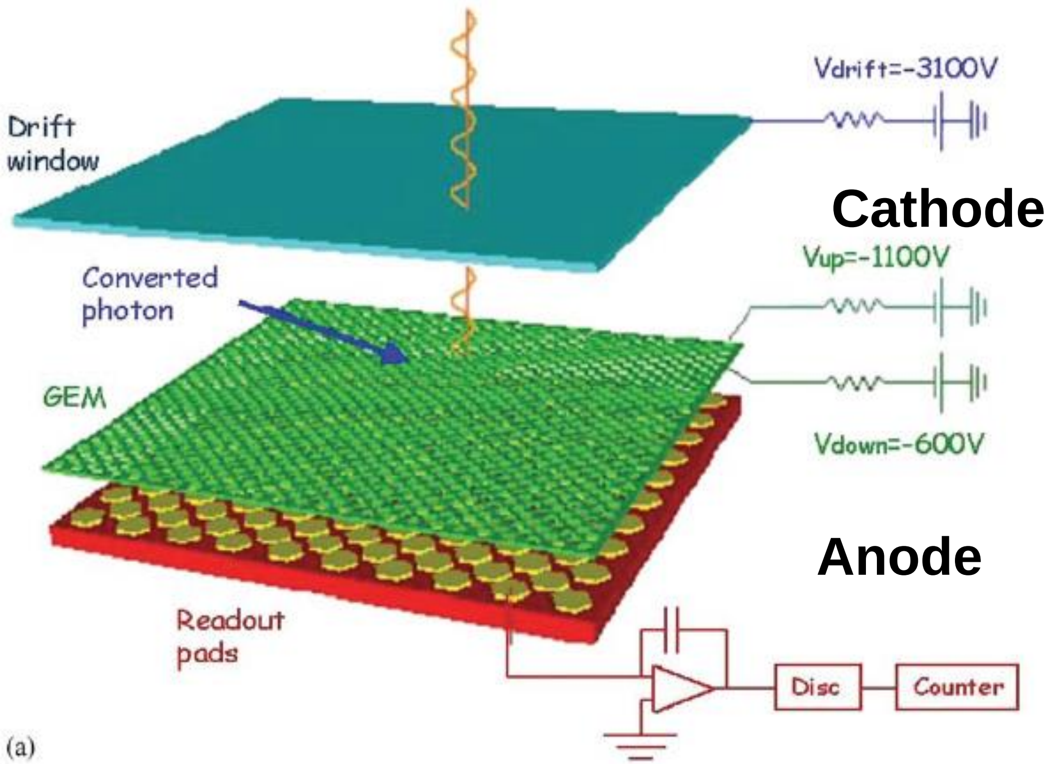
Plasma Boundary with SXR: the GEM Detector

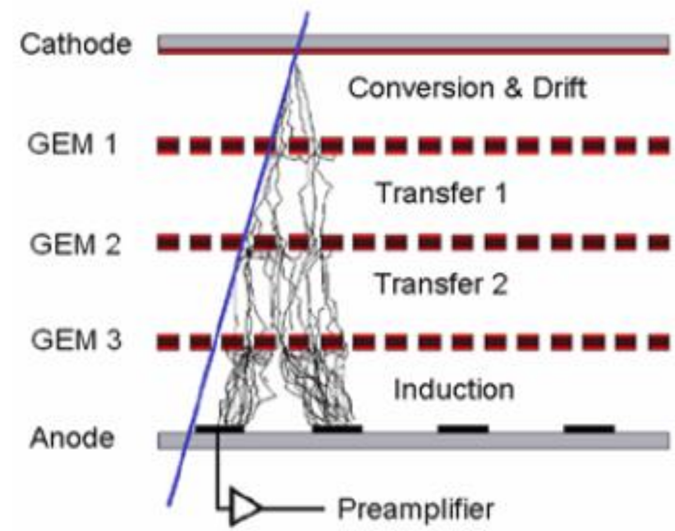
•Pick-up coils have problems in a radiation hard environment (close to the plasma, integrators etc)

•The next generation of plasmas will be so hot that even the boundary will emit in the SXR

• Adapt Gas Electron Multipliers detectors

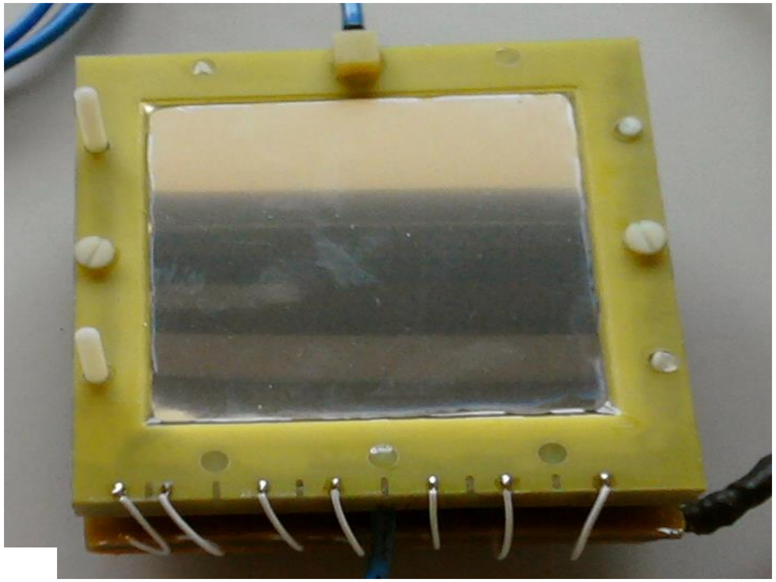
Current~few nA





The triple GEM Detector

Mylar foil with aluminium

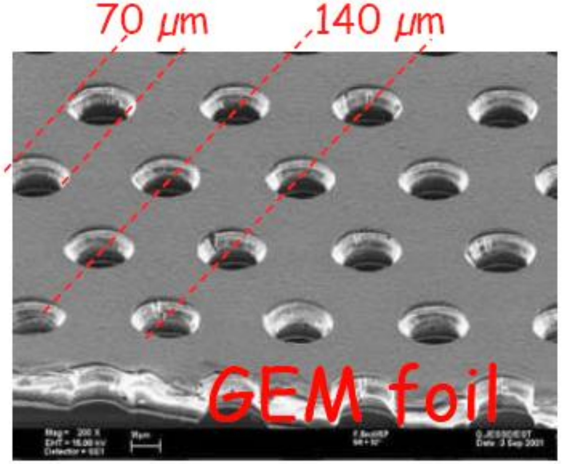


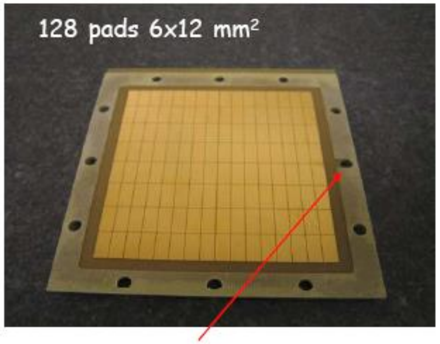
10cm x 10cm

Main potential advantages:

- Flexible
- Radiation hard
- High count rate

The capability of properly simulating these detectors has improved dramatically recently

