EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Spectroscopy for JET programme: challenges and opportunities

By Andrea Murari

on behalf of TFD and the spectroscopy groups

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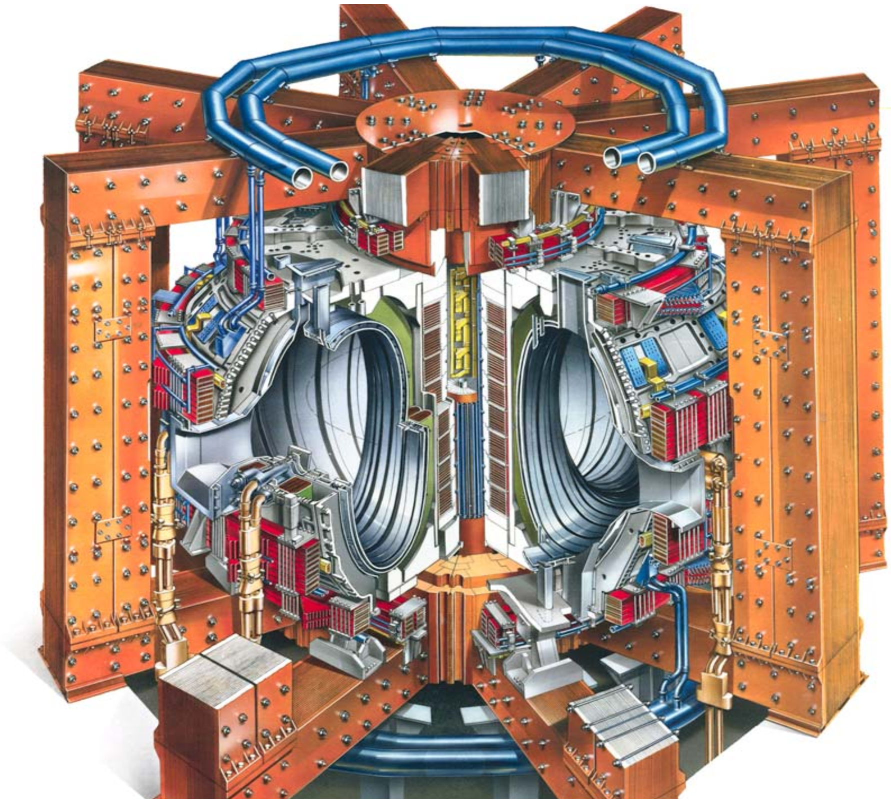
The Joint European Torus (JET)

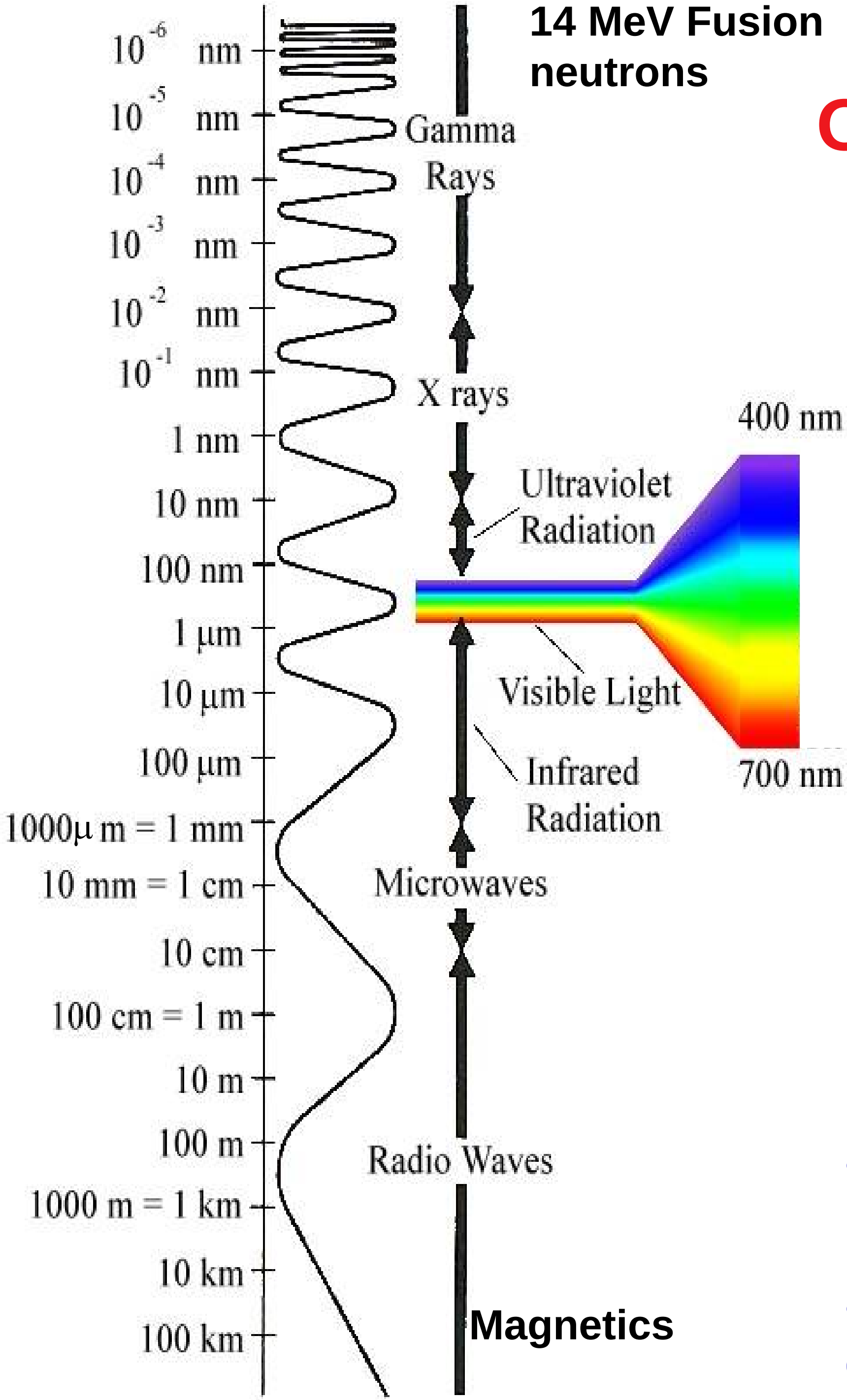


Plasmas closest to ITER

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 in present configuration
Toroidal field	up to 4 Tesla

JET can achieve the plasma parameters closest to ITER and has some unique technical and scientific capabilities:

- Tritium Operation
- Beryllium Handling
- Plasma Volume to confine the alphas



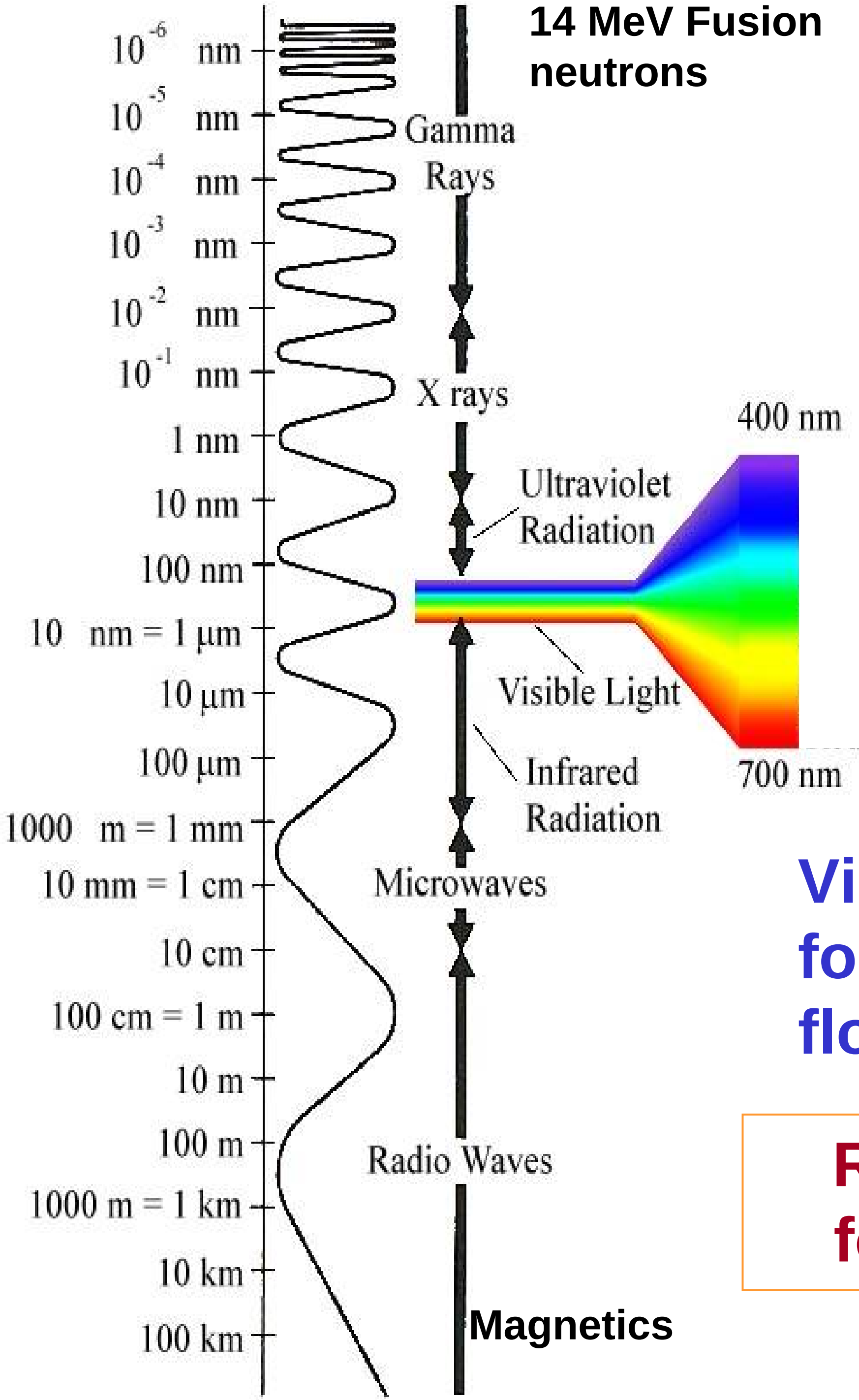
On JET Measurements along the whole EM spectrum

