# Burning Plasma Diagnostics on JET:
## past results and future plans

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# Aknowledgments

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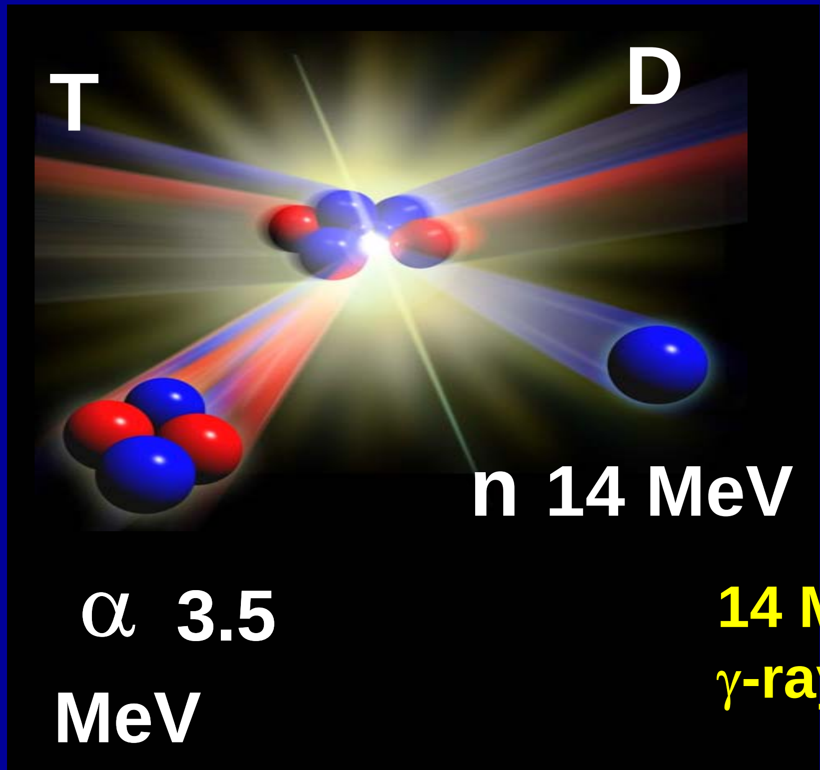
# Outline

**JET has a key contribution on providing Diagnostics for ITER Scenario development and ITER prototypes**

**This presentation will address the existent JET diagnostics and foreseen enhancements for the measurement of “Burning plasma” relevant quantities:**

**The “fuel mixture” or isotopic composition**




**Tritium retention**

**3.5 MeV αs and He ash**

**14 MeV neutrons and γ-rays**

# Neutron

# And

# Gamma ray

# Principles of Neutron Detection

**The main method to detect neutrons consists of "transforming" them (via nuclear processes:strong interactions) to charged particles, 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:**

**•Recoil protons**

**scintillators: the recoil protons excite suitable materials which in turn emit light collected by a photomultiplier**

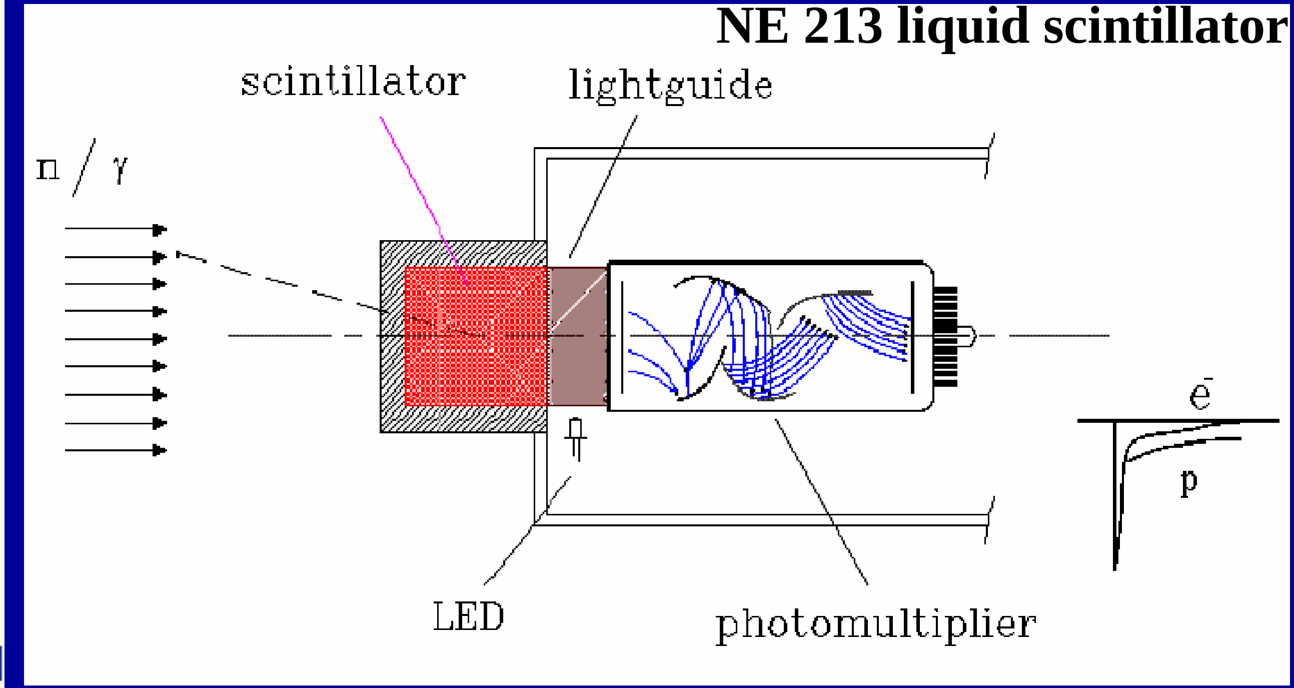
**•Conversion reactions producing $\alpha$s (n,$\alpha$)**

**in semiconductors the reaction products create electron-hole pairs and the charge is collected (Si or Diamond detectors)**

**•Induced fission in materials (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**

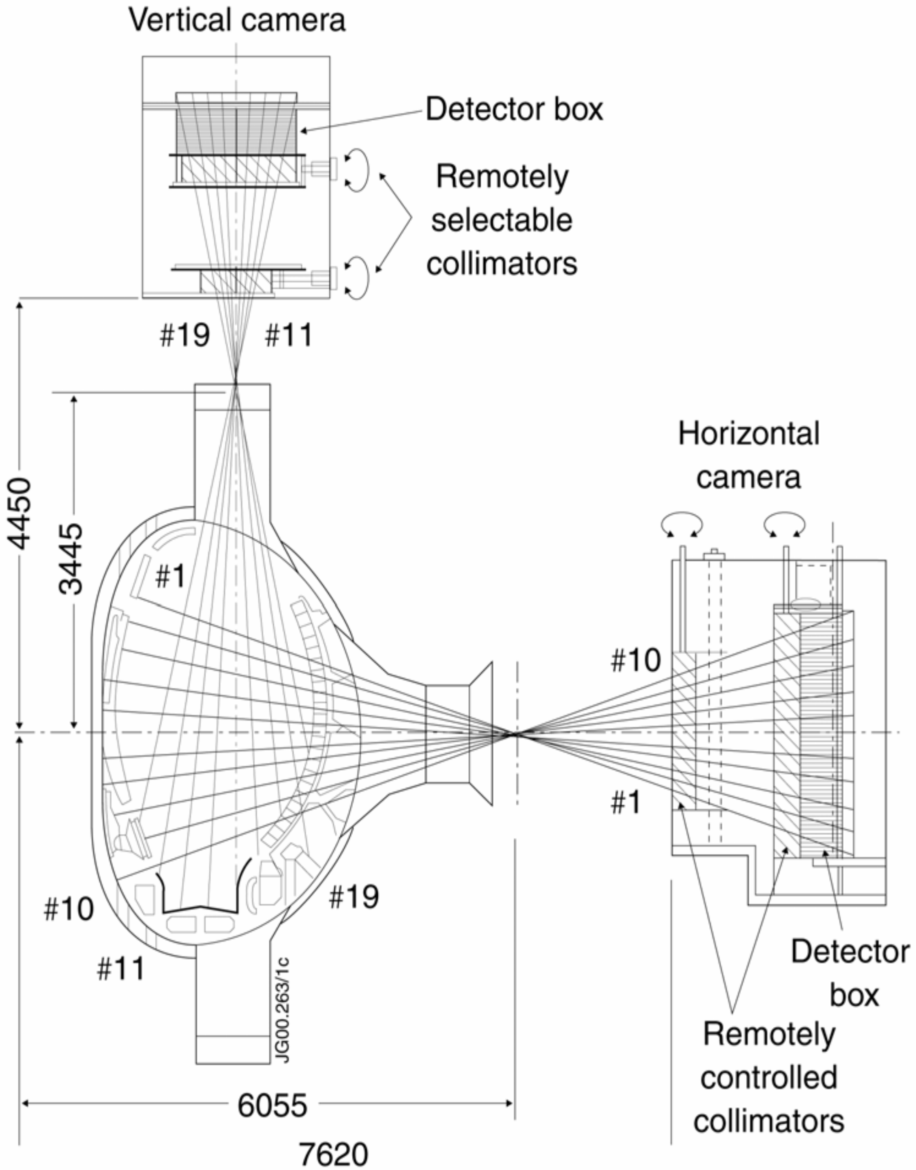
**The shape of the current pulse allows discriminating the neutrons from the γ s**

*Neutrons* → *Recoil protons* → *Light*

*Gammas* → *Electrons* → *Light*

*Light* → *Photoelectron Multiplication* → *Pulse Discrimination*

# JET Neutron and γ-ray Cameras




Vertical camera: 9 lines-of-sight
Horizontal camera: 10 lines-of-sight
Collimators: Ø10 and 21 mm
Space resolution: 10 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:

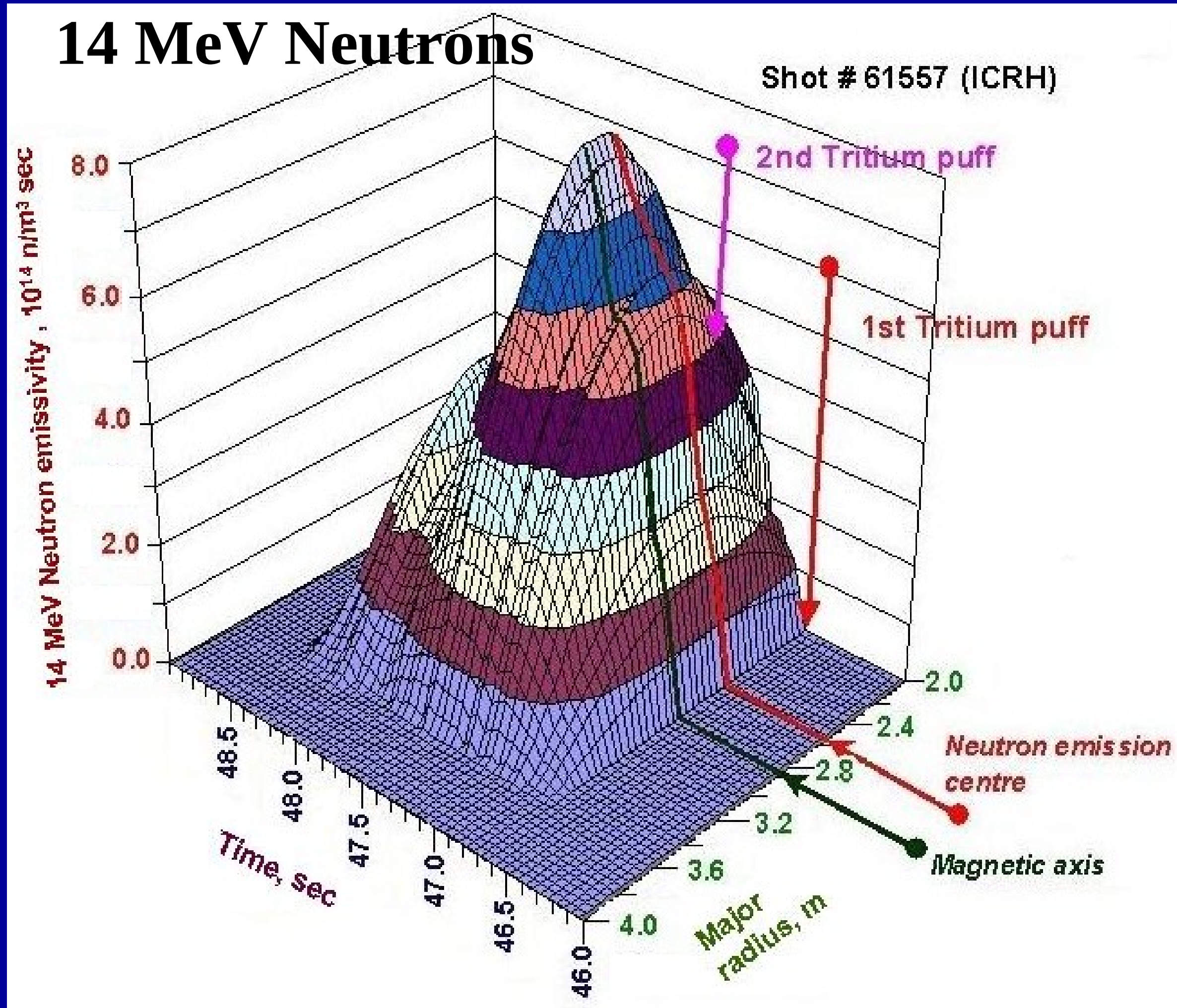
- 19 CsI(Tl) solid state detectors for the γ-rays

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

Used also for Hard X rays

# 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, peaks off axis close to the T cyclotron layer.




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

# Information from the spectrum of a thermal plasma

Spectral width (FWHM):

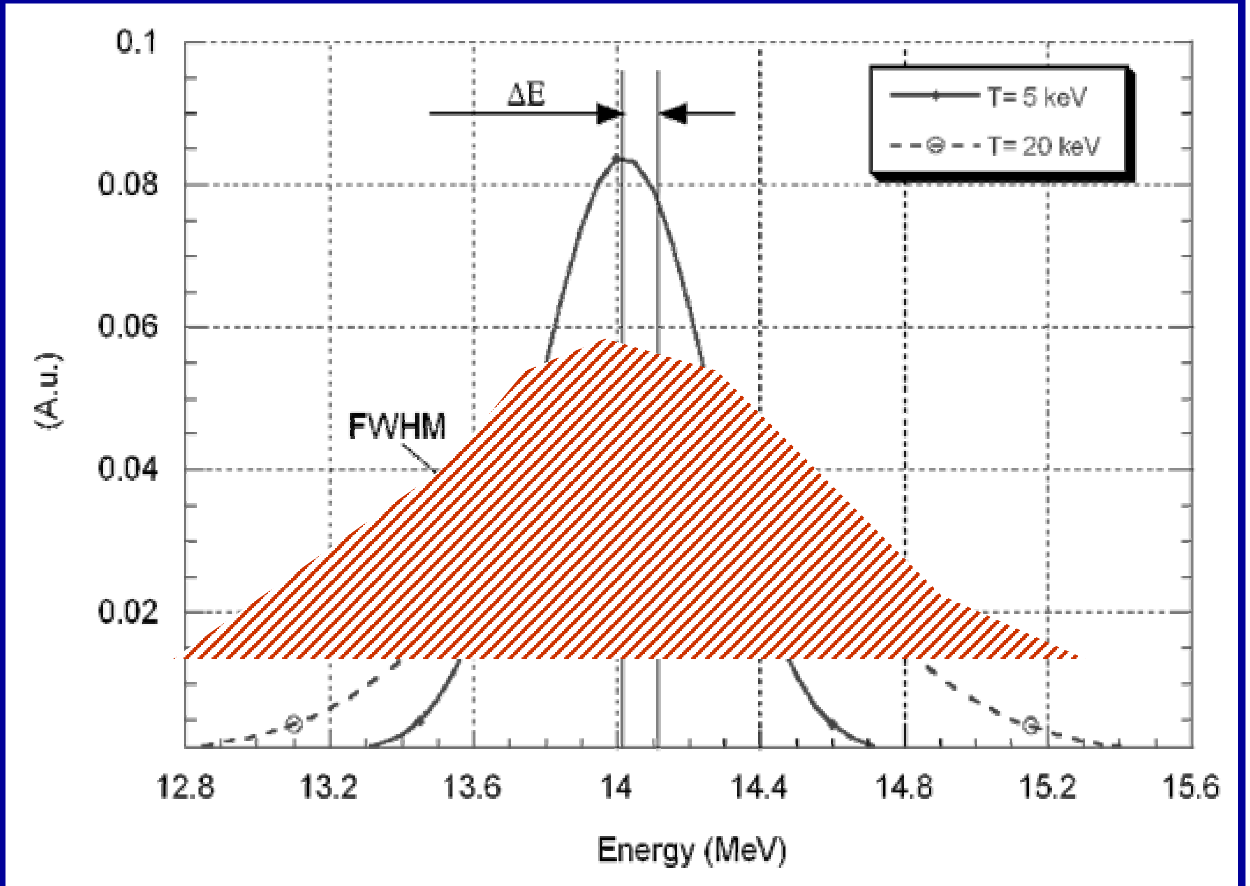
**Doppler Broadening** → $T_i$

Peak position (ΔE):

**Energy shift** → $v_{tor}$

Area

**Total yield** → $Y_n$



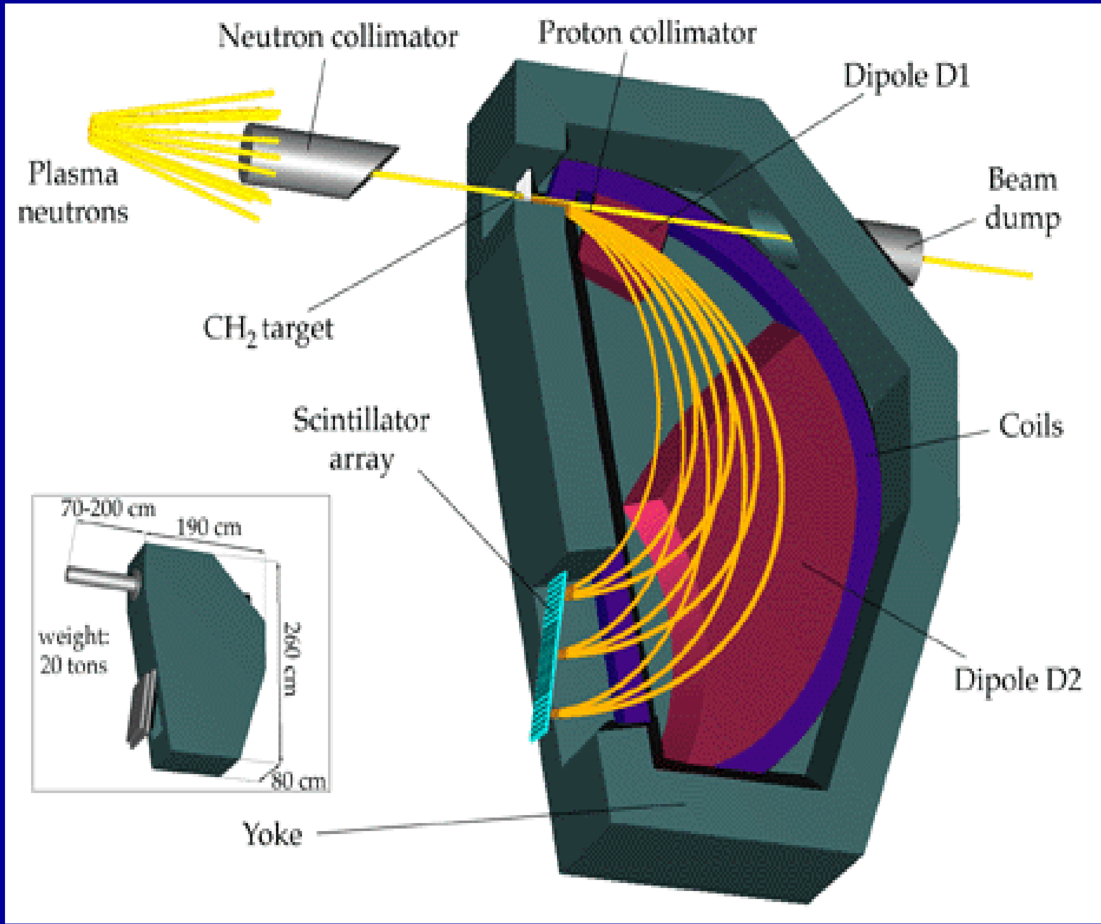
# Magnetic Proton Recoil (MPR) spectrometer
# 14 MeV neutrons