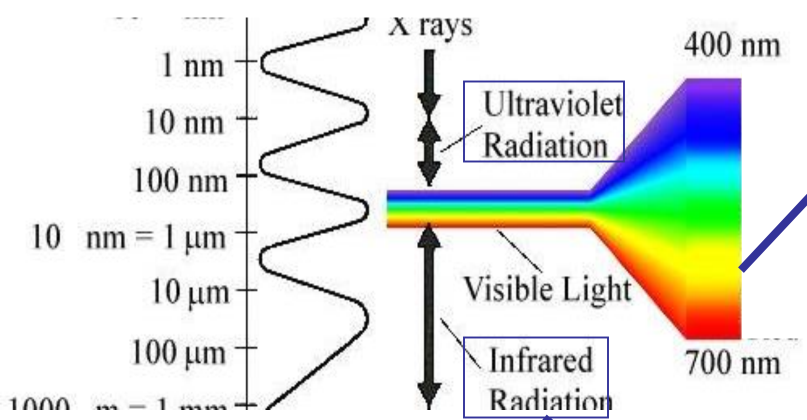




Width 50 mm (Kapton)

Measuring the properties of the electron fluid

Visible + near UV- IR



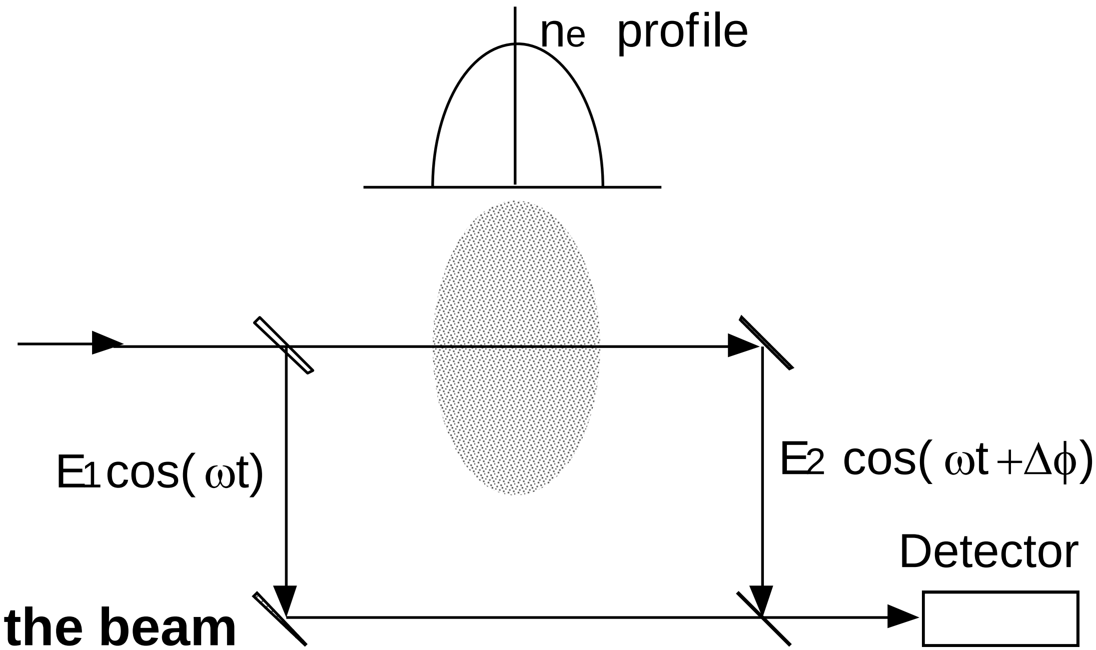
Laser Thomson Scattering (T_e, n_e)

- **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 mm) crossing the plasma and a second reference beam:



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

where:

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

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

Detectors are Bolometers InSb working at liquid He

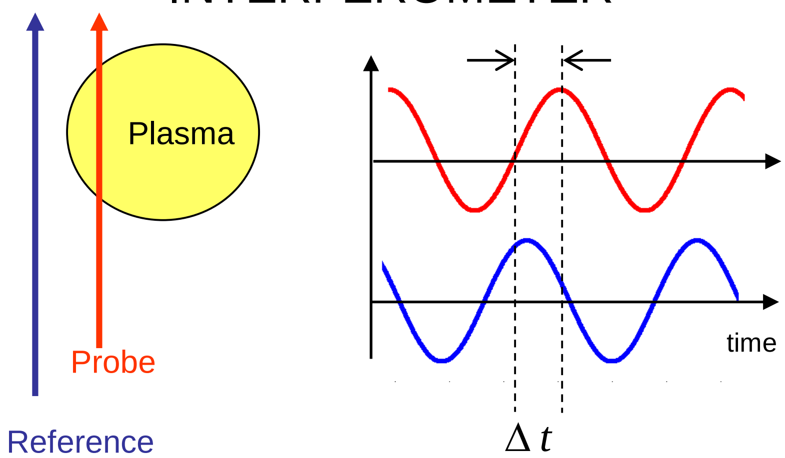
$\Delta\phi$ can be determined by interference: $V = \frac{E_1^2}{2} + \frac{E_2^2}{2} + E_1 \cdot E_2 \cos(\Delta\phi)$

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

FIR diagnostics

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).