- **About 100 diagnostics. Already acquired a maximum of more than 10 GBytes of data per shot. Cruising at about 5 GBytes per shot (previously maximum 2 GBytes)**
- **Diagnostic Upgrades under EFDA involved all European associations plus USA and the Russian Federation**

Diagnostic activities involve:

- **About 1/3 of the Fusion staff (plasma physicists)**
- **2/3 of the University collaborations**

Spectroscopic Potential



EUV and Visible spectroscopy for alpha (fast) particles and He ash

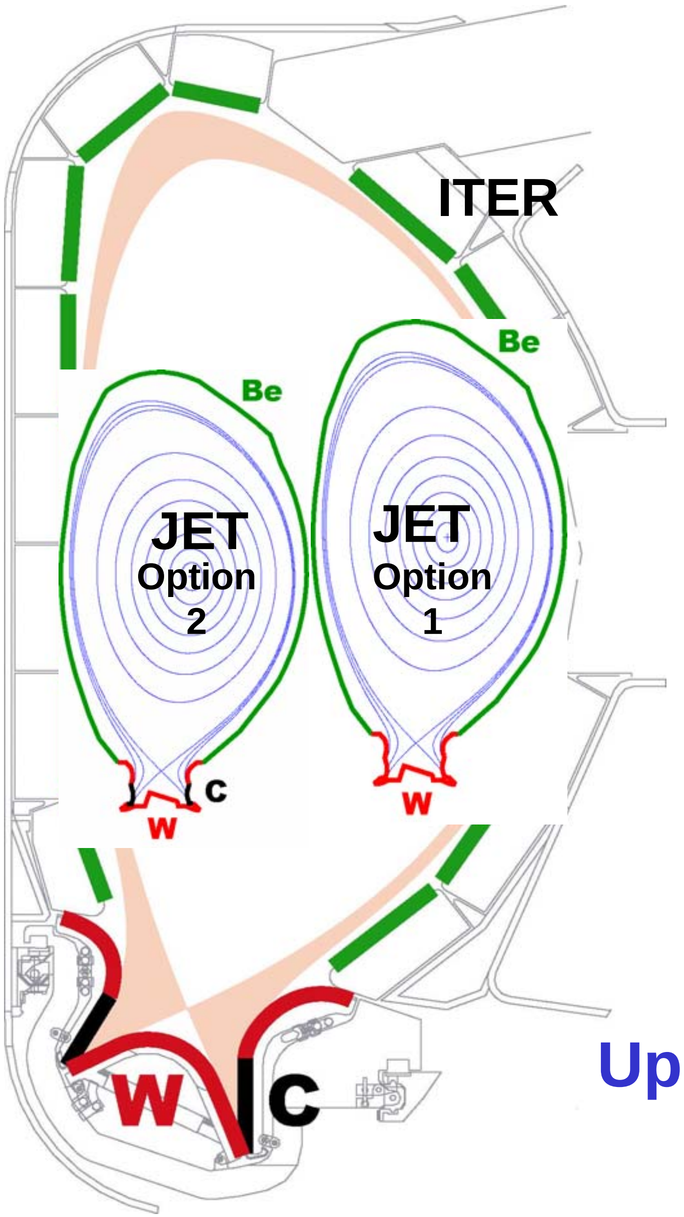
Visible and UV spectroscopy for impurities

Visible spectroscopy for main plasma parameters: J and n_i T_i V_i

Visible and IR spectroscopy for n_e and T_e and material flows at the edge

Real Time: visible spectroscopy for total radiation control

JET New Wall



ITER-like Wall Experiment

Main wall

- **Bulk beryllium** where possible

Divertor

- Plan for **all W coated CFC** (Reference Option)
- *Fall-back Option:* ***CFC on targets***

Study of wall's materials is really an EU programme (ASDEX U)

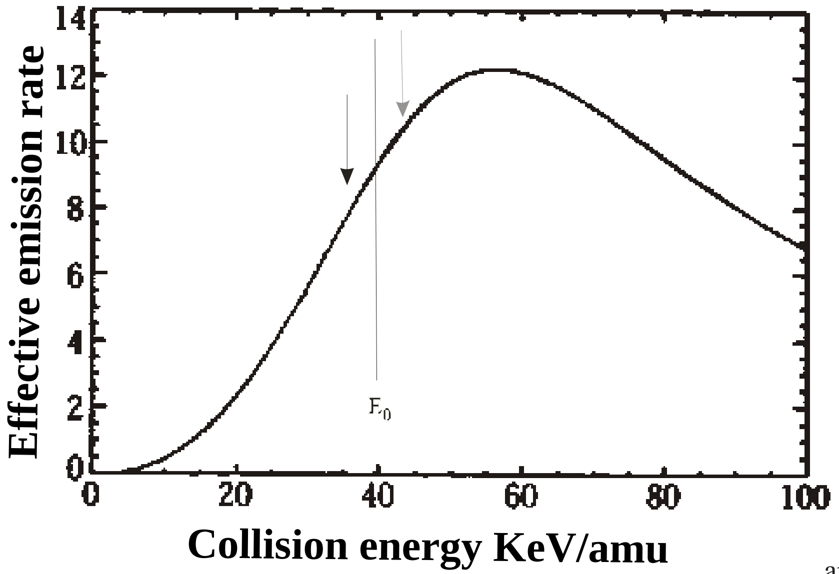
Upgrade of NB power to 35 MW for 10 s. Even NIB 4 all PINIs at 130 kV

Main plasma parameters: ion fluid

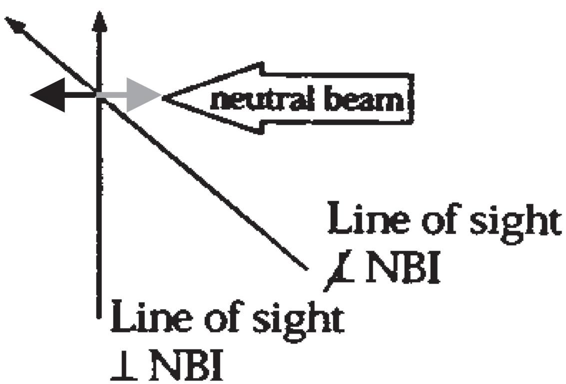
- In the fusion perspective the ion fluid is the relevant one: it is normally less diagnosed because it is more difficult (ions surrounded by the electron fluid which interacts preferentially with the electromagnetic waves)
- With the new wall will probably not be possible to rely only on C for spectroscopic measurements
- With the new wall the radiation will be lower. ITER is supposed to work at 90 % of radiation losses (JET typically about 50% of input power)

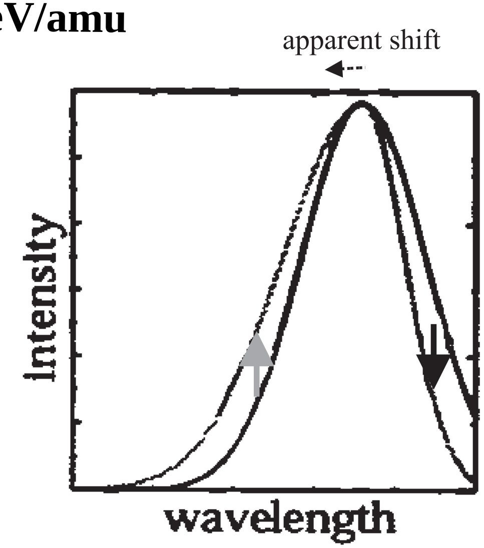
- In the reactor perspective, at higher temperatures additional atomic physics can play a significant role
- Example: effects of high Ti on poloidal velocity measurements with Charge eXchange (CX)

Effect of the not constant CX cross section



- CX cross-section depends on collision energy between C^{6+} ions and beam neutrals
- Leads to an apparent line shift in the CX spectra (artificial velocity component in the direction of the beam)
- Apparent velocity increases with temperature → larger difference in collision energy between co- and counter NBI moving ions