- Absolute calibration from first principles

- Flexible settings and high reliability and stability

- Well known response function

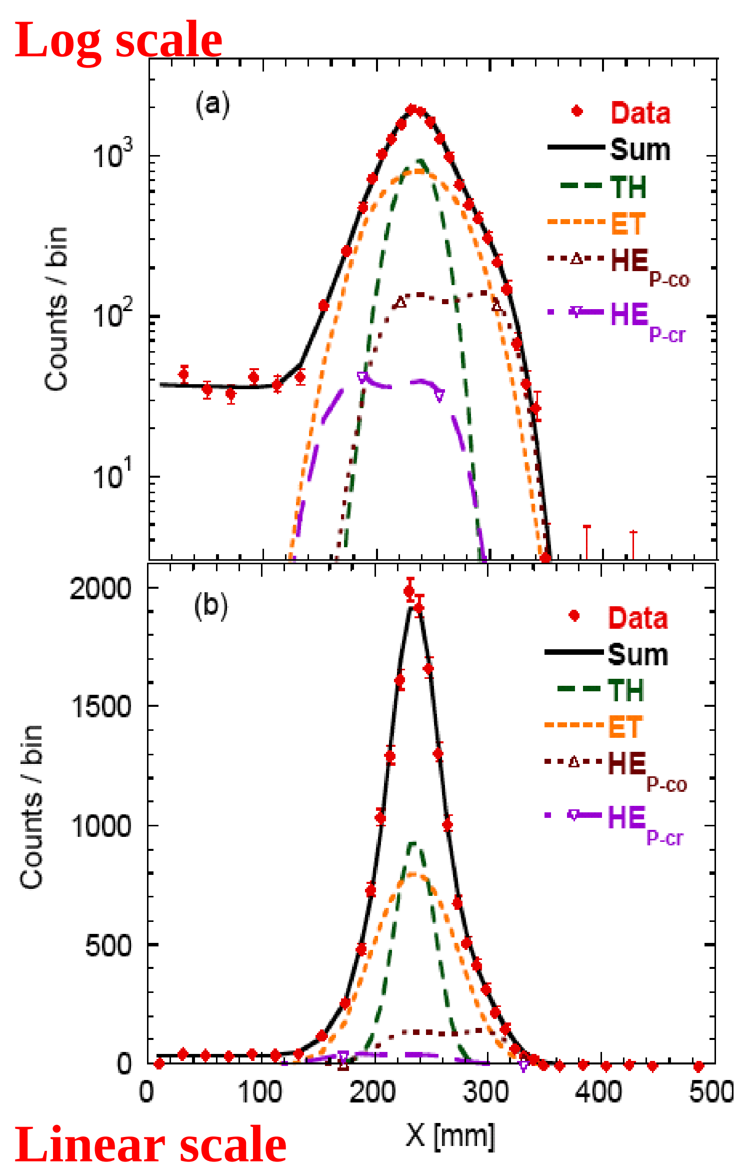
- High
Energy resolution




**Total 14 MeV neutron yield**

(with profile factor from neutron cameras)

# Spectra with additional heating more complex than in thermal plasmas

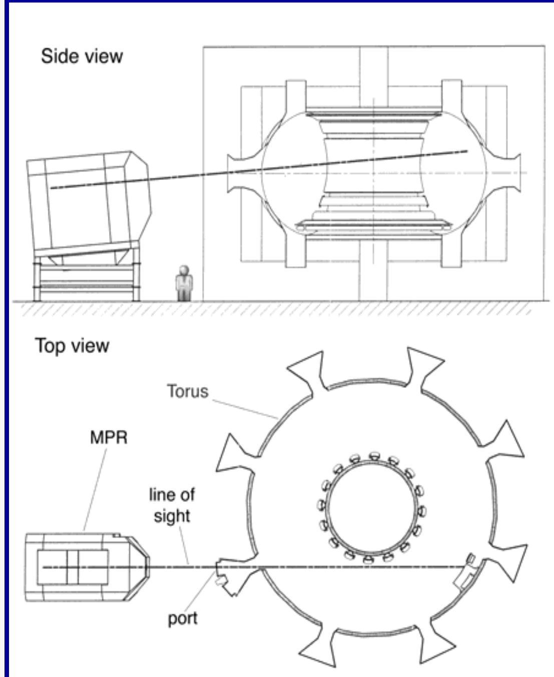



In the spectra the following components are present:

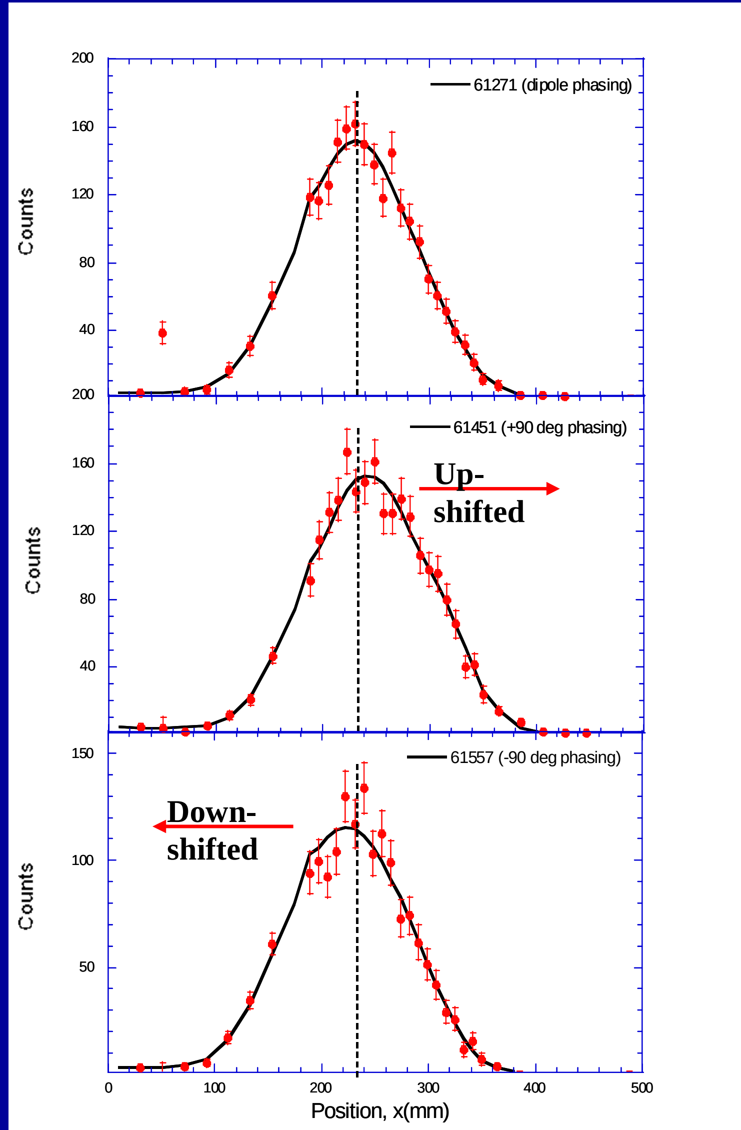
- The thermal component (TH)
- The high energy component (HE): due to accelerated particles in co and counter
- The epithermal component (ET) slowing down of accelerated particles
- Forward modeling needed

**Only Experimental technique capable of providing an estimate of the thermal neutron yield $Y_{th}$**

# Velocity of the ions depending on ICRH phasing




Velocity of ions depends on ICRH phasing, the direction the heating waves are injected into the plasma




**Dipole,** $\Delta E_S$ = 21±15 keV --> $\mathbf{v_{tor}}$ **= 57 ± 41 km/s**

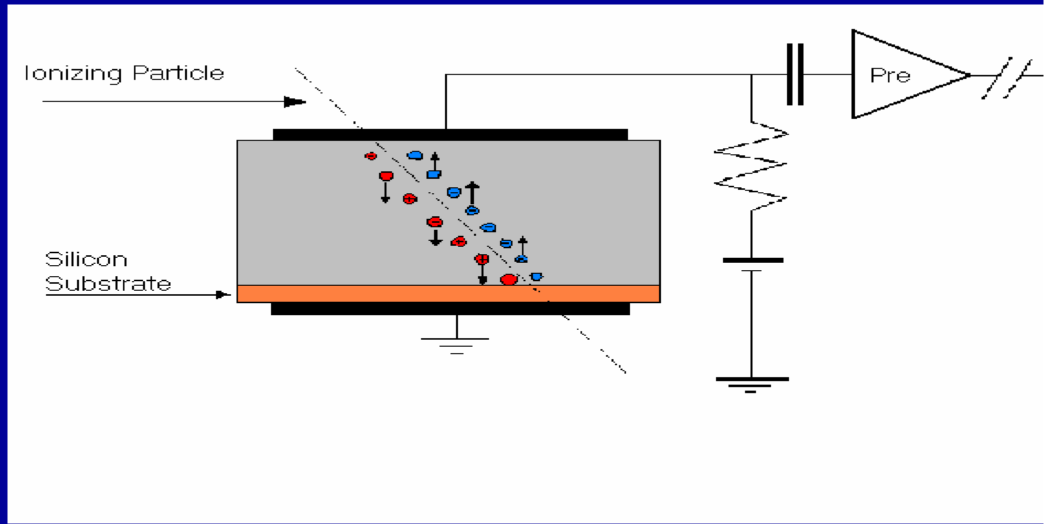
+90°, $\Delta E_S$ = 114±13 keV --> $\mathbf{v_{tor}}$ **= +309 ± 36 km/s**