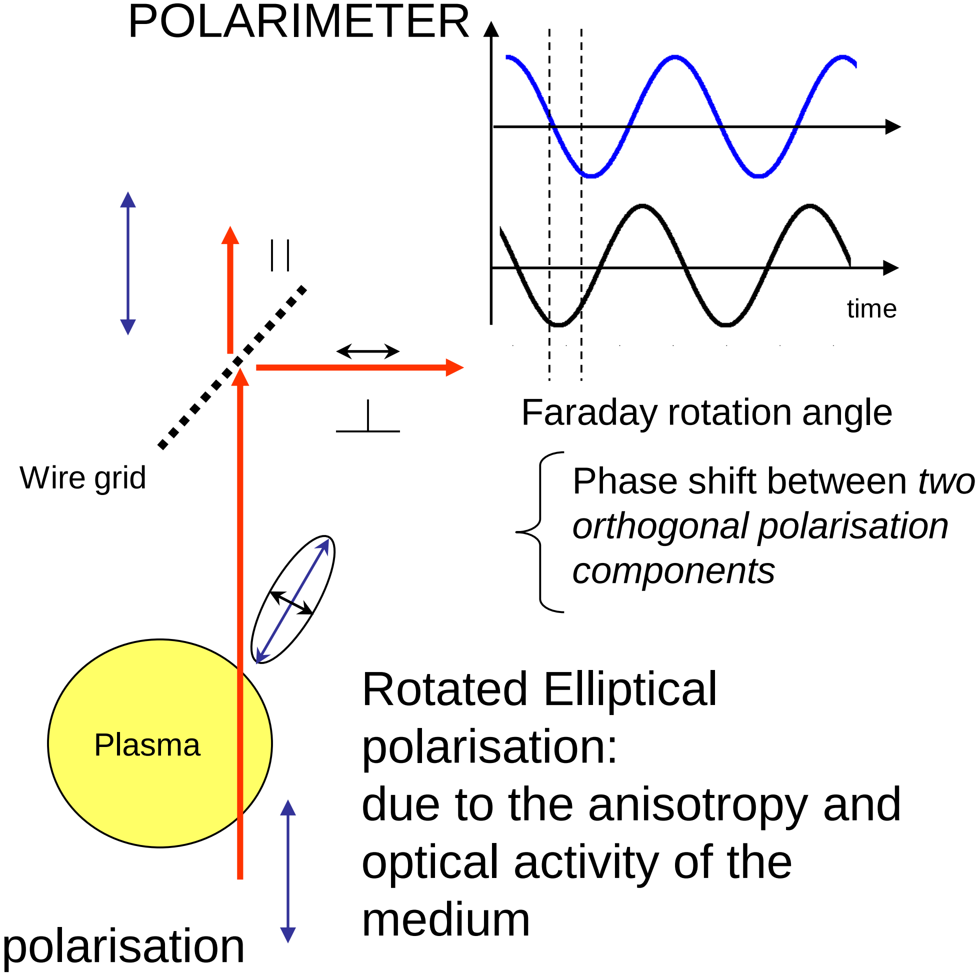
INTERFEROMETER



Phase shift between *reference* and *probe* signals

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

POLARIMETER



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

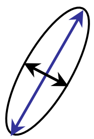
Polarimeter

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

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

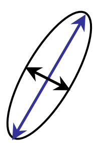


Cotton-Mouton effect

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

$$\Phi \approx \lambda^3 \int n_e B_t^2 dz$$



Interferometric Diagnostic at JET

4 vertical channels 1÷4

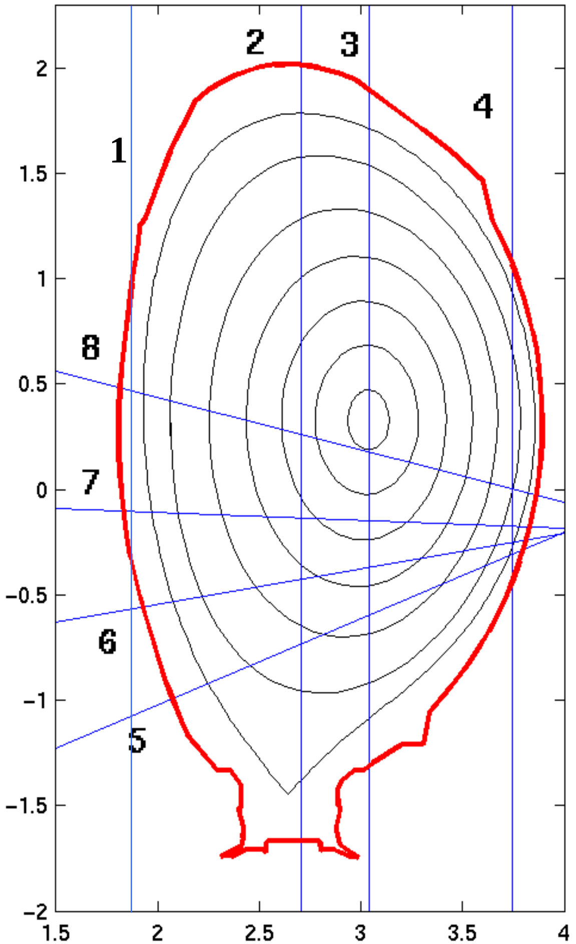