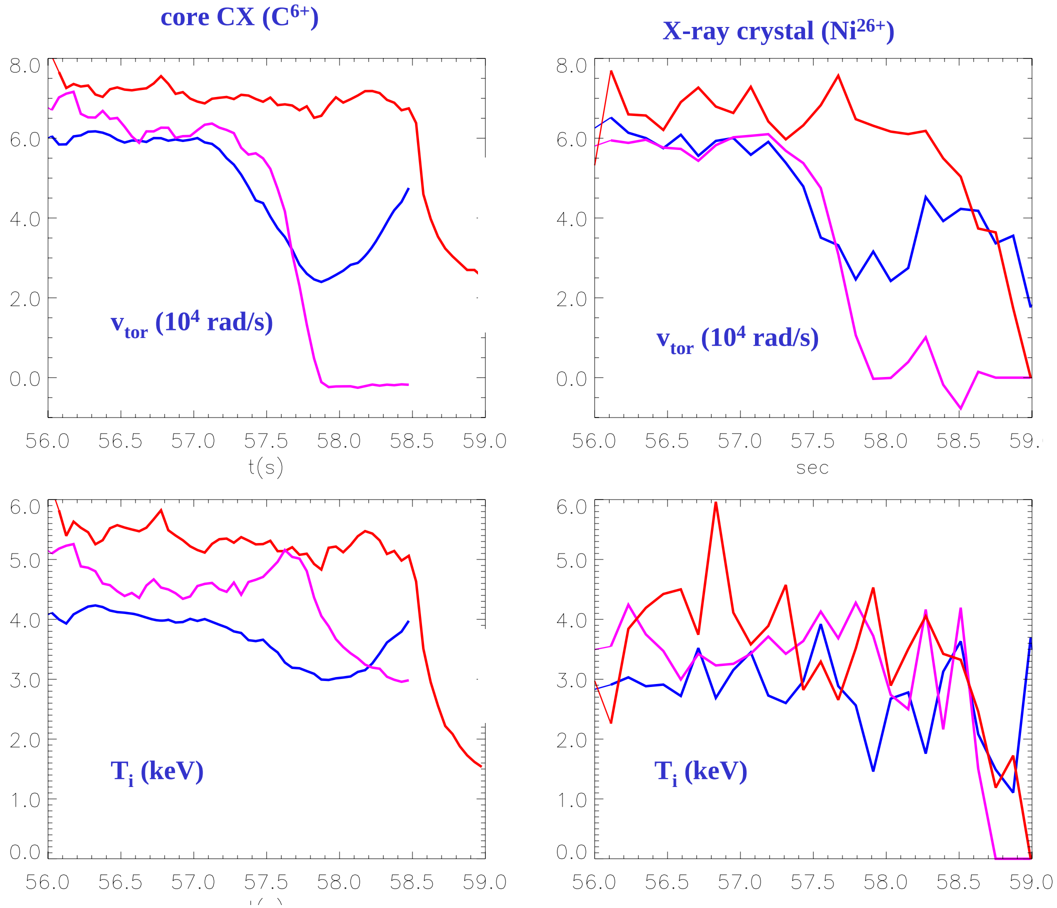


Experimental investigation of Vpol at JET

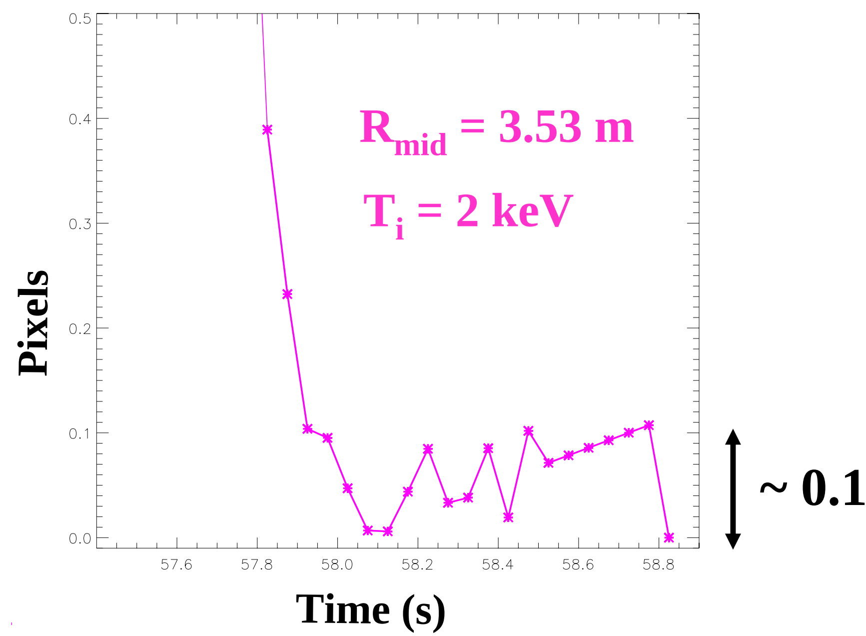
Plasma rotation stopped by braking with external error fields

67958 no EFCC # 67957 breaking

67955 locking



67955 Vpol at locking



Remaining shift when locked < 0.1 pixels

Corresponds to < 3 km/s

Picture of impurity generation and transport in present devices

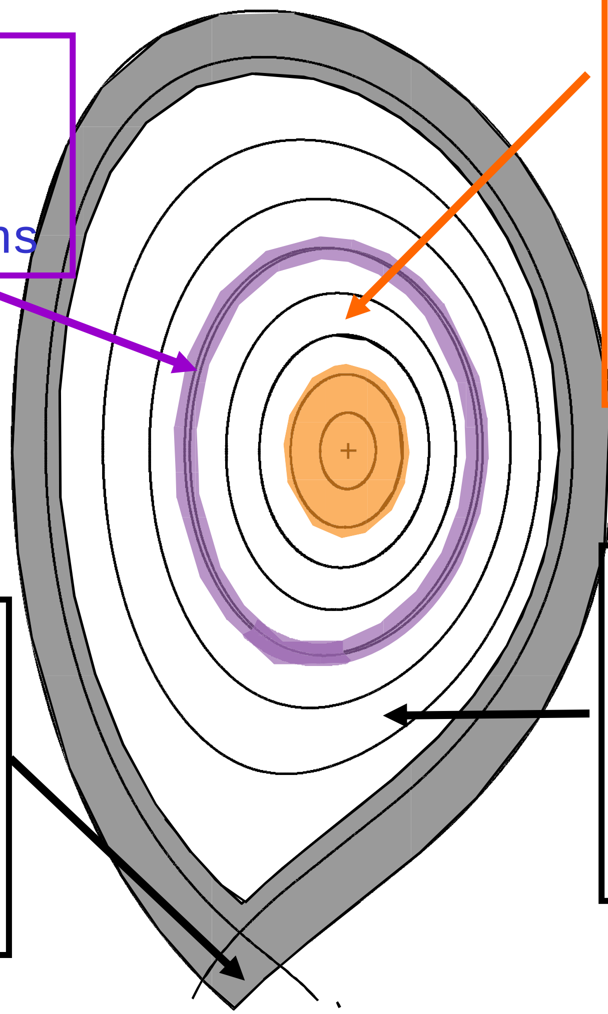
•Plasma purity is essential to achieve the desired neutron yield.

- <u>Within ITB region:</u>

  Transport can be close to neoclassical predictions

- <u>Inside core region</u>

  W accumulation observed with peaked density profiles without central wave heating in ASDEX