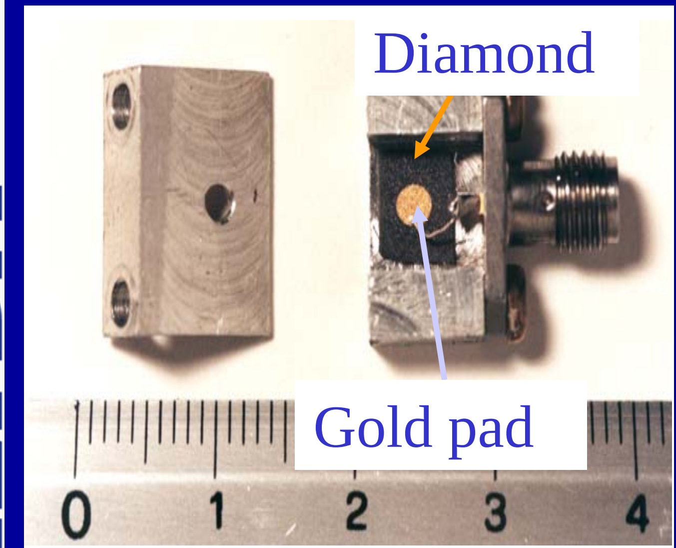
–90°, $\Delta E_S$ = -103±15 keV --> $\mathbf{v_{tor}}$ **= -279 ± 41 km/s**

# Compact spectrometers: Semiconductor and CVD Diodes

**Neutrons induce nuclear reactions in the material. The charged products generate electron-hole pairs and their charge is detected.**
**Solid state detectors are very fast, compact and consolidated technology**
**Silicon has a very poor radiation hardness.**

- ✓ Diamond detector
- ✓ Reaction $^{12}C(n,\alpha)^{9}Be$ cross section 72 mbarn (typical)
- ✓ Bulk detector




- ✓ Diamond: higher neutron resistance than Silicon
- ✓ Diamond: better discrimination 2.45-14 MeV neutrons
- ✓ Low cost: 20 Euros per μm

# 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)

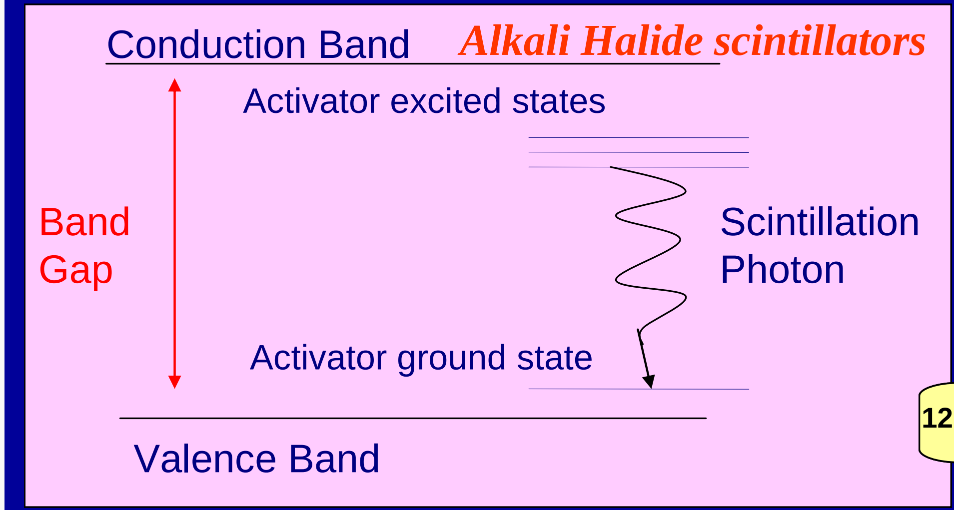
α-particle diagnosis at JET is based on the $^9$Be(α,nγ)$^{12}$C reaction

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

## $^9$Be(α,nγ)$^{12}$C reaction

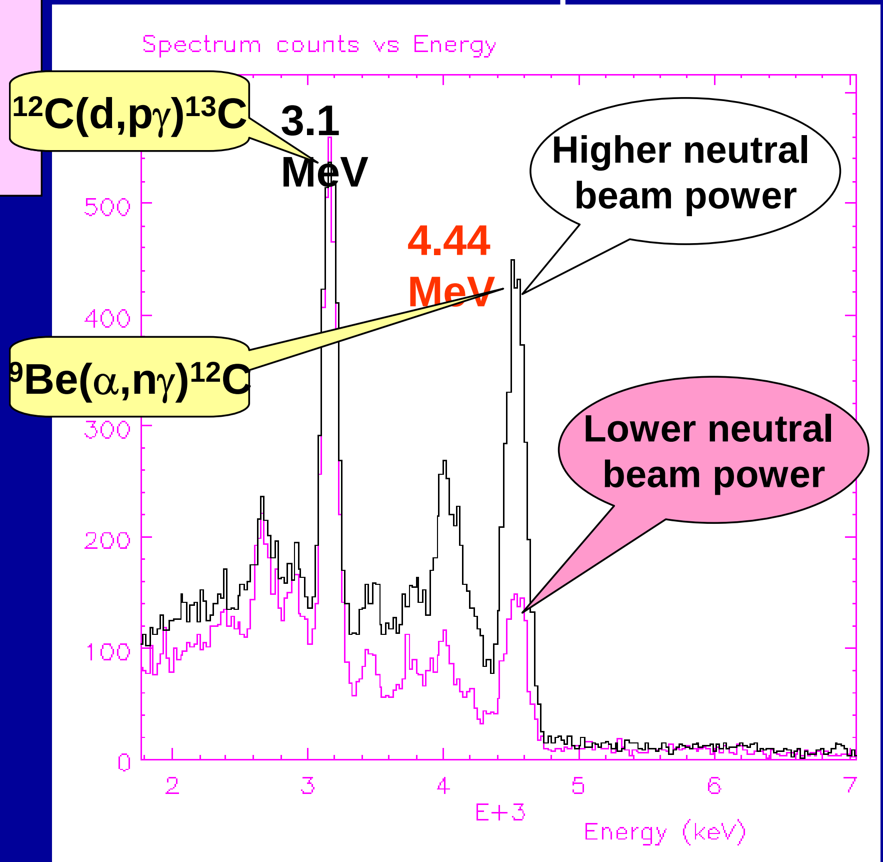
$$^{9}\text{Be} + \alpha \rightarrow {}^{13}\text{C}^{*} \xrightarrow{n} {}^{12}\text{C}^{*} \xrightarrow{\gamma} {}^{12}\text{C}$$

# γ-ray Detection: Solid State Scintillator CsI(Tl), NaI(Tl)

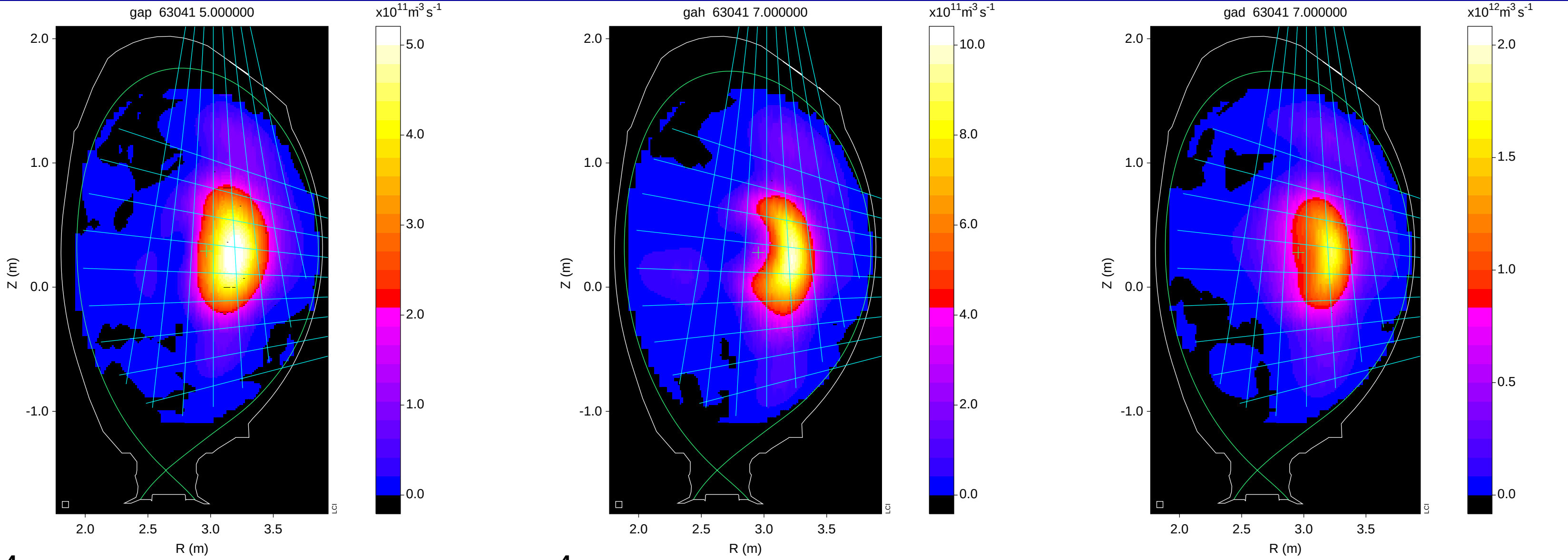



- An energetic photon creates electron - hole pairs.
- The electrons and holes migrate to the activator sites (Tl).
- De-excitation of the activator atoms produces radiation more efficiently.
- The light is then detected with photomultipliers as in the case of organic scintillators.
- The properties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