Single Colour Interferometer
λ=195μm

4 lateral channels 5÷8

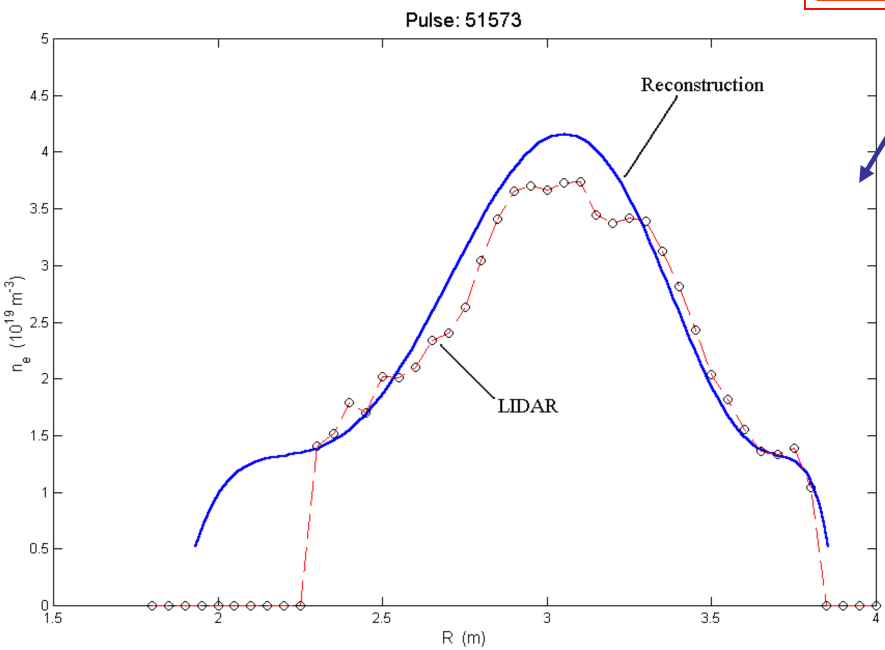
2 Colours Interferometer

λ=195μm (DCN laser) main laser

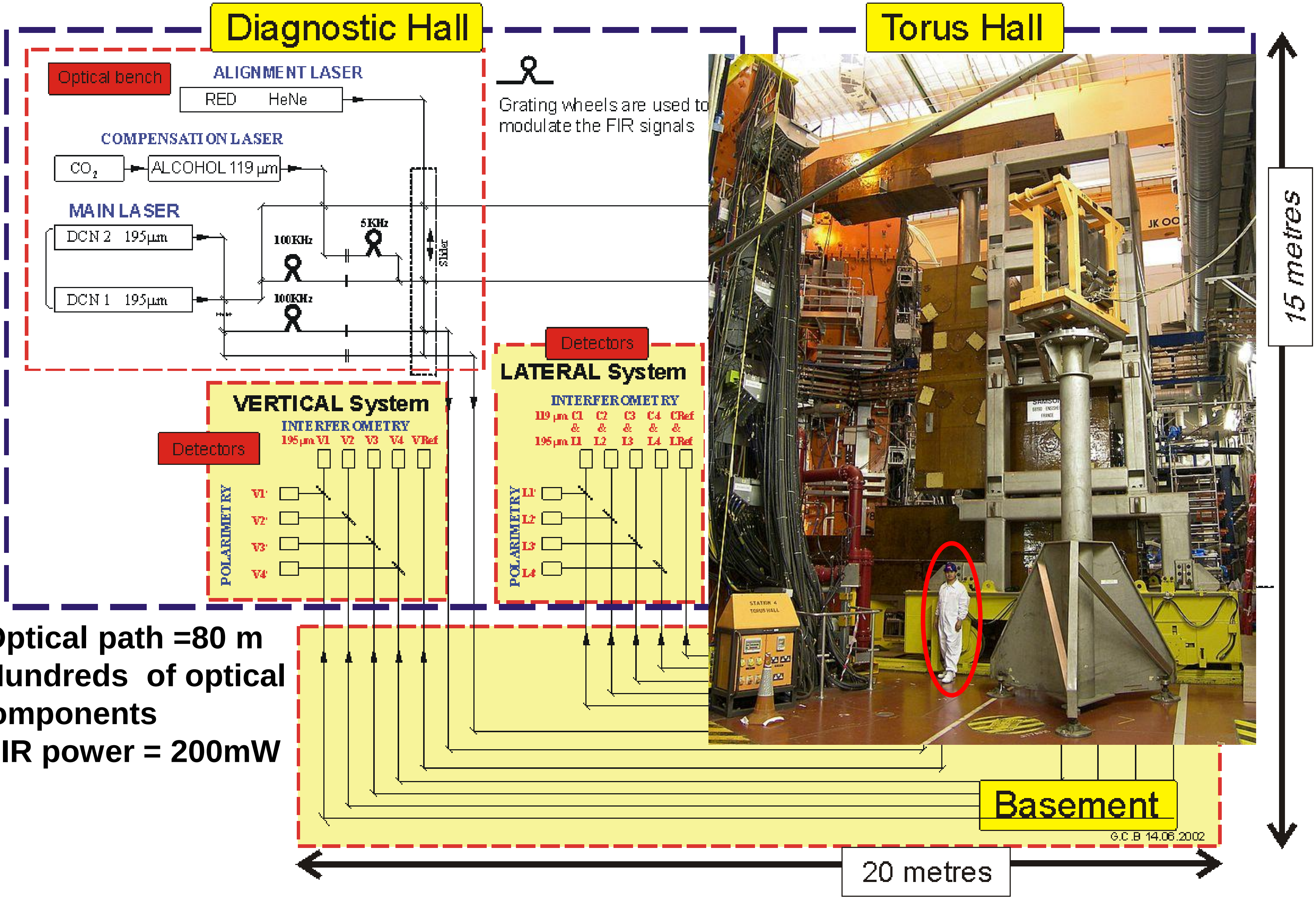
λ=118.8μm (Alcohol laser) compensation laser



Comparison with LIDAR: profile

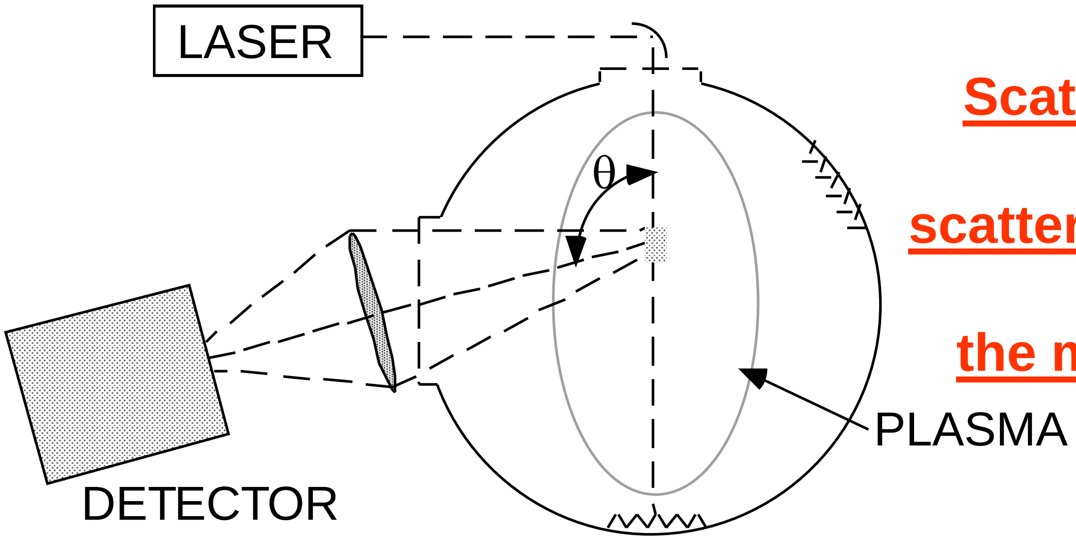


JET FIR Interferometer/polarimeter diagnostics in reality



- 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

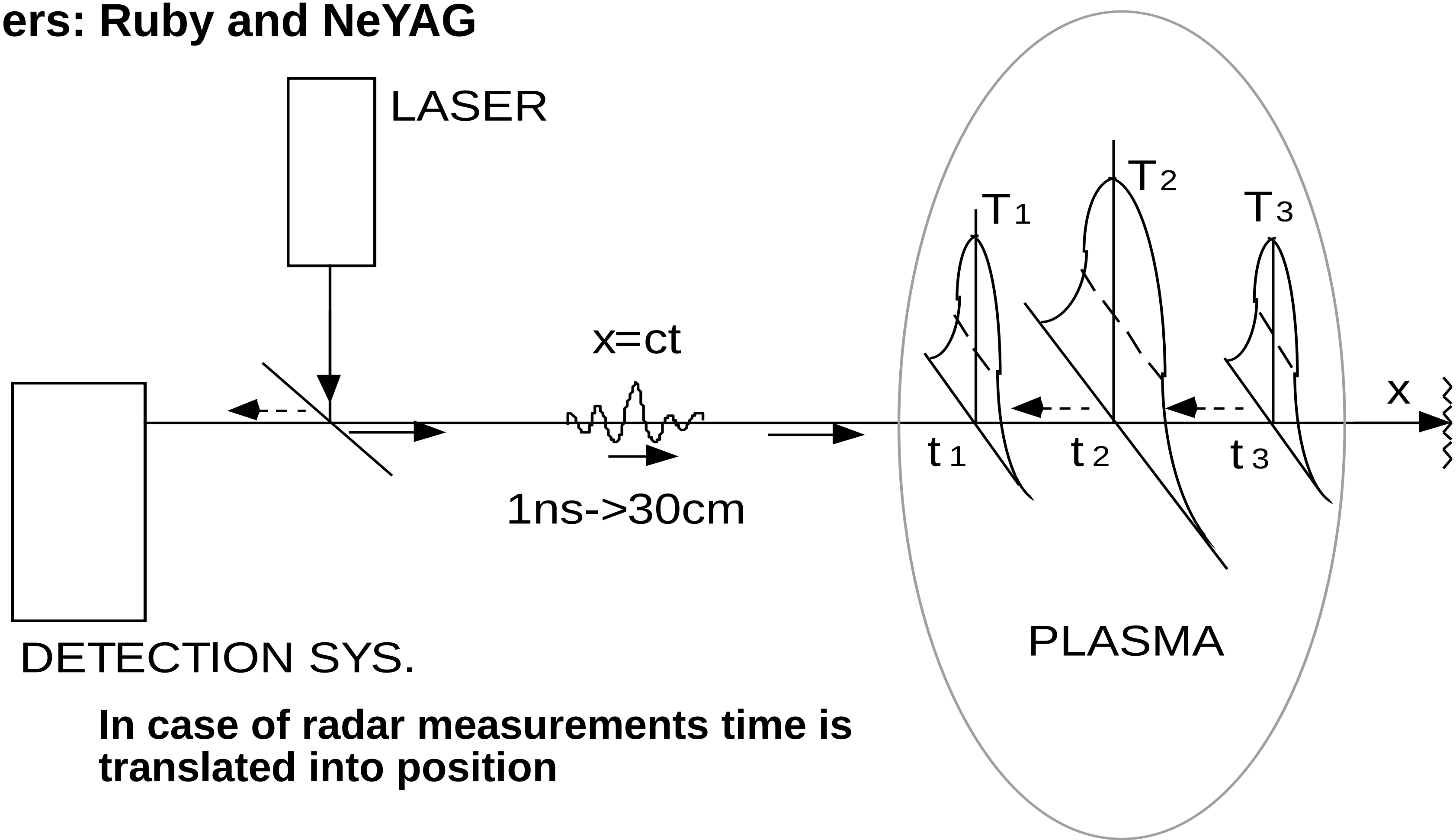
This diagnostic was used by scientists from Culham in 1968 to confirm the high temperatures reached in the first Russian Tokamak, leading to the development of Tokamak devices all over the world.