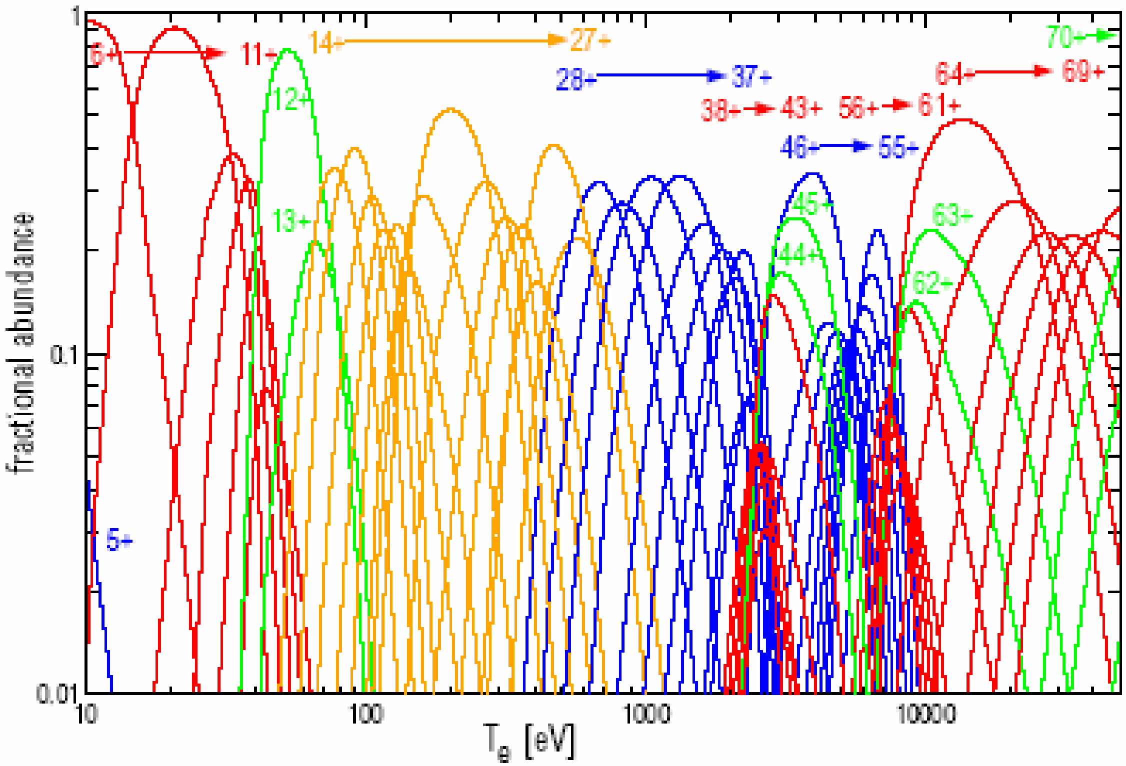
- <u>Edge Plasma</u>

  Where the influxes generated at the wall penetrate into the interior

- <u>Divertor:</u>

  Plasma conditions which render measurements very difficult. Example detachment

W spectrum



Transportless ionization balance for W at n_e=1 10^{20}

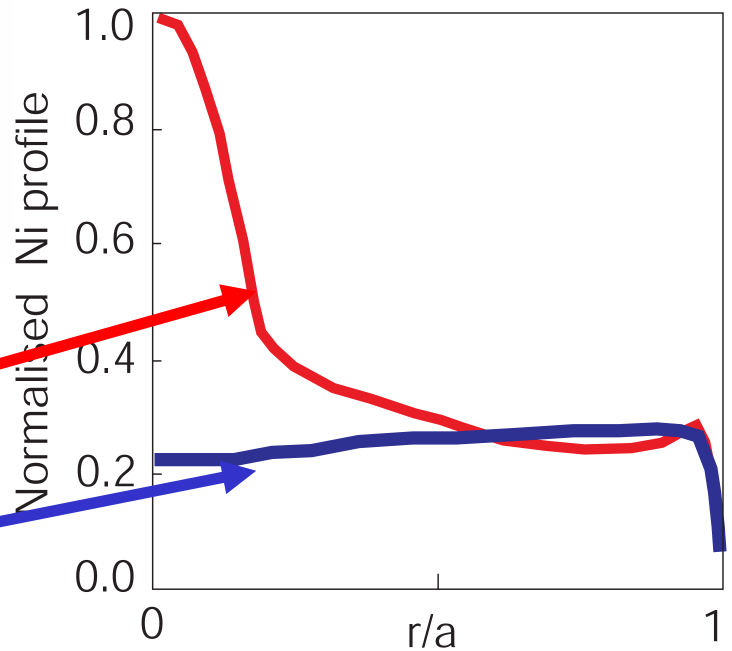
Plasma Transport Influence

ICRH dominant ion heating

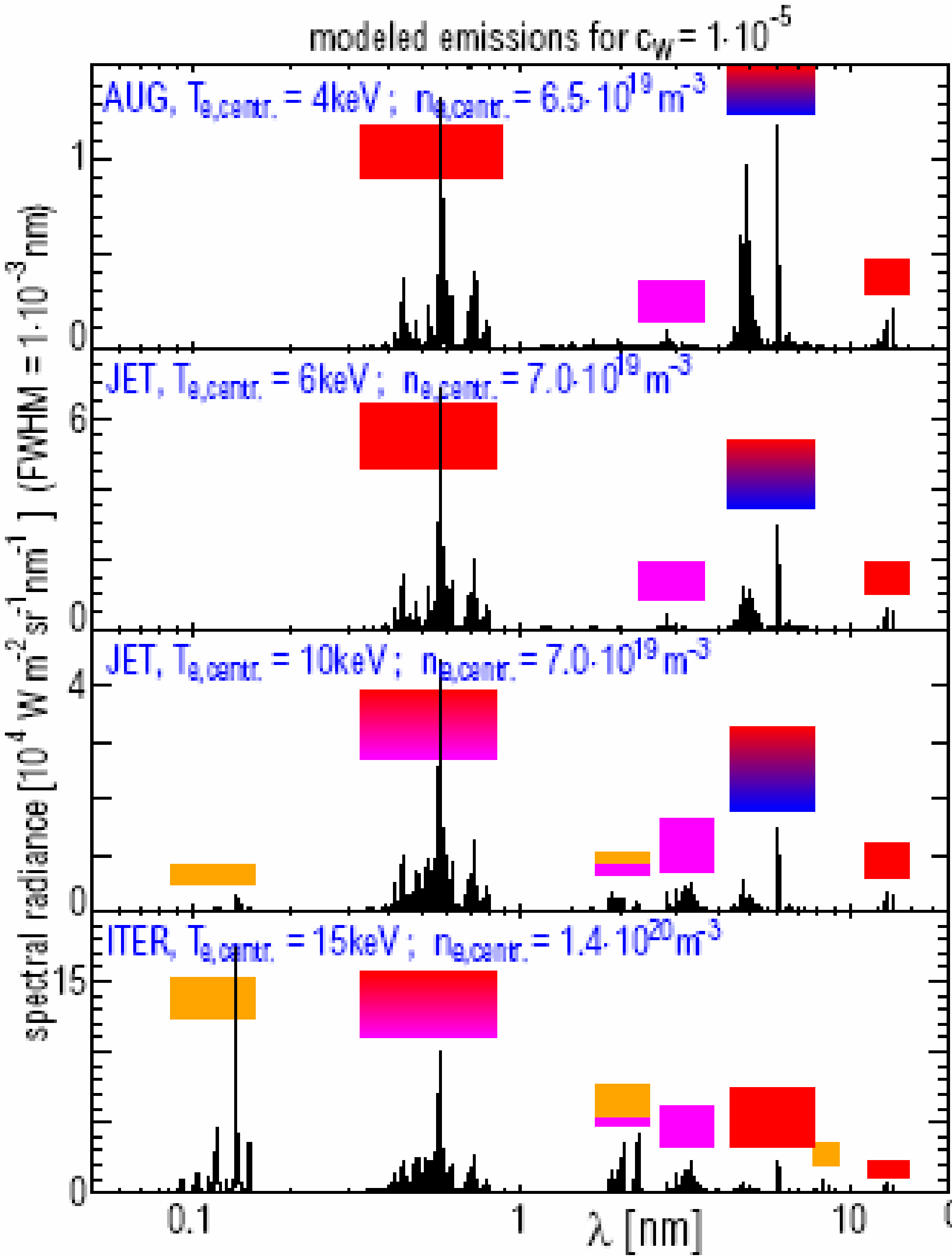
Peaked Ni profile

ICRH dominant electron

Slightly hollow Ni profile



Some W lines only in JET and ITER



Predictions for W spectra in ASDEX, JET and ITER

Aims
- better understand the spectra,
- benchmark new theoretical tools,
- produce predictive atomic data,
- improve the diagnostic capabilities in present experiments and in future fusion devices like ITER

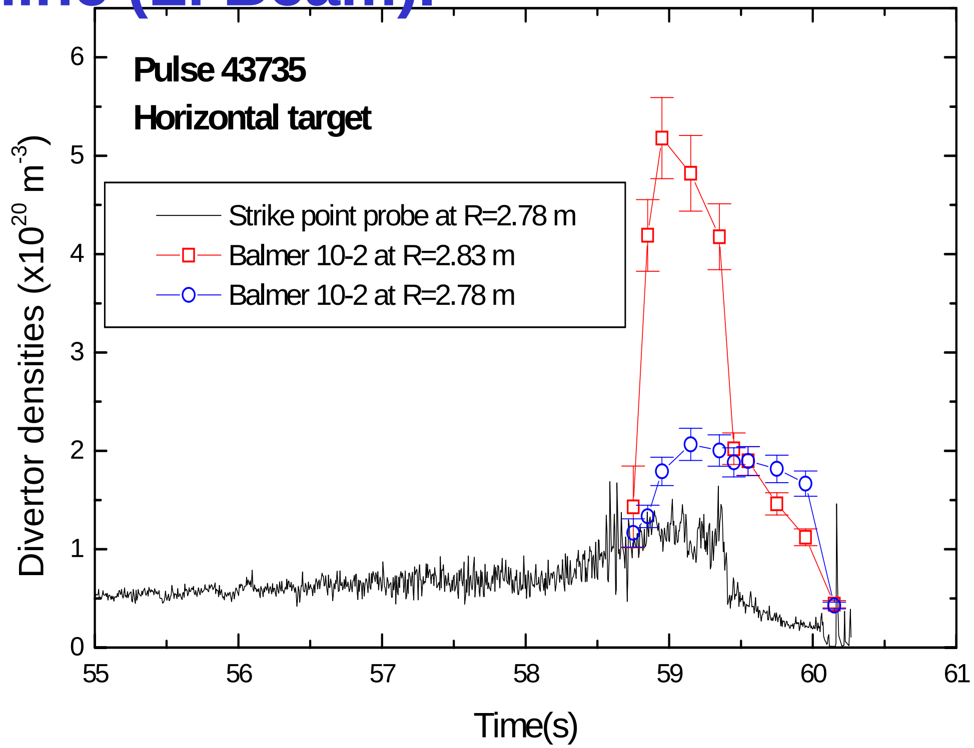
- The work on W can be complemented by investigations on other high-Z elements (Xenon diagnostic capabilities and cooling factor)