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



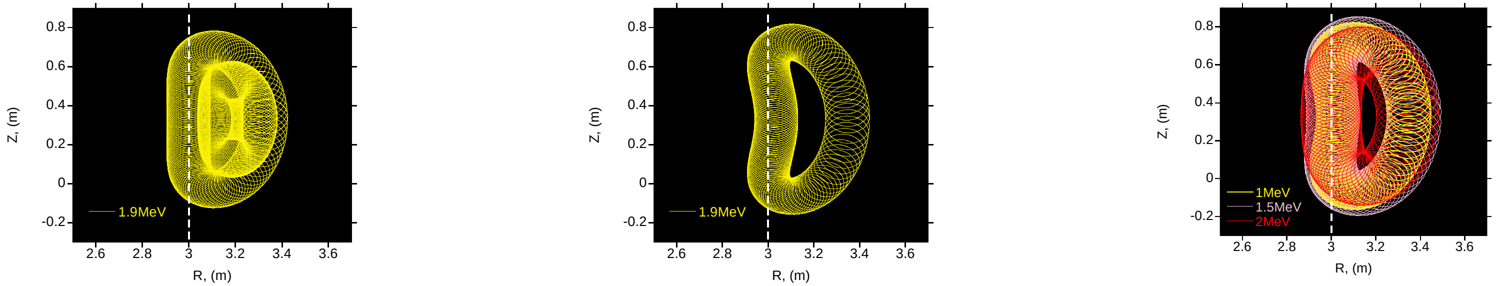
# Visualization of Fast Particles




$^4$He in reversed-shear discharge

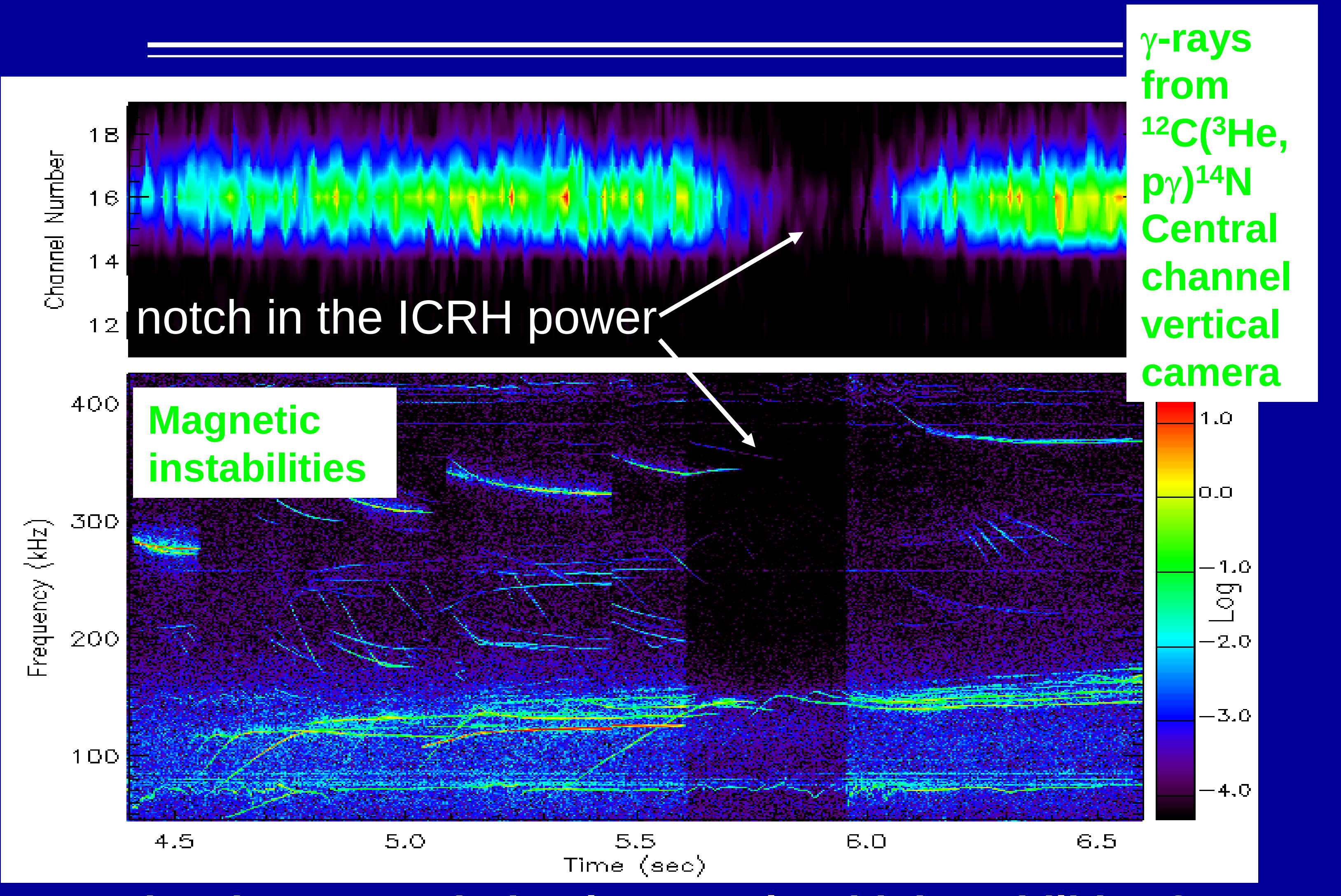
$^4$He in monotonic q(r)-plasma

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**

# Wave Particle interactions




- Fast Ions (Top) Measured Simultaneously with instabilities from magnetic coils (Bottom)
- Notches (of ICRH power) show modes most sensitive to fast $^{3}He$ ions

# Improving the present n and γ systems

1) **Analog electronics** very old

- Difficult to operate and to refurbish
- S/N not always satisfactory
- Raw data lost after the shot

2) **Strong neutron background** which jeopardizes the gamma ray measurements in discharges with Neutral Beam

**Ongoing projects**
1) Neutron attenuators
2) New digital electronics

**Upgrades important not only for D-T operation**

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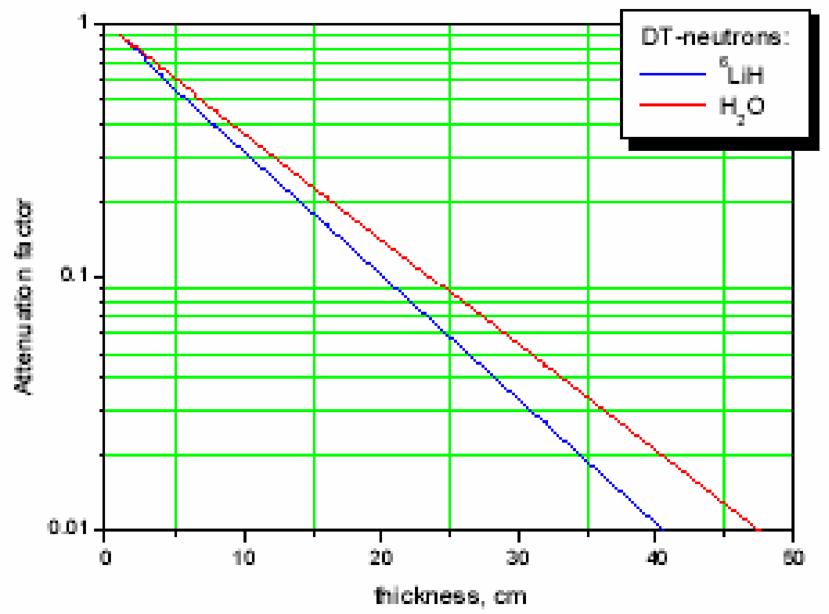
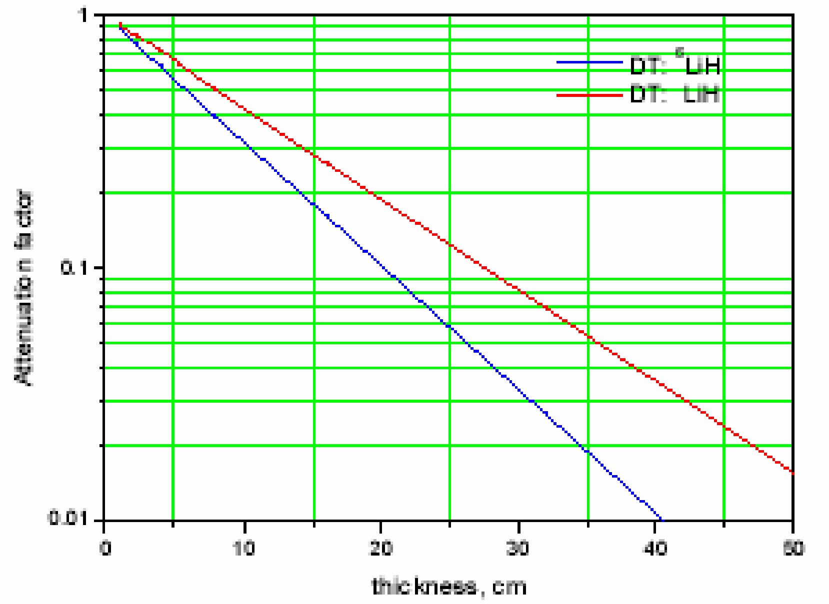
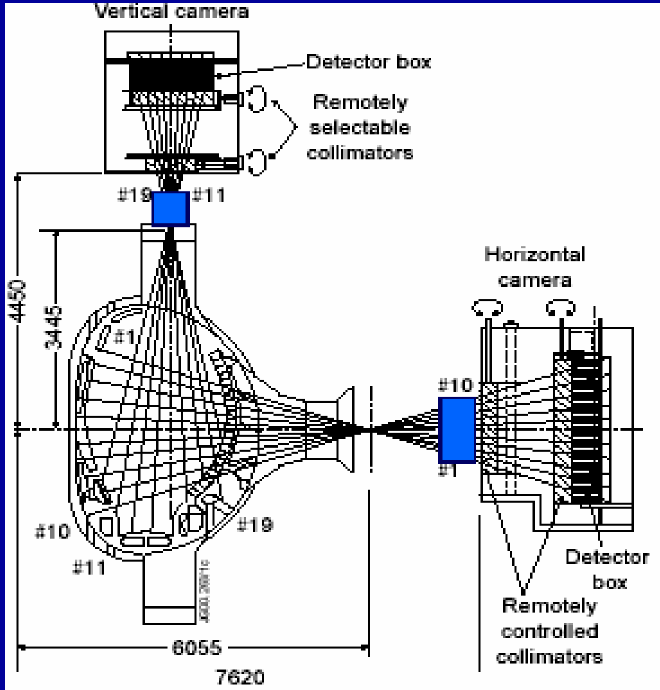