Incoherent Thomson Scattering: LIDAR

Broadening gives the electron temperature Te

Absolute intensity gives the electron density ne

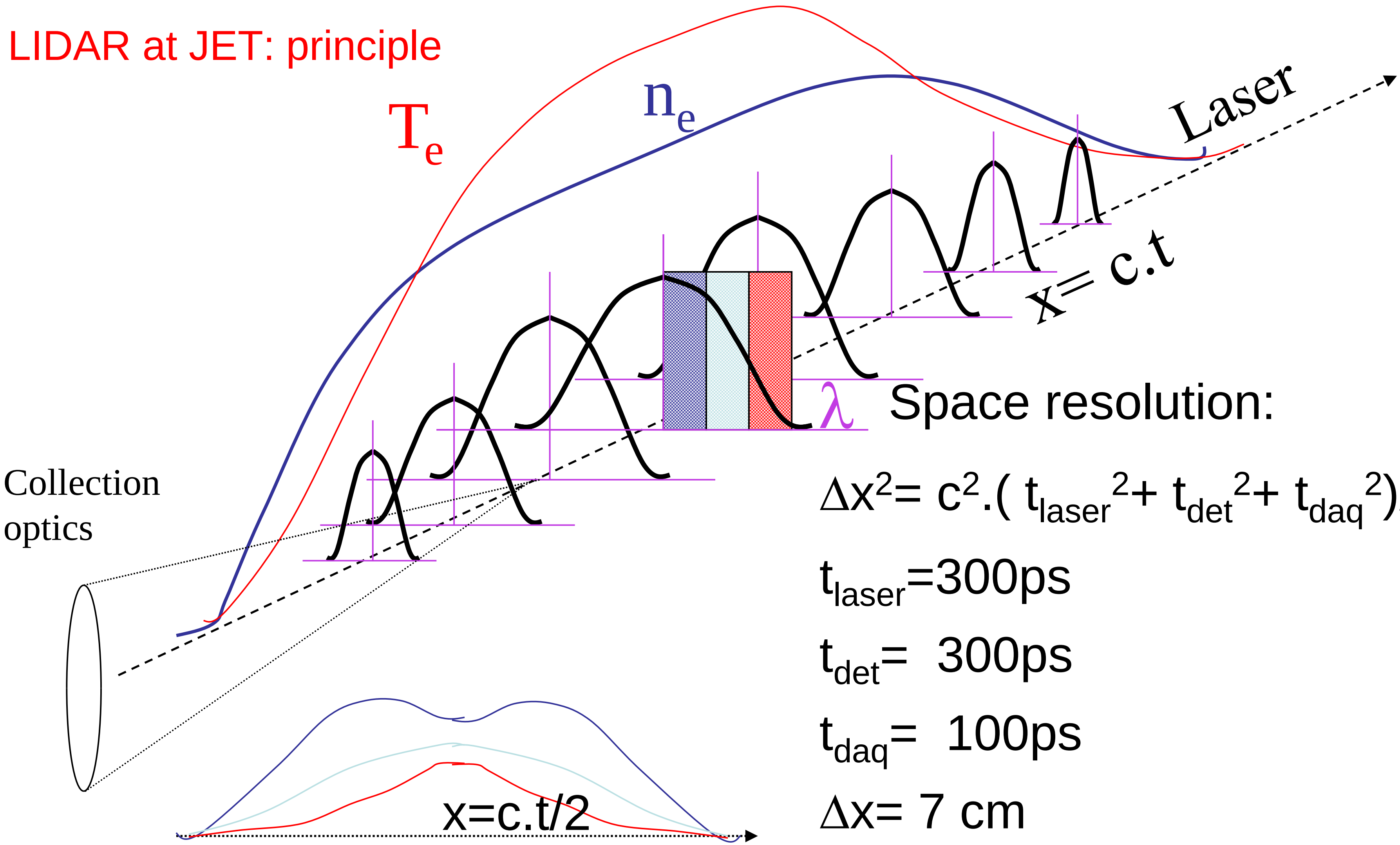
Lasers: Ruby and NeYAG



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

Thomson scattering optical path

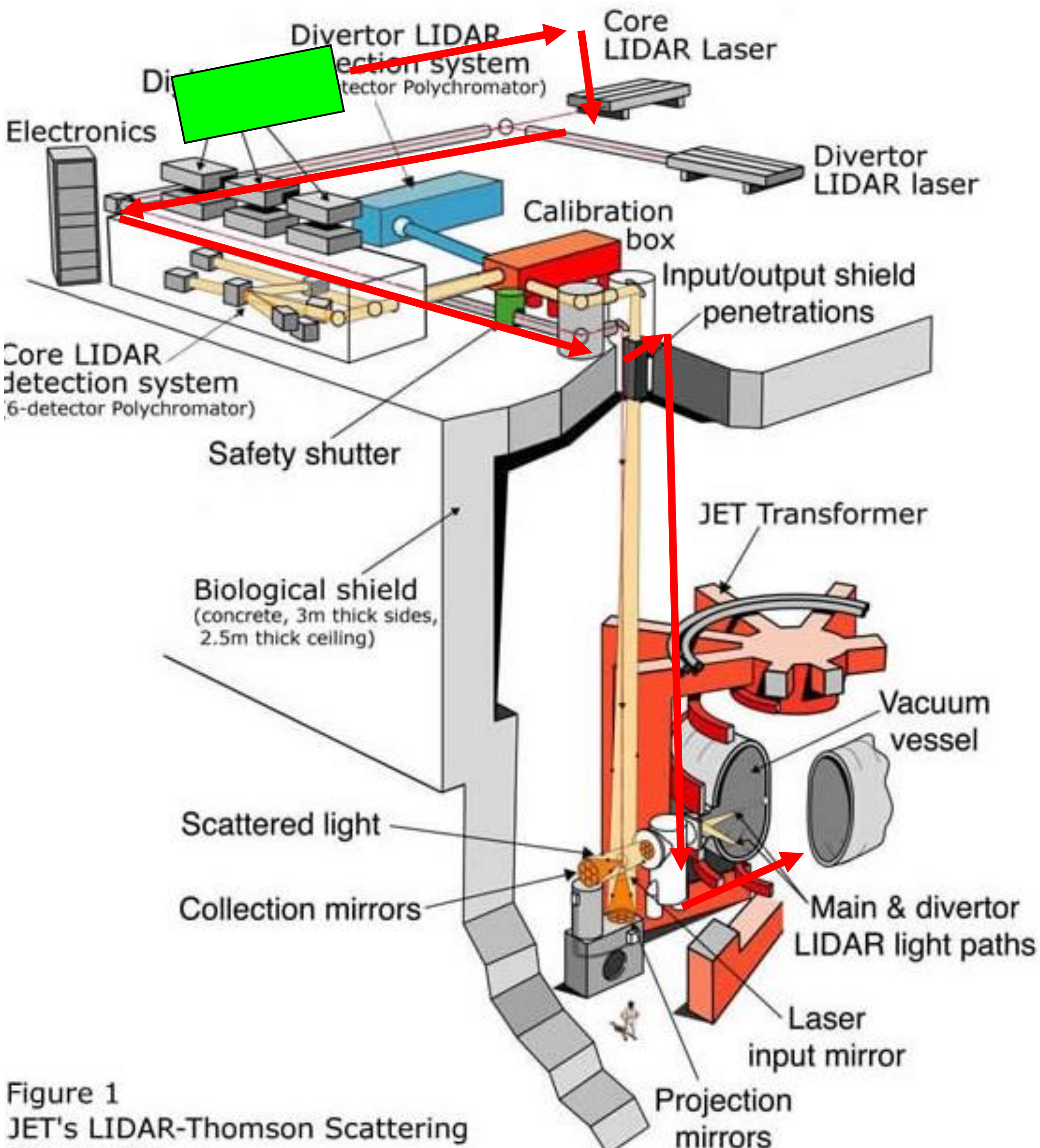


Figure 1
JET's LIDAR-Thomson Scattering
Diagnostic