Motivation

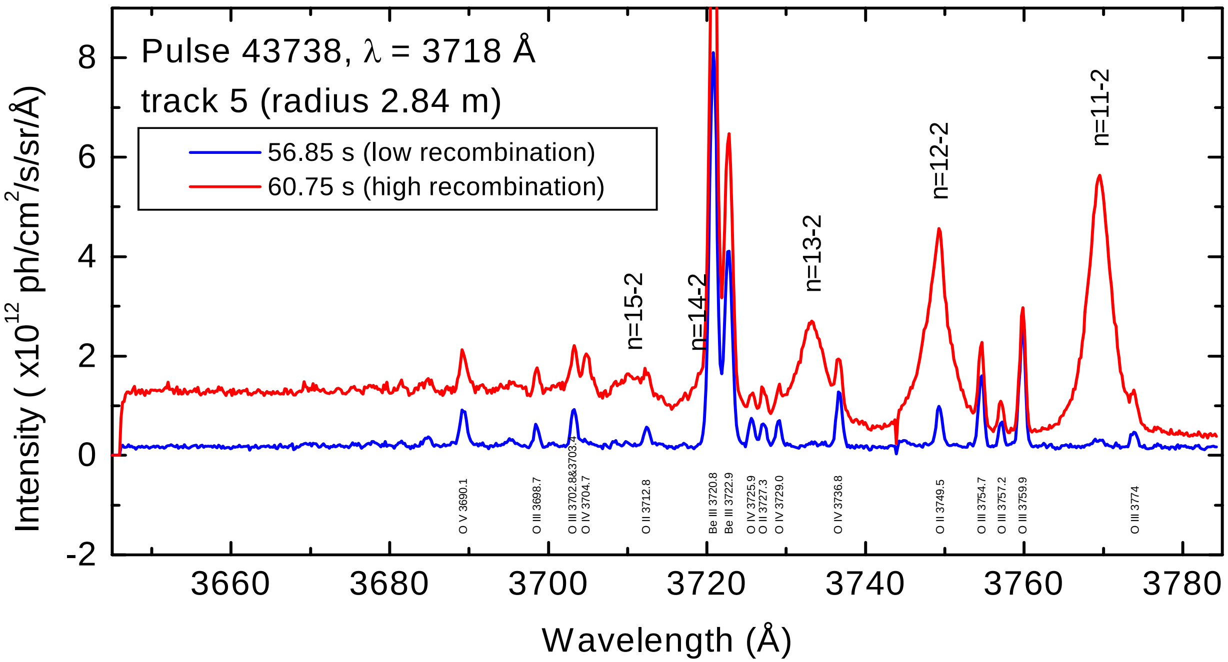
Te and ne at the edge are extremely important (contribute to determine the severity of the plasma wall interactions) but very difficult to achieve with required accuracy, spatial and temporal resolution (traditional techniques like ECE and TS become problematic in the range of parameters typical of edge plasmas). Current density at the edge is also difficult to determine (Li Beam).

Particularly severe are the problems at plasma detachment in the divertor (because also the standard edge diagnostics like Langmuir probes become less useful).

At detachment n_e so high and Te so low that there is significant neutral gas at the target (recombination)



Series Limit Spectra



Balmer/Paschen Series Limit Spectra

Diagnostic KT3D

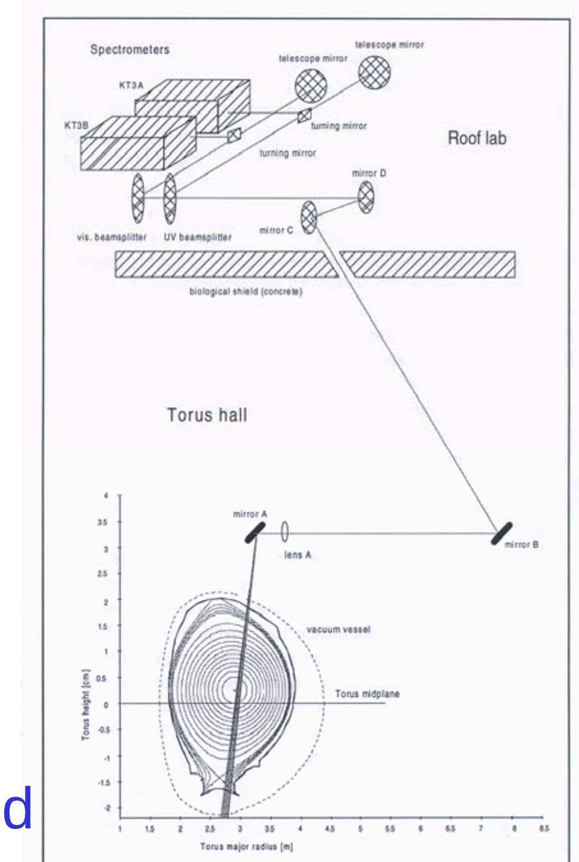


Figure 2.1 Location of the KT3 diagnostic. Torus hall components are to scale.

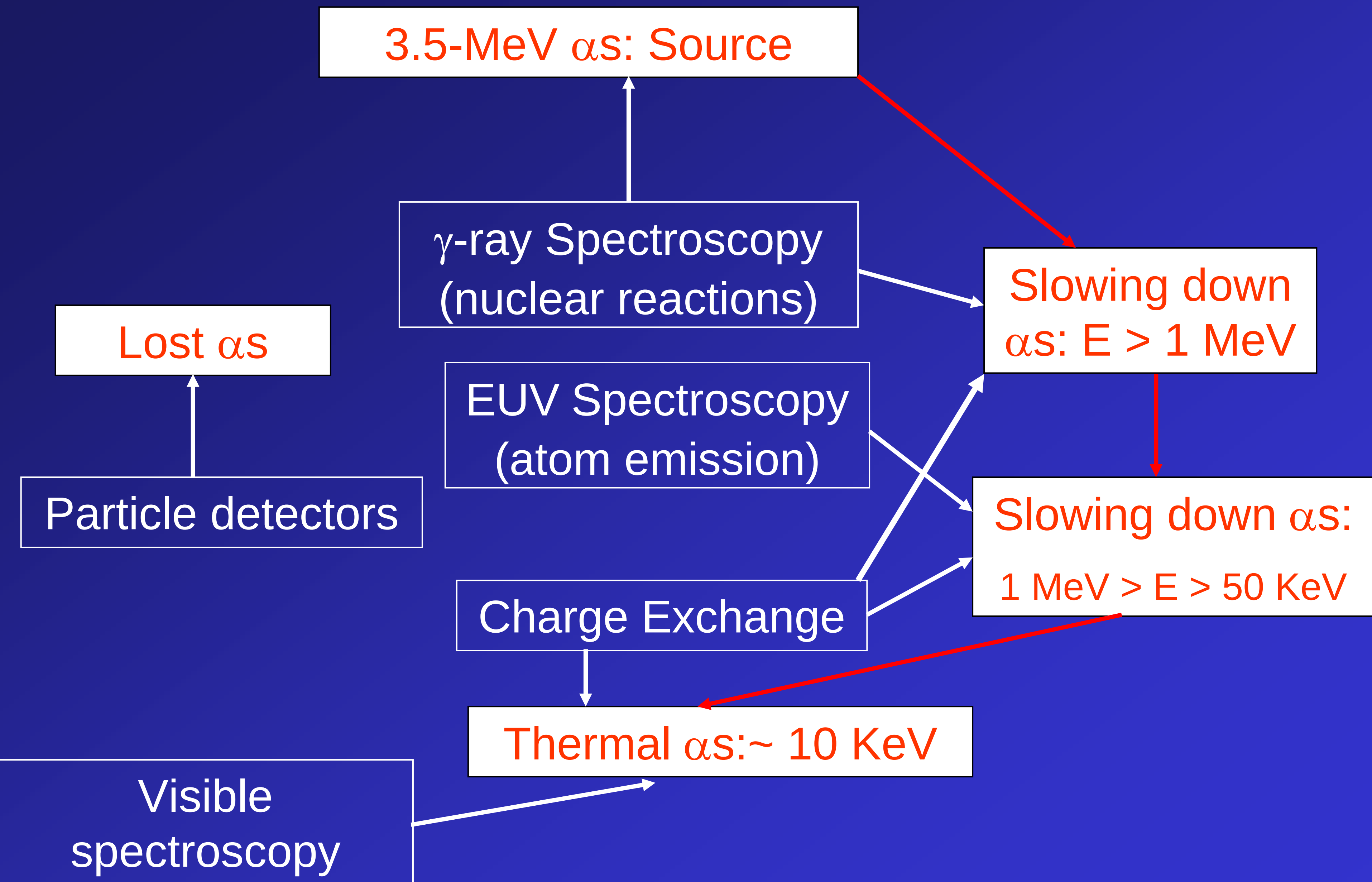
Two main issues influence the **theoretical spectrum**:

- the population of excited levels
- and the line broadening of these levels.

The effect of impurity species additional to deuterons could also be significant

Same diagnostic can be used to measure lines from hydrocarbons (IR) to study the codeposited layers (molecular emission of hydrocarbons)

Alpha Particles

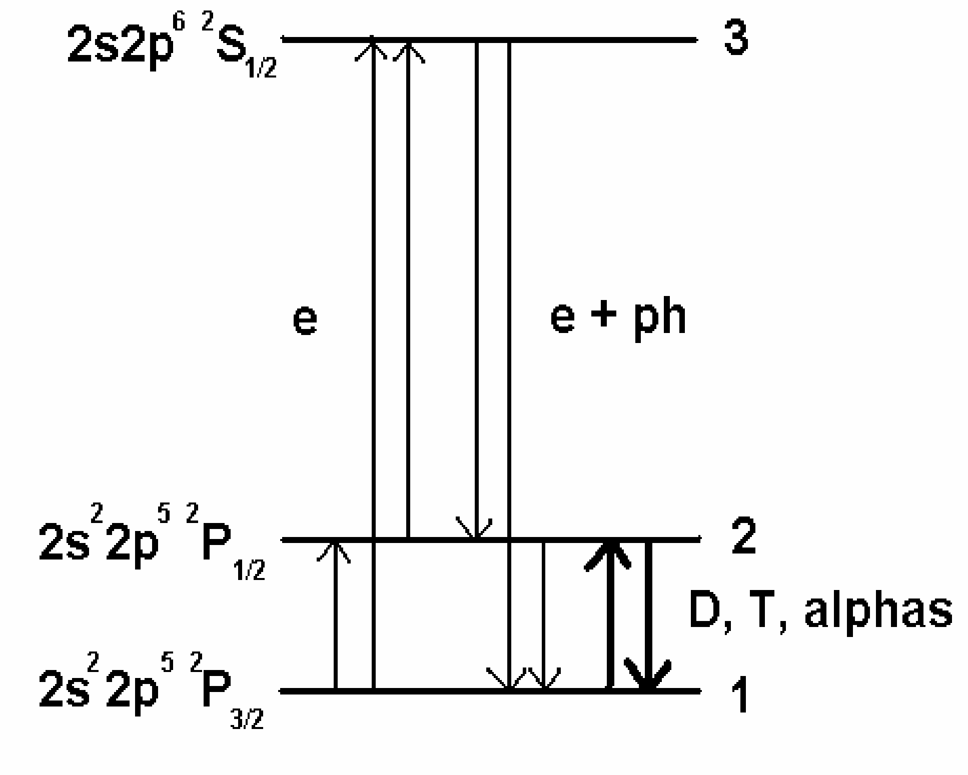


EUV Spectroscopy of Extrinsic Impurities

γ-ray spectroscopy is an excellent tool but it provides information only about particles with energy in excess of about 1.5 MeV (the threshold of the nuclear reactions). On the other hand for the study of wave particle interactions the real relevant range is between 50 and 600 keV. Atomic physics more suited.