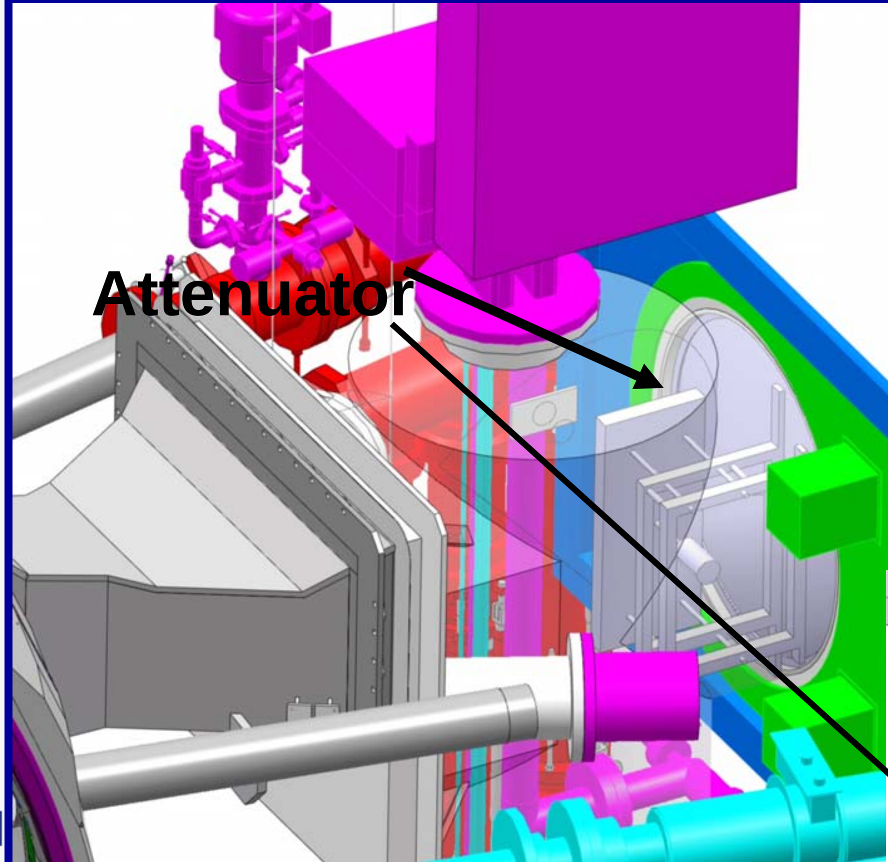

# LiH/ Water attenuator

<u>Neutron Attenuator materials:</u>

- LiH (ITER relevant) tested on a spectrometer (single line of sight)
- Water adequate for JET operation (even D-T) in the focus of the cameras

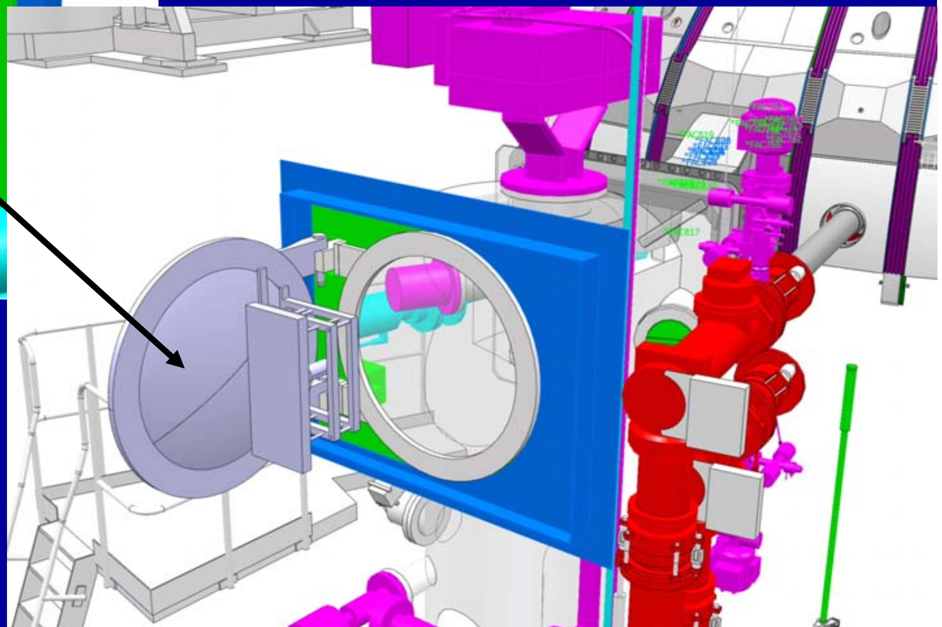


# Horizontal view Neutron attenuator



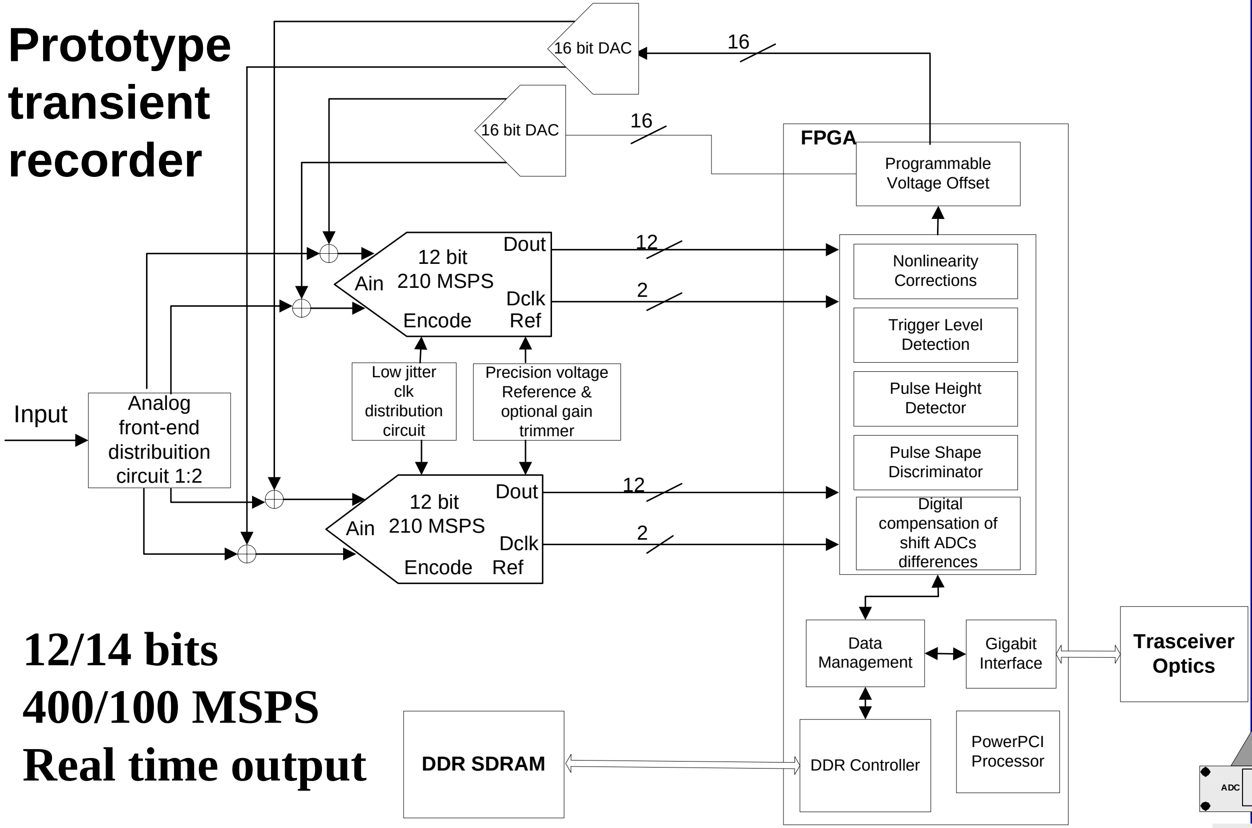

**located in the focus of the camera**

Proposal to modify the port (displace the vacuum boundary). Heavier for the operator but much safer.



# Electronics upgrade (for n and γ-ray diagnostics)

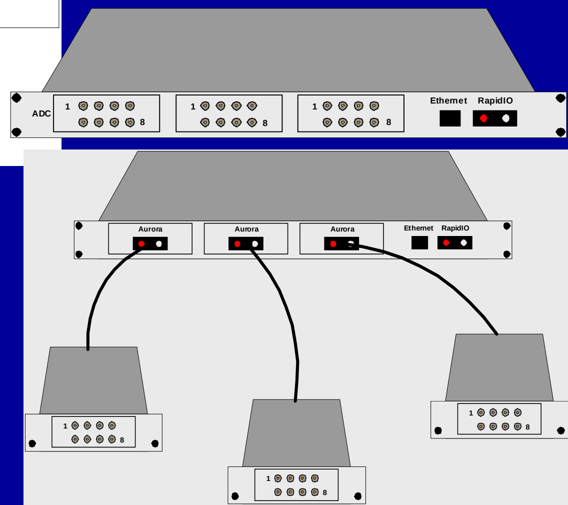
**Prototype transient recorder**




**12/14 bits**
**400/100 MSPS**
**Real time output**

## Advantages

- Digital electronics
- Real time capability
- Pulse discrimination and processing
- High count rate
- High energy resolution




- Alternated operation of two ADCs for time resolution
- Real time signals compatible with the system provided