Thomson scattering optical path: about 50 meters

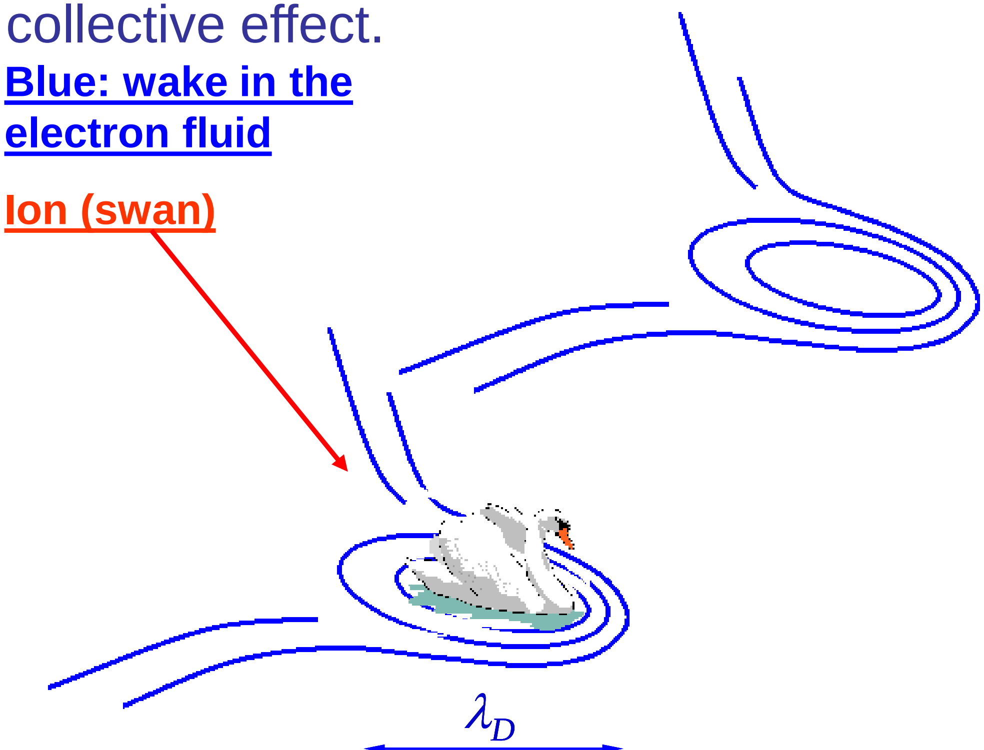
- **Power density of about 10 GW (for only 300 picoseconds)**
- **Frequency of laser pulses: 20 Hz**

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.



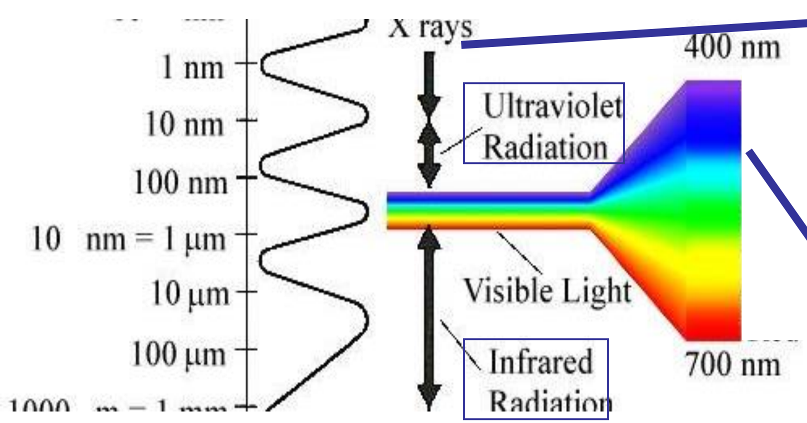
Light scattered coherently from the electrons give information about the presence of the ions.