A solution could be Spectroscopy of Extrinsic Impurities whose F-like and B-like ionisation stages are sensitive to energetic ions.

- The diagram is illustrated for the F-like ionization stage. Transition 2-1 (22.4 nm) is dipole forbidden for electrons but sensitive to fast particles (Tr 3-1 5.26 nm)

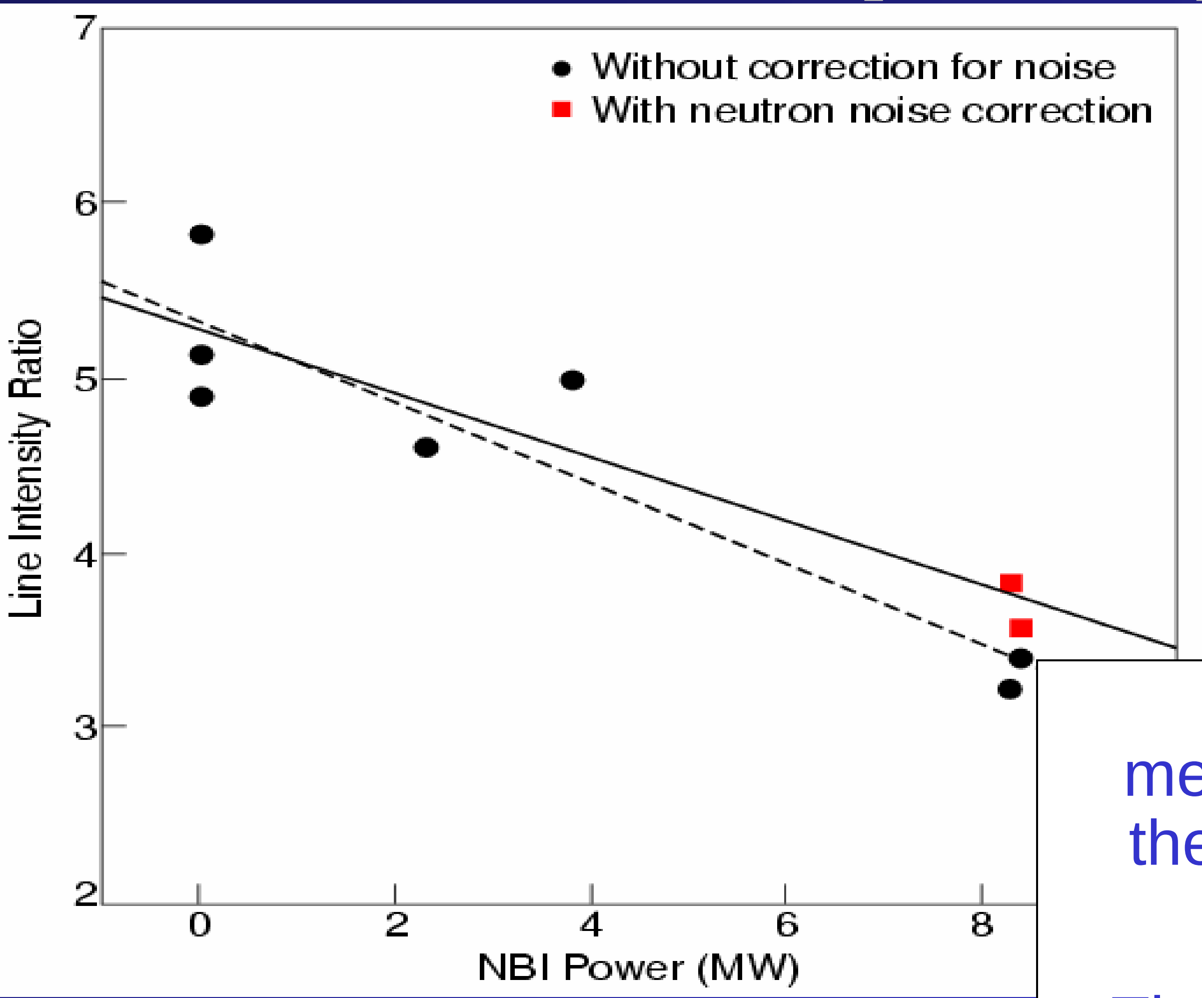


- The spectral line intensity ratio is

$$\frac{I_{31}}{I_{21}} = \frac{n_3}{n_2}\frac{A_{31}}{A_{21}}(photons)$$

where n_j is the population of level j and A_{ji} is the transition probability of the radiative decay j -> i

XUV Spectroscopy



Change in the KrXXVIII line intensity ratio due to D NBI as a function of NBI power

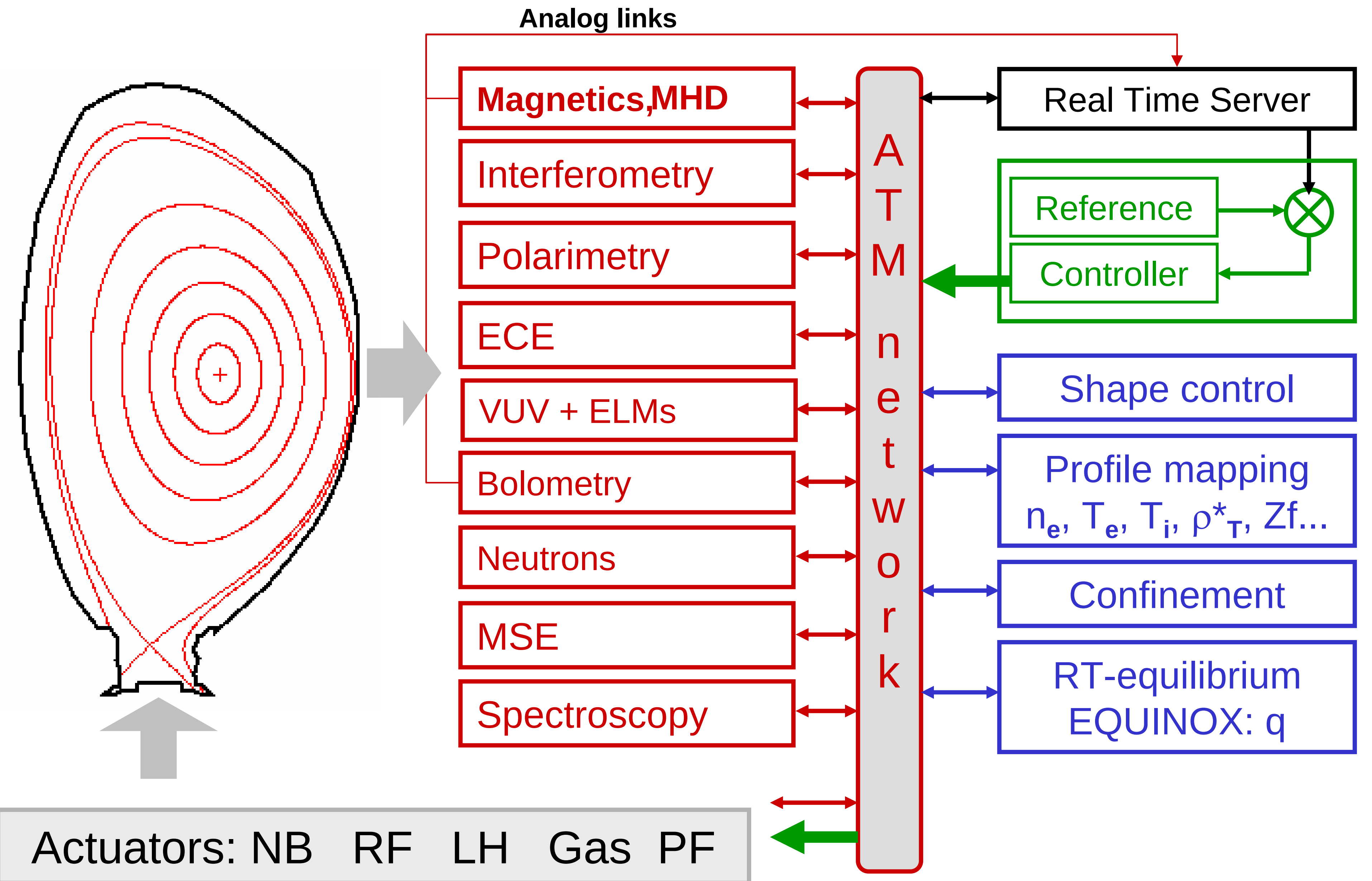
B-like ionisation stages also good candidates.