Prototype to be tested next campaigns

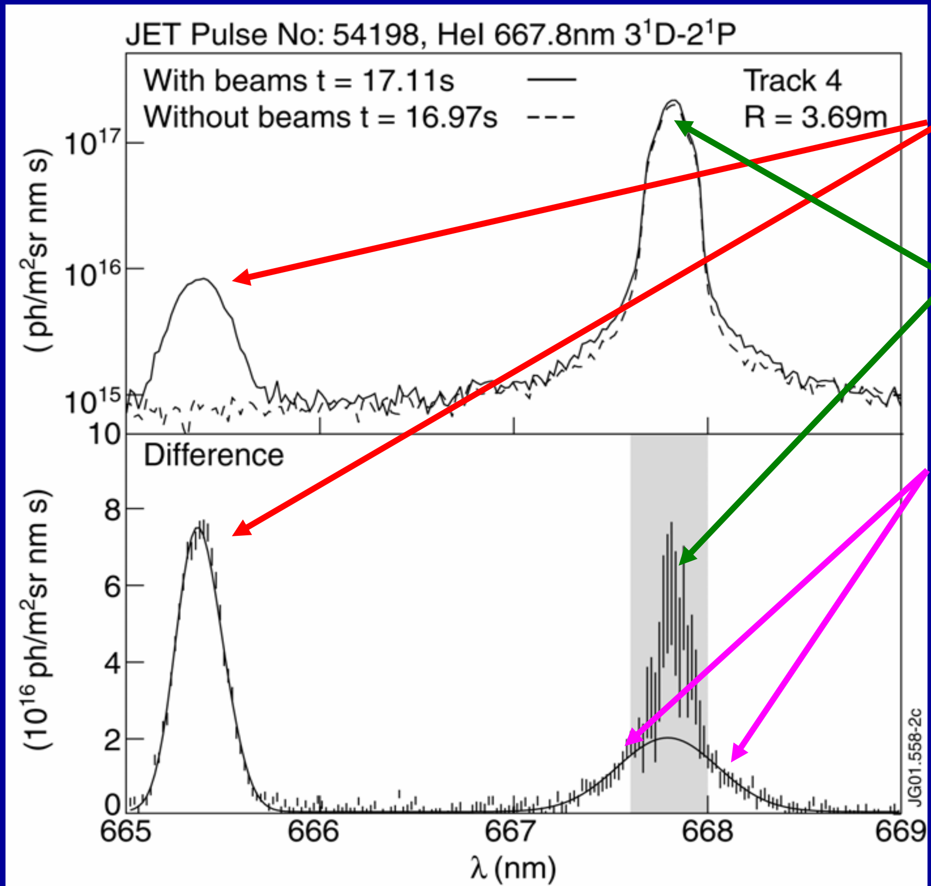
# α particles diagnostics

# And

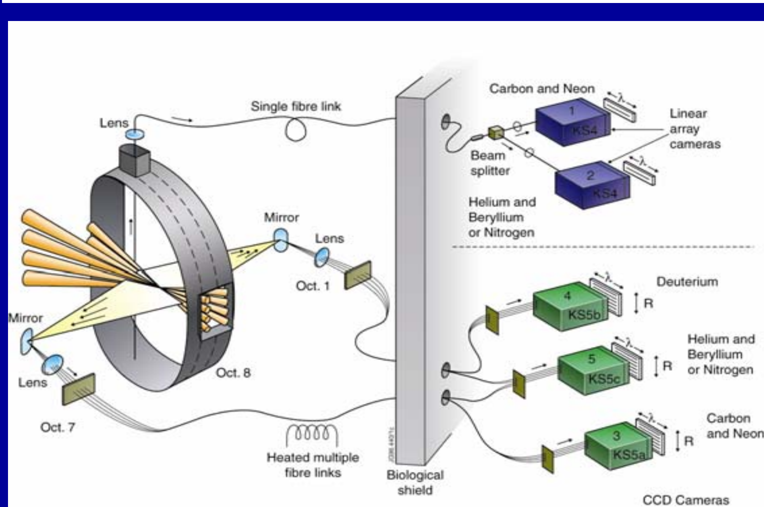
# Fuel mixture

# Measurement of He Ash

$He^{2+}$ (thermal) + $He^{0}$ (beam) ⟶ $He^{0}$ (thermal) + $He^{2+}$ (high energy)




- Beam emission Doppler shifted.
- Cold (<100 eV) component always present, increases slightly with beams.
- Hot (2 keV) component strongly enhanced with beams.




Pioneering technique which needs validation but very important application of active spectroscopy.

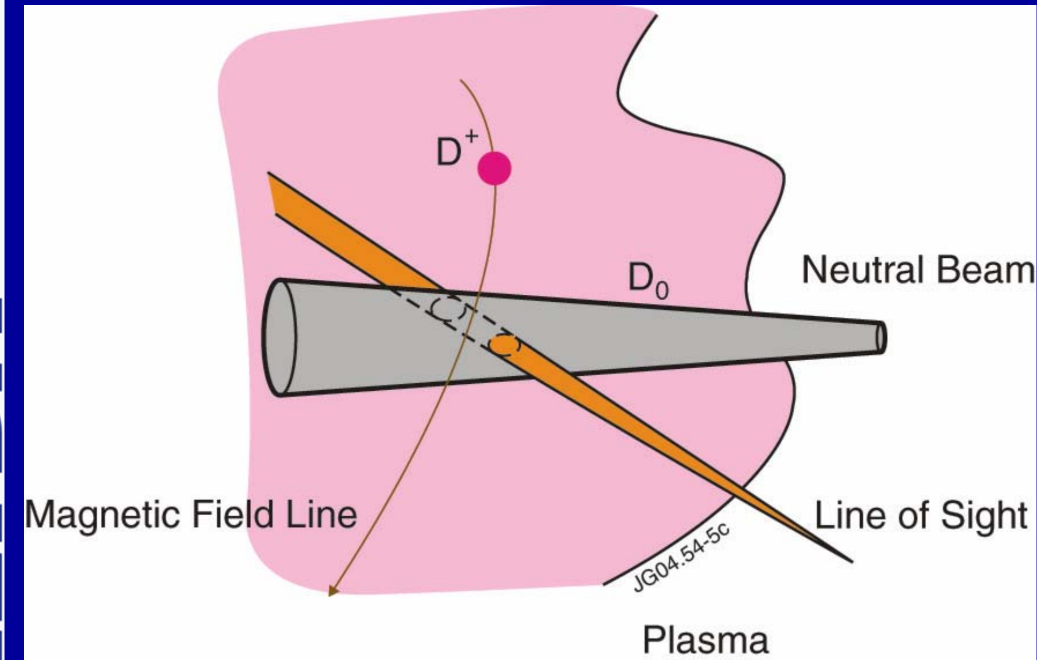
# Neutral Atom Diagnostics

**Neutral Atoms are injected in the core of a high temperature plasma with neutral beams and perform charge exchange with the thermal particles which**

**a) move freely in the magnetic field and can escape providing information about the ion fluid**

**b) emit line radiation and can be detected spectroscopically**

$$D^{+}\ (thermal) + D^{0}\ (beam) \longrightarrow D^{0}\ (thermal) + D^{+}\ (high\ energy)$$

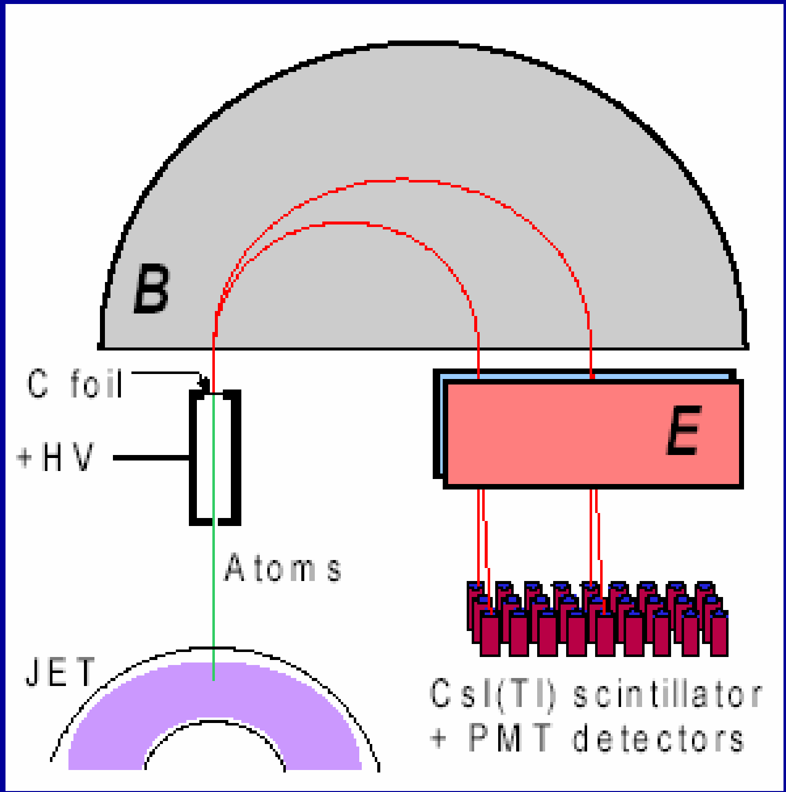


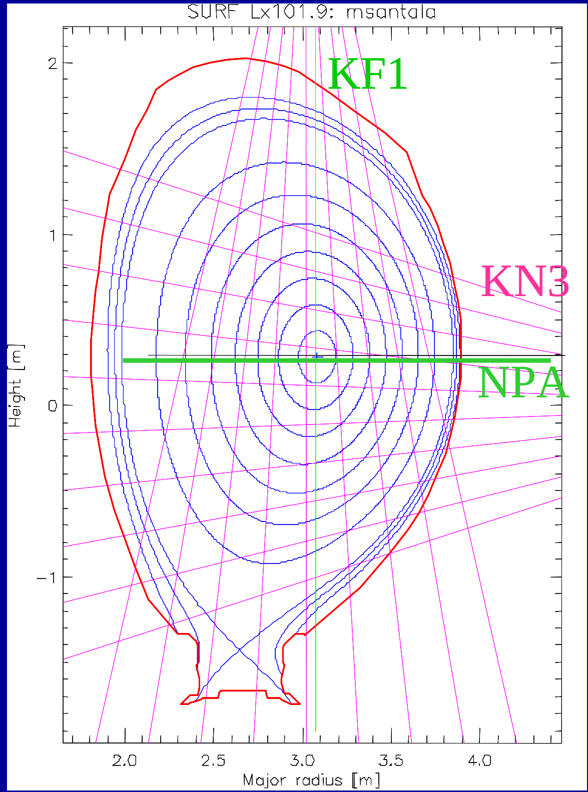

Several diagnostics (active and passive) exploit neutral particles:

- **Beam Emission Spectroscopy**
- **Charge Exchange Recombination Spectroscopy**
- **Neutral Particle**

# Neutral Particle Analyser (NPA)

**Neutral particles coming from the plasma are ionised and boosted in energy (separation from background) and then analised by the usual combination of E // B fields (separation of both momentum and mass).**




**Isotopic composition** by simultaneous detection of the neutral fluxes of all H isotopes ($H_0$, $D_0$, $T_0$) leaving the plasma at various energies