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

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…

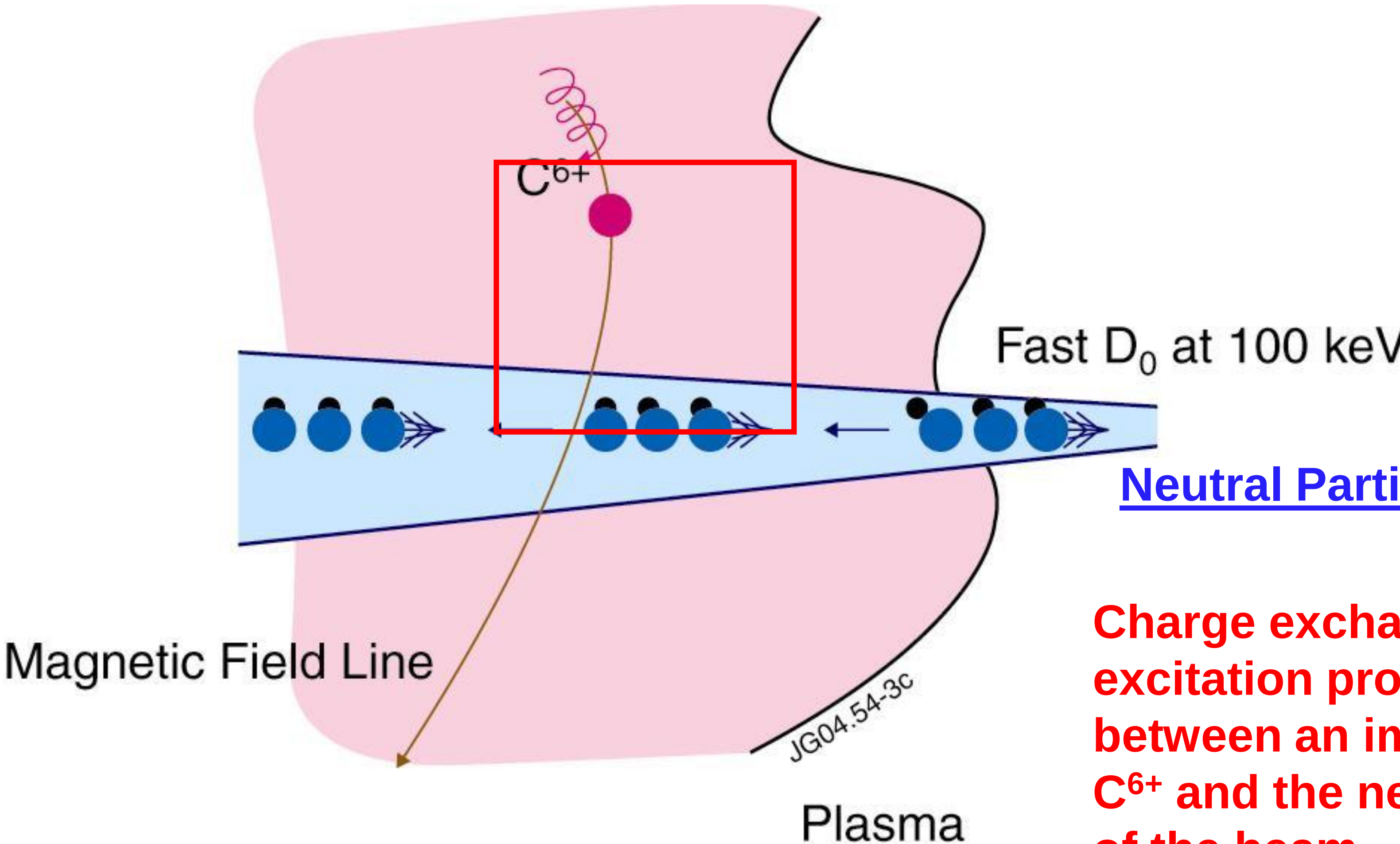
<u>Charge-exchange recombination spectroscopy</u>:

Visible lines for ion fluid and impurity studies

Need extensive database on atomic physics

Ion Diagnostic: Charge eXchange Recombination Spectroscopy (CXRS)

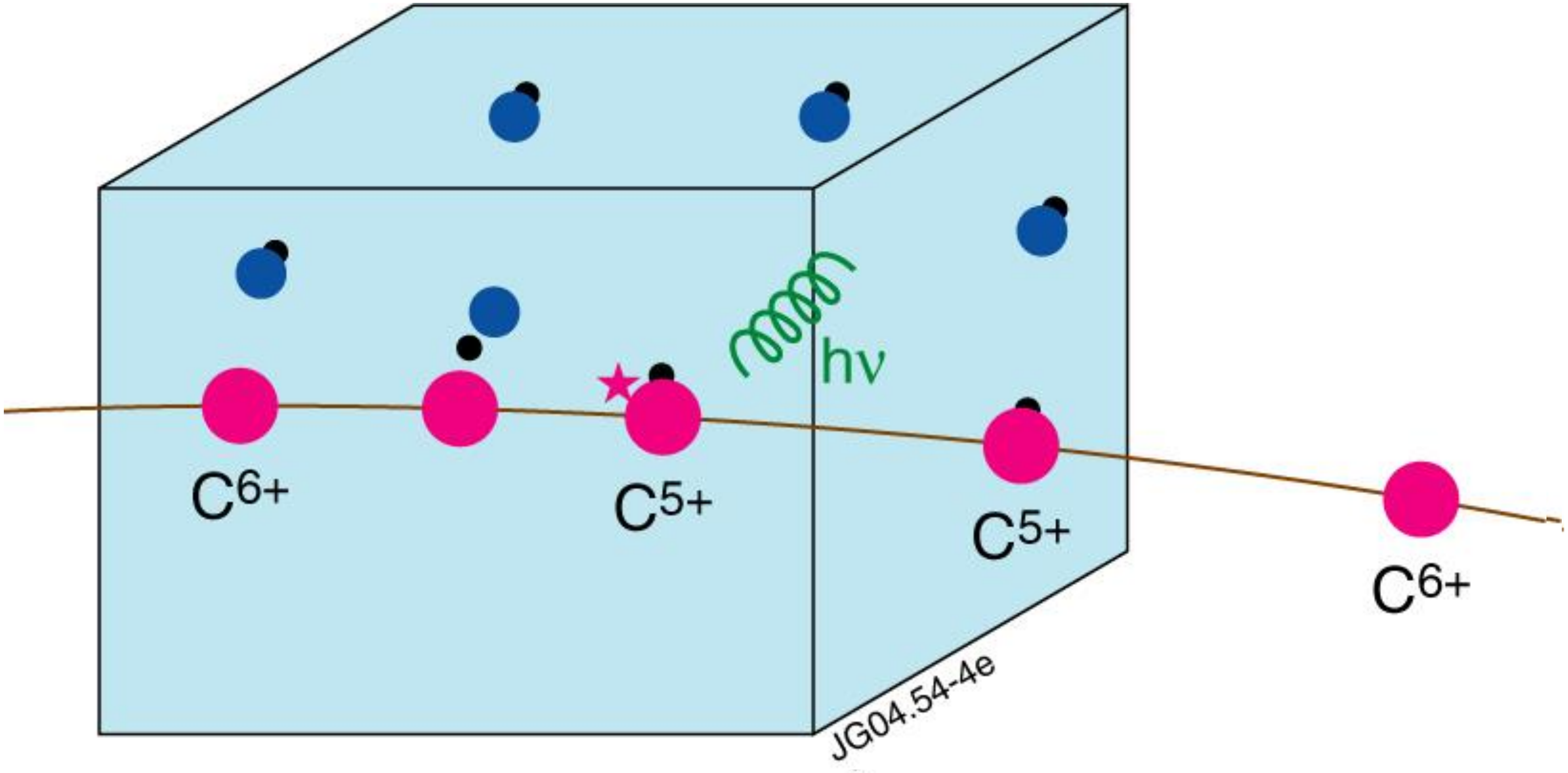
Principle: derive information about the main plasma ion fluid by measuring the properties of intrinsic impurities which are thermalised (have the same temperature and rotation as the main plasma)