The technique has the potential to give information about the velocity distribution function of the fast particles in the range 50-600 keV

Accurate quantum mechanical calculations of the various cross sections are required.

These cross sections could be useful in atmospheric physics (fast particles entering the atmosphere)

JET Real Time Measurements and Control Network



Real time control of radiated power by absolute spectroscopy

Aim: to control and feedback on the radiated power from various impurity species rather than from the *total radiated power*.

Motivation:
Want to demonstrate a physics based controlled mechanism

This could allow a more efficient use of impurities to reach a certain level of radiation (to minimise <u>the impact on Zeff</u>, to reduce the severity of the <u>plasma-wall interactions</u>)

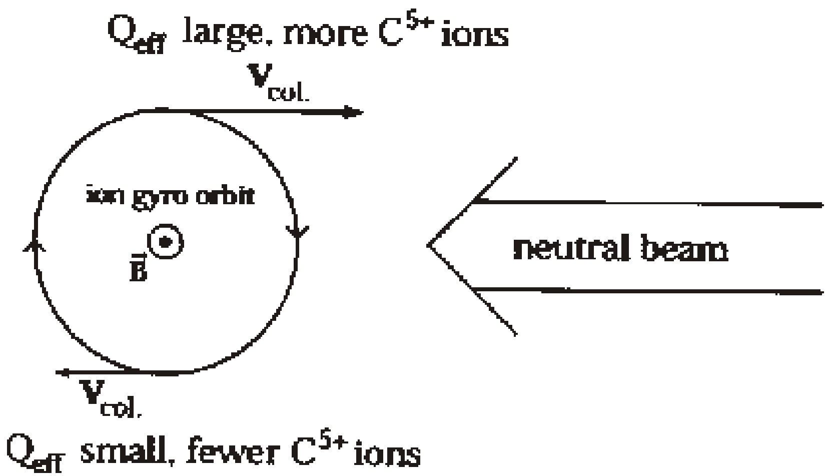
Better basis for extrapolation to ITER scenarios.

New Be/W wall will see reduction/removal of carbon radiation. Important to assess the potential of other impurities to radiate in a controlled manner

Summary and Future Prospects

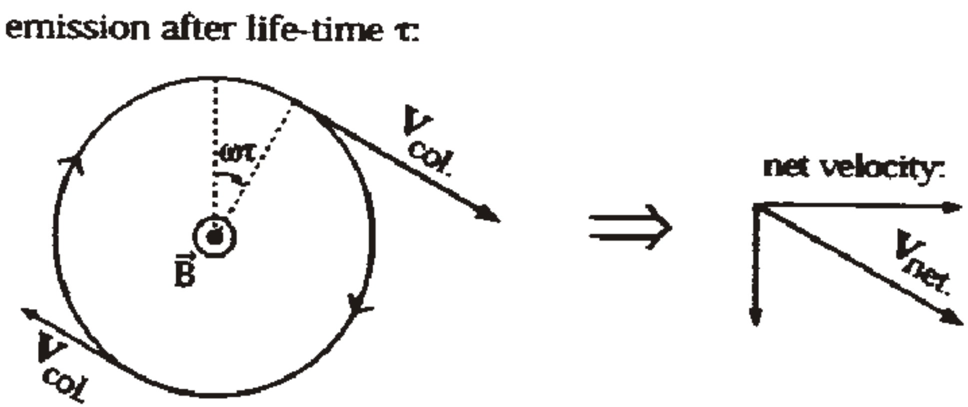
- JET has an integrated programme of diagnostic developments to support the experiments and to develop ITER relevant solutions
- Spectroscopy is a key ingredient in JET pool of diagnostics, particularly for the characterisation of the ion fluid, the purity of the plasma, the plasma current and the fast particles.
- A series of new projects has been launched for next framework programme, whose major elements are a new Be wall with a W divertor and a significant increase in the additional power.
- This change in the first wall material mix and the additional emphasis on burning plasma diagnostics will require significant modelling work to obtain the required atomic physics data.

Background 2



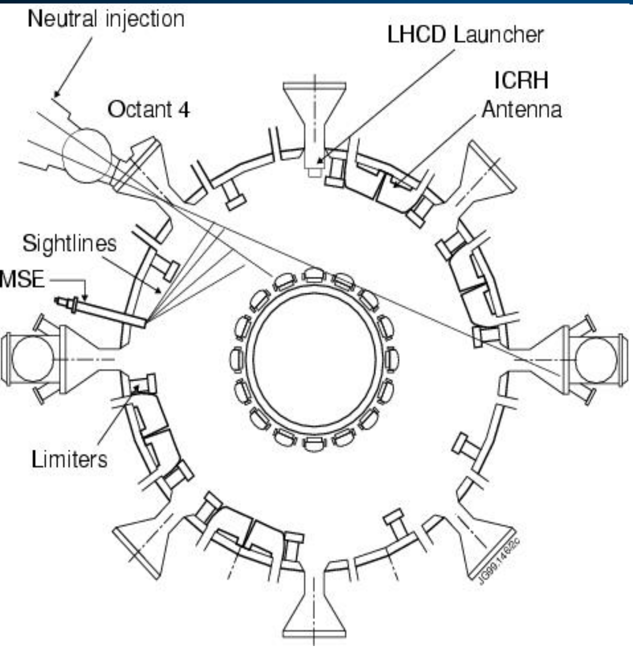
• Apparent velocity is initially in the direction of NBI → sightlines perpendicular to NBI direction do not suffer from this effect, but …

•The gyro-orbit motion during the finite lifetime of the excited state of the C^{5+} ions transfers the direction of this apparent velocity

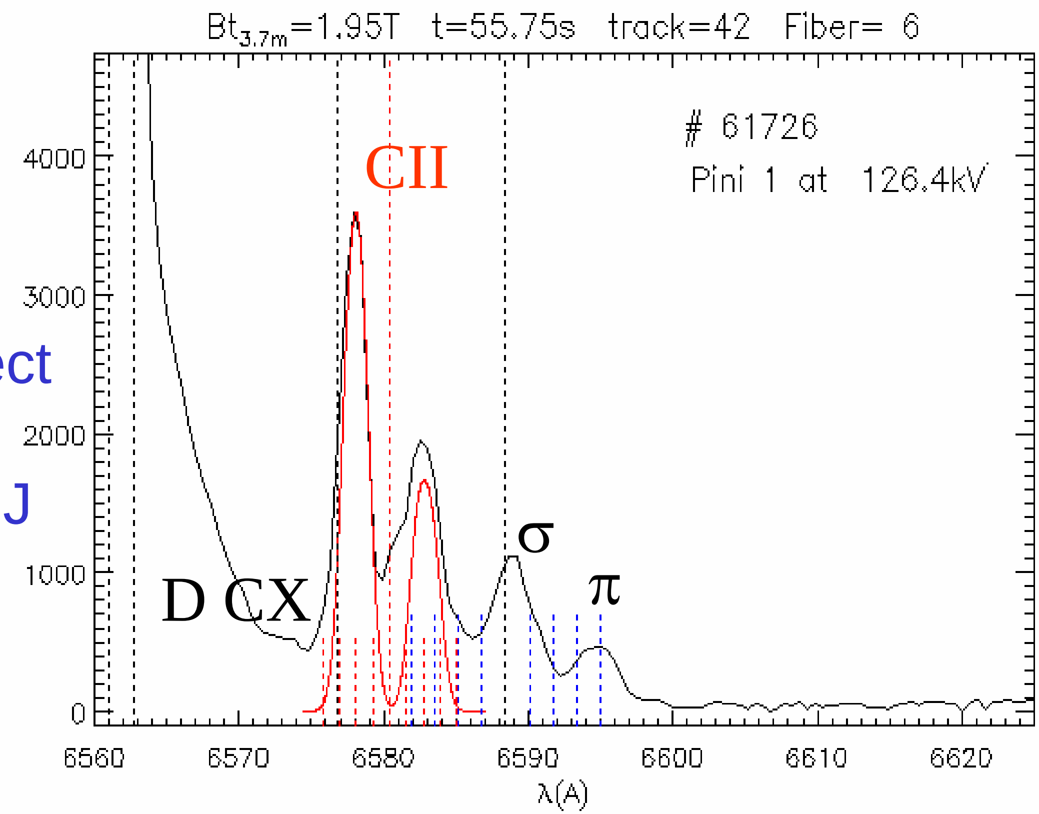


• Apparent velocity is partly also perpendicular to NBI

Measurement of the Current profile with MSE



The determination of the current profile has become a very important element in the Tokamak programme because of its link to the steady state operation (Advanced Tokamak Programme) and performance (ITBs, Hybrid scenario)



Beam Emission Spectroscopy based on the Motional Stark Effect is the most spatially resolved of the diagnostic measurements of J (Faraday rotation provides line integrals)

Future issue: operation of the PINIs at the same energy

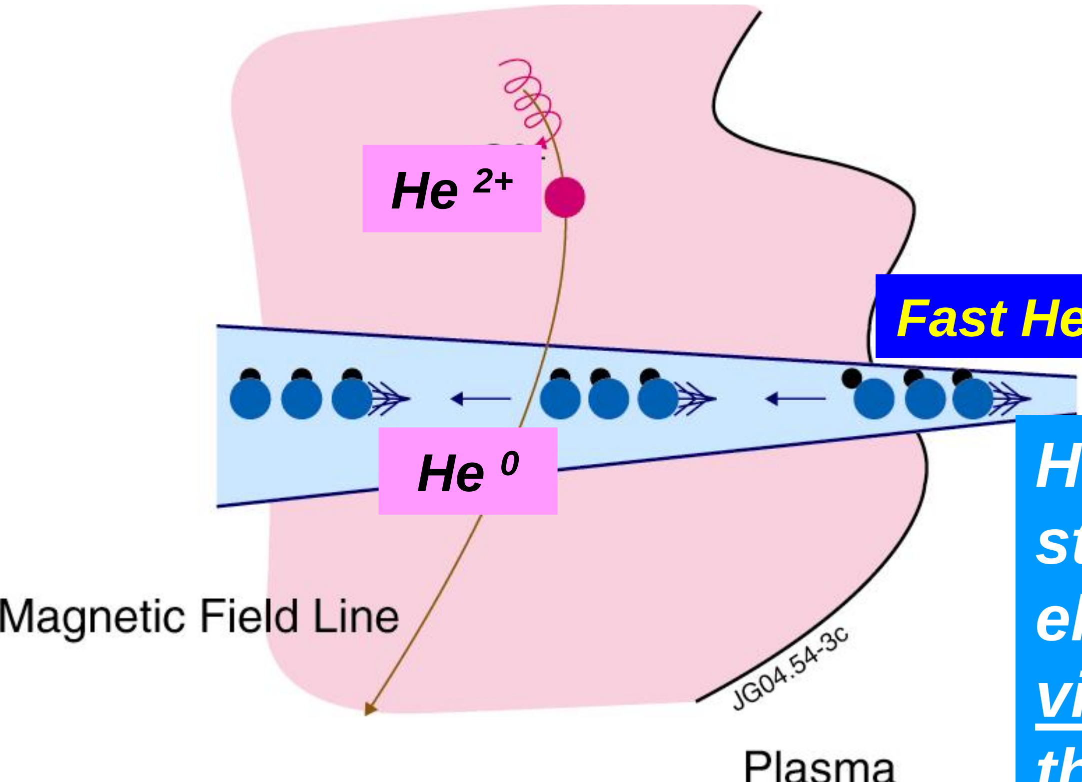
Series Limit Spectra

- **Balmer/Paschen series spectra of hydrogen/deuterium, in particular the merging of the individual lines into the continuum, represent a possible tool for diagnosis of the divertor electron temperature and density.**
- **The diagnostic technique, when fully developed, will have application to the diagnosis of fully detached divertor operation in ITER where Langmuir probes will be less useful.**
- **The spectra in question are in the visible**
- **Significant current interest: With respect to the Balmer series in the divertor, JET can provide more ITER-like operation than other machines.**

Diagnostic potential of Double Charge Exchange Transfer for He ash (thermalised He): dilution of plasma fuel

The approach exploits the double charge exchange reaction:

$$He^{2+} + He^{0} \longrightarrow He^{0} + He^{2+}$$

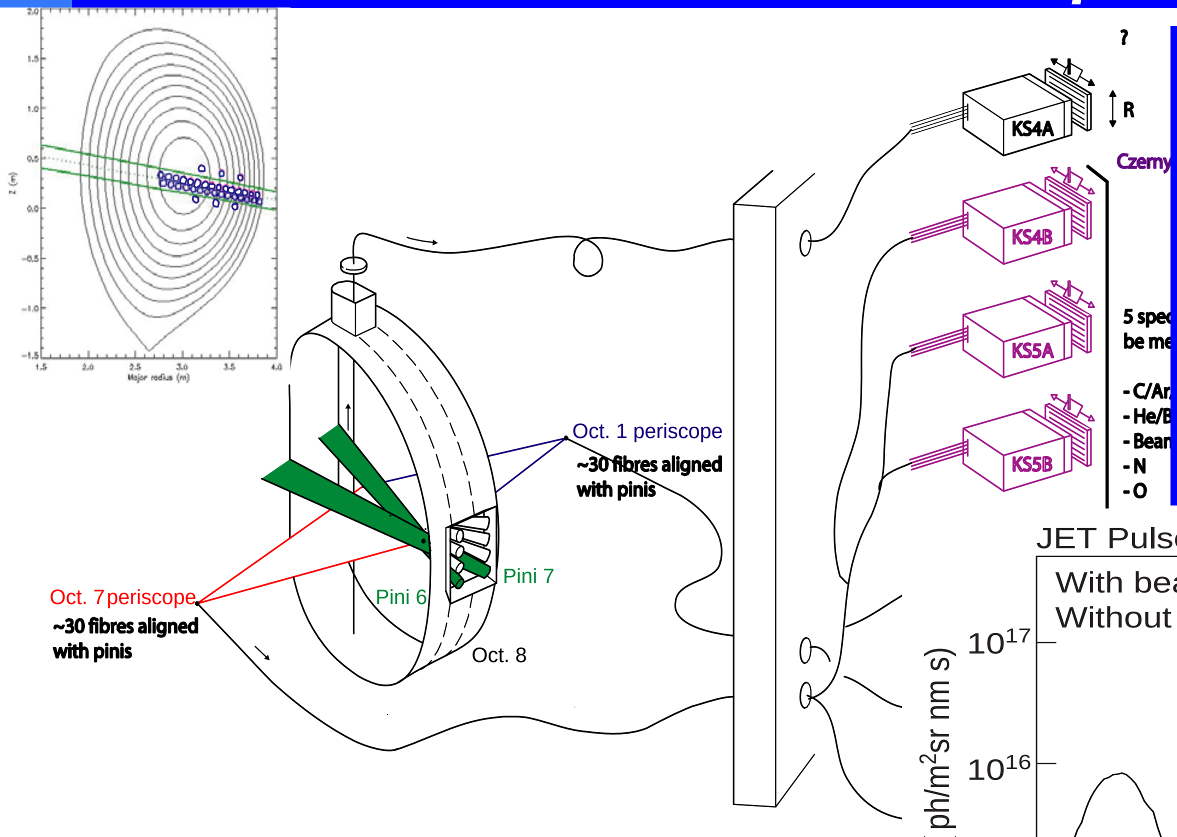


Neutral Helium forms an halo about beam axis

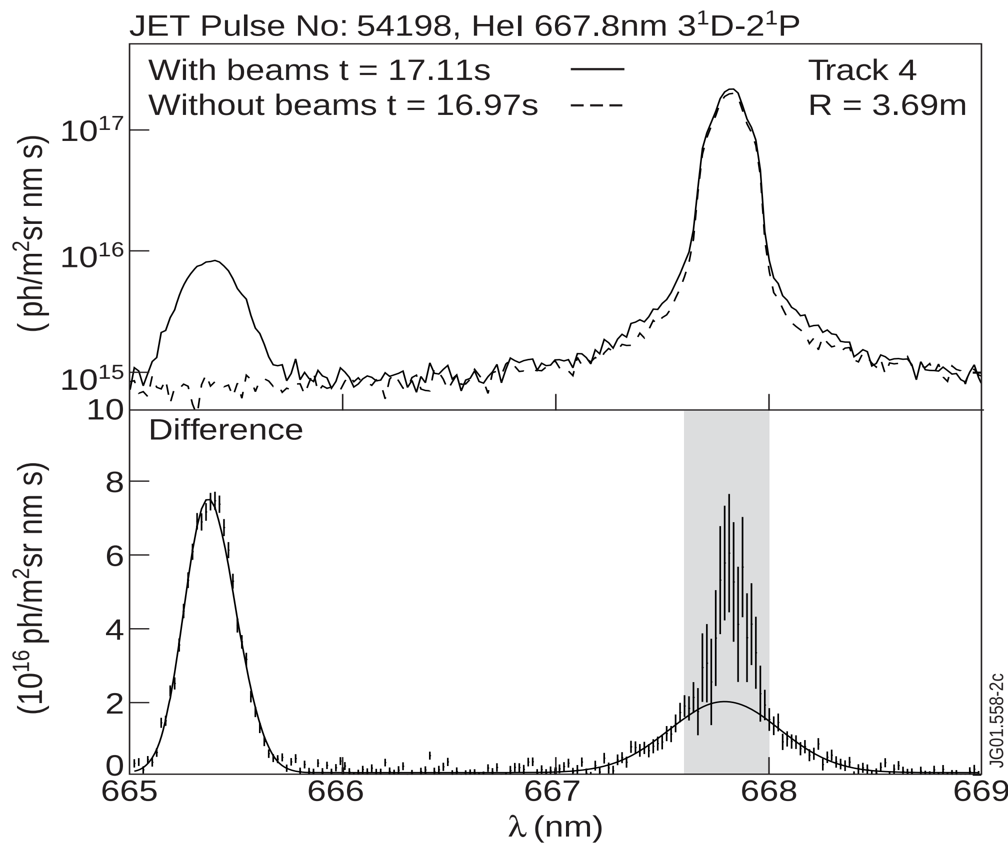
He is formed in ground state and is then excited by electron collisions emitting visible radiation, which is the entity detected

Experimental conditions of first preliminary tests:
^{4}He neutral beams at 29.5 keV/amu into 90 % He plasmas
HeI line at 667.8 nm from electron excitation is observed

Detection with JET active spectroscopy System



- No fast ion contamination (they leave los before emitting)
- Cross section double CX measured at JET



Measurement quite difficult but:

- Beam density not required
- Errors in calibration and alignment do not propagate to He $^{2+}$ density

Real time

Real time: extremely important for JET and indispensable for ITER

- **Length of the pulses**
- **Safety issues**
- **Complexity of the device**

- **Establish Scenarios**
- **Exploration of the operational space**
- **Control of performances**

As for any other feedback scheme, for Tokamak real time control the identification of the system to be controlled (the plasma) is the fundamental first step.

Diagnostics are therefore essential for both the operation and the scientific exploitation of the device