Neutral Particle beam

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

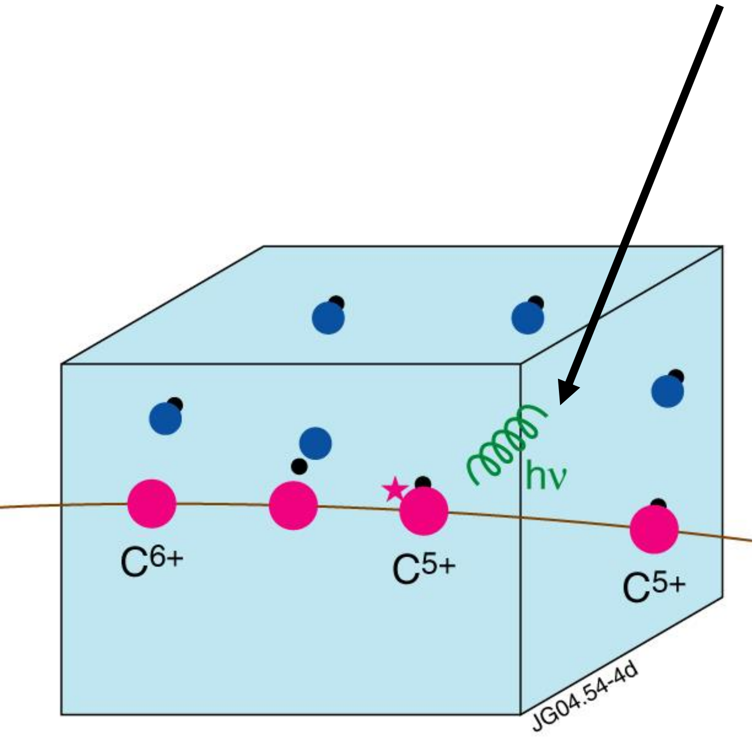
Charge eXchange Process



Charge exchange excitation process

Information derived by CXRS

Principle of Charge Exchange spectroscopy



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

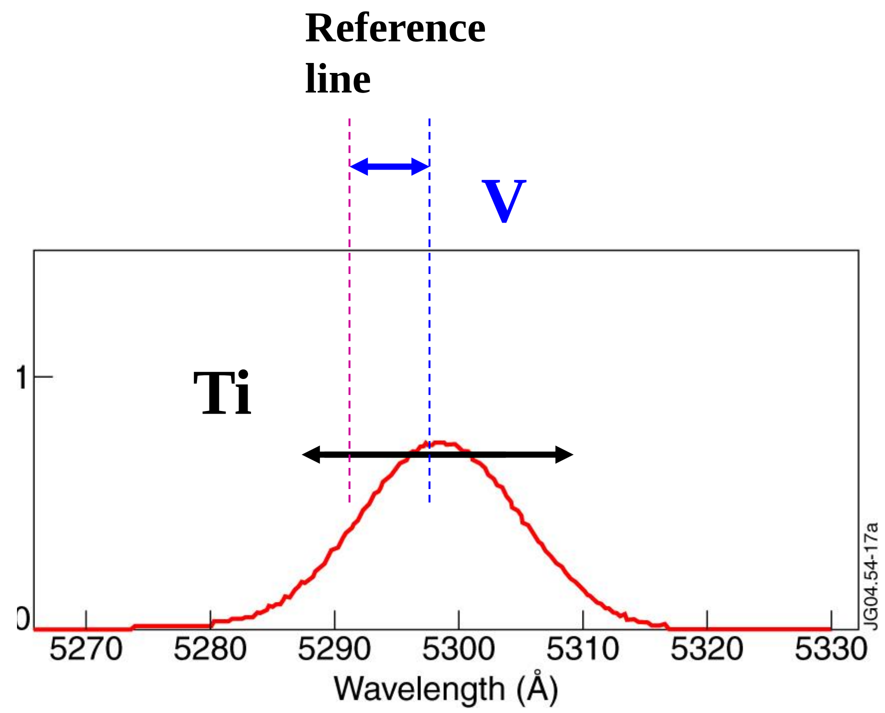
- **temperature**
- **momentum :** The CX reaction does produces very little momentum change for the recombined ion and hence does not disturb the ion velocity distribution.
- **the number of C^{6+}**

Temperature, velocity and impurity measurements

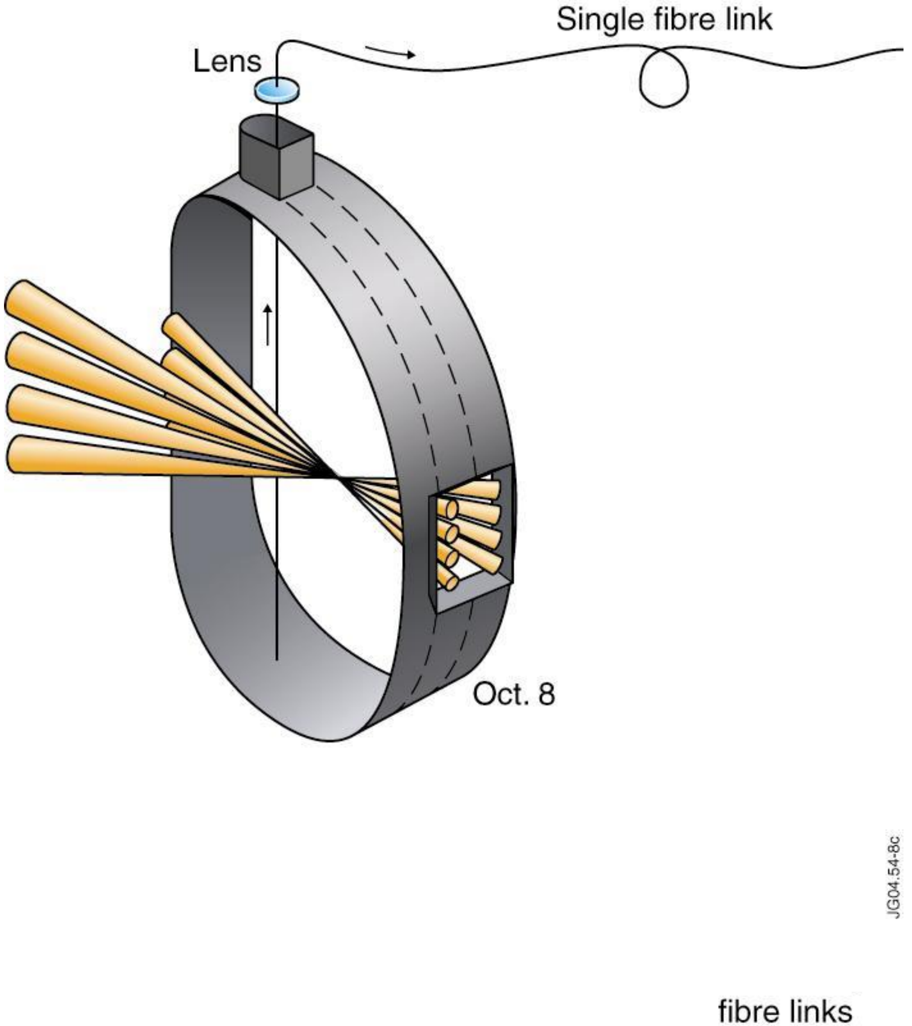
- **Broadening dominated by Doppler width.**

- **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.

Summary

- Magnetic fusion plasmas are complex, open systems, kept out of equilibrium to maximise performance

- Magnetic Confinement Fusion is one of the fields of physics which requires the highest number of different diagnostics (all major measuring techniques of physics are represented).

- This variety is due to the fact that
  - the temperature range covered is enormous (from liquid He to 100 million ^{0}C)
  - the density range is also significant (from 1 bar to UHV 10^{-8}-10^{-9} mbar)

- The amount of data available is quite remarkable. Since nuclear plasmas require an holistic understanding (more like the Health Sciences than the High Energy Physics) the interpretation task is formidable.