# NPA Detector Upgrade

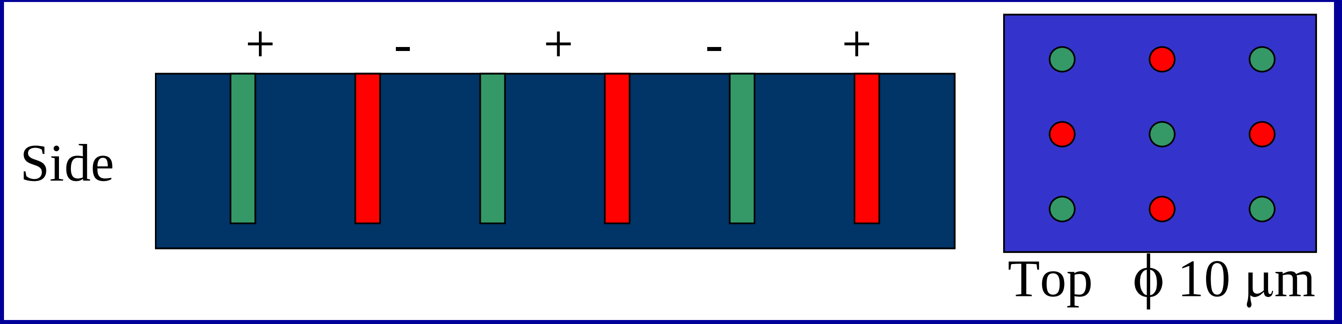
## Present detectors

- CsI(Tl) scintillators + photomultipliers
  - slow: 3 μs scintillation time
  - difficult signal/background separation
    - sensitive to neutron & gamma background
  - long cabling carrying analogue signals
  - PMT's require highly stable high voltage

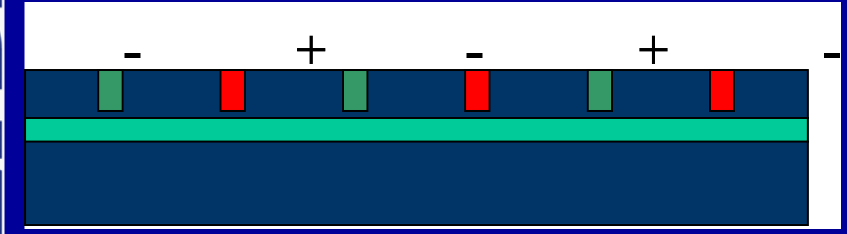
## Objectives of the Upgrade

- Improvements S/N ratio by reduction of background
  - Better measurements
  - Ability to detect particles at lower energies (below 1 MeV)
- Ability to discriminate alphas and fast deuterons (with PHA)

# 3D silicon detectors (R&D project)




- Proposed in 1997 by Parker et al.
- Electrodes built into vertical channels etched into detector bulk silicon
  - fast, low depletion voltage, low capacitance
  - radiation hard, tested (MIP) to $10^{15}$ p/cm$^2$
- Still too thick (100-300 μm) for NPA ions as free-standing detector




- Thin 3D silicon detector to be built using Silicon-on-Insulator technology
- Advantages of 3D detectors but thickness matched to ion range

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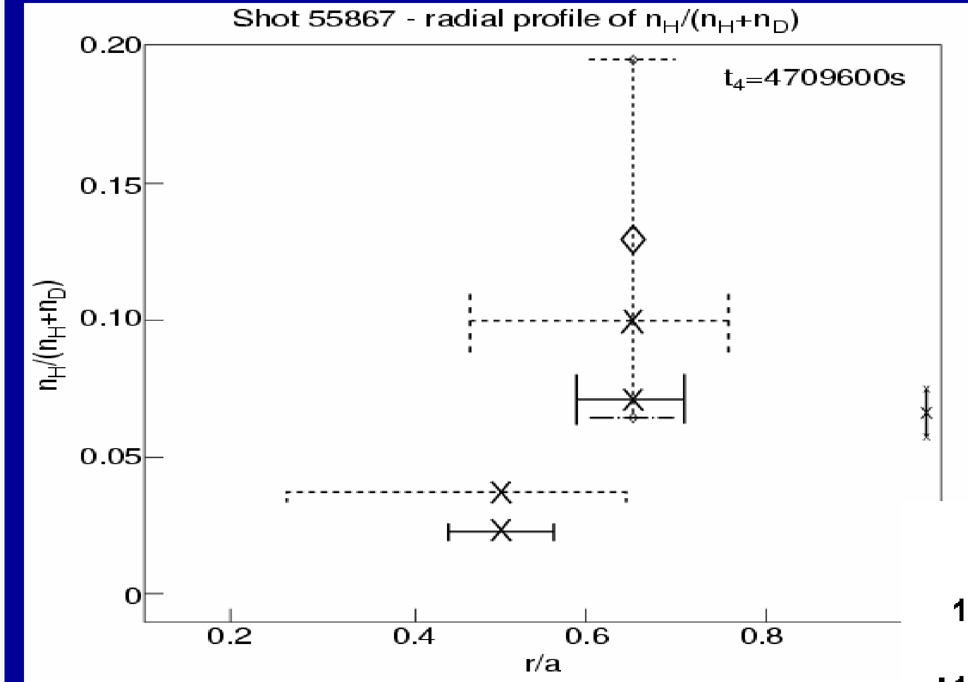
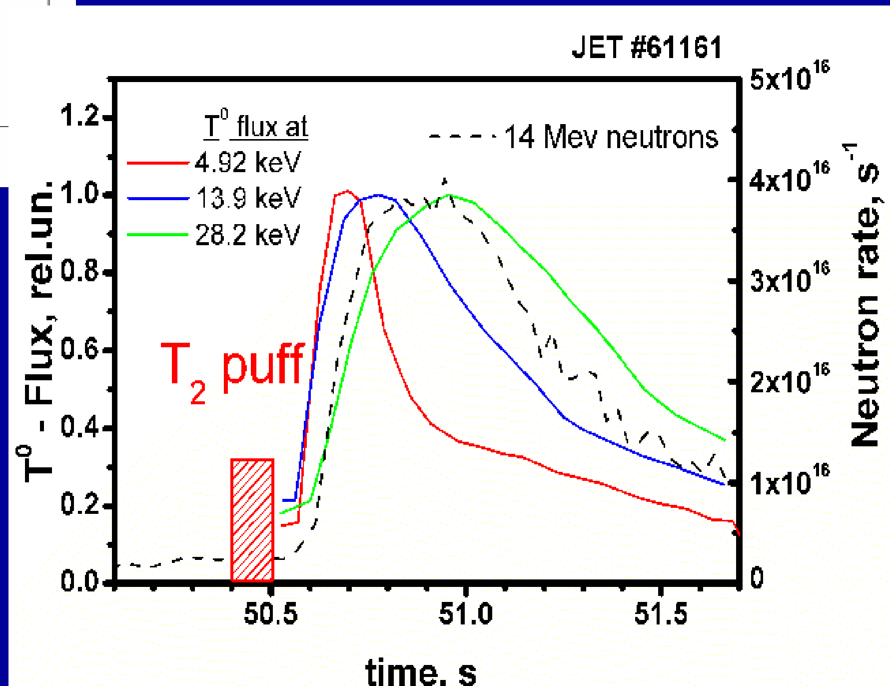
# Measurement of the fuel mixture profile




**NPA measurement of Fuel Mixture nH/(nH + nD) is essential for 50/50 operation when the D-D neutron contribution is overwhelmed by D-T**




**Spatial resolution linked to the energy of the particles (more energetic from the core. Example of the different time arrivals of the neutral after T gas puffing in TTE.**

# Fast Wave Reflectometer

**Rationale**:

a) Measurement of the fuel ratio

b) Support ICRH heating (by helping to keep the minority species under control)

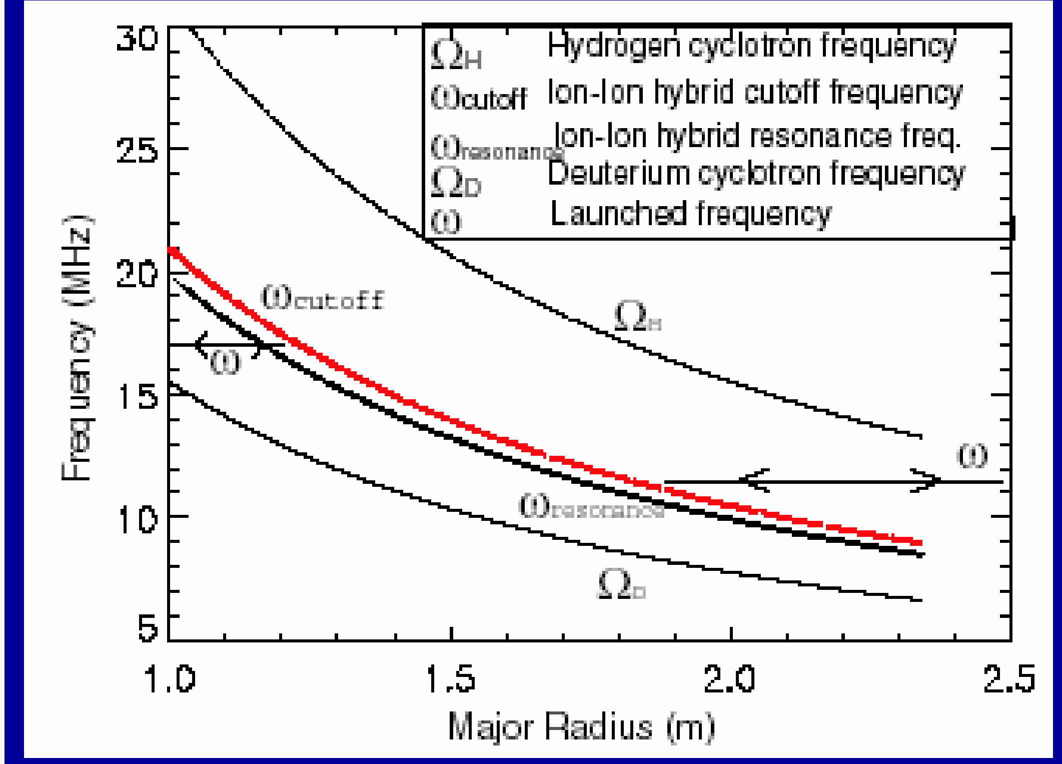
c) Transport studies

The technique exploits the ion-ion hybrid resonance in the MHz region for JET plasmas

Some questions to be addressed before proceeding with project:

•Coupling with the plasma
•Possibilities of routine operation for fuel mixture measurement
•Real Time capability

# Fast Wave Reflectometer: principle of operation




$$\omega_{cutoff} \simeq \Omega_1 f_2 + \Omega_2 f_1,$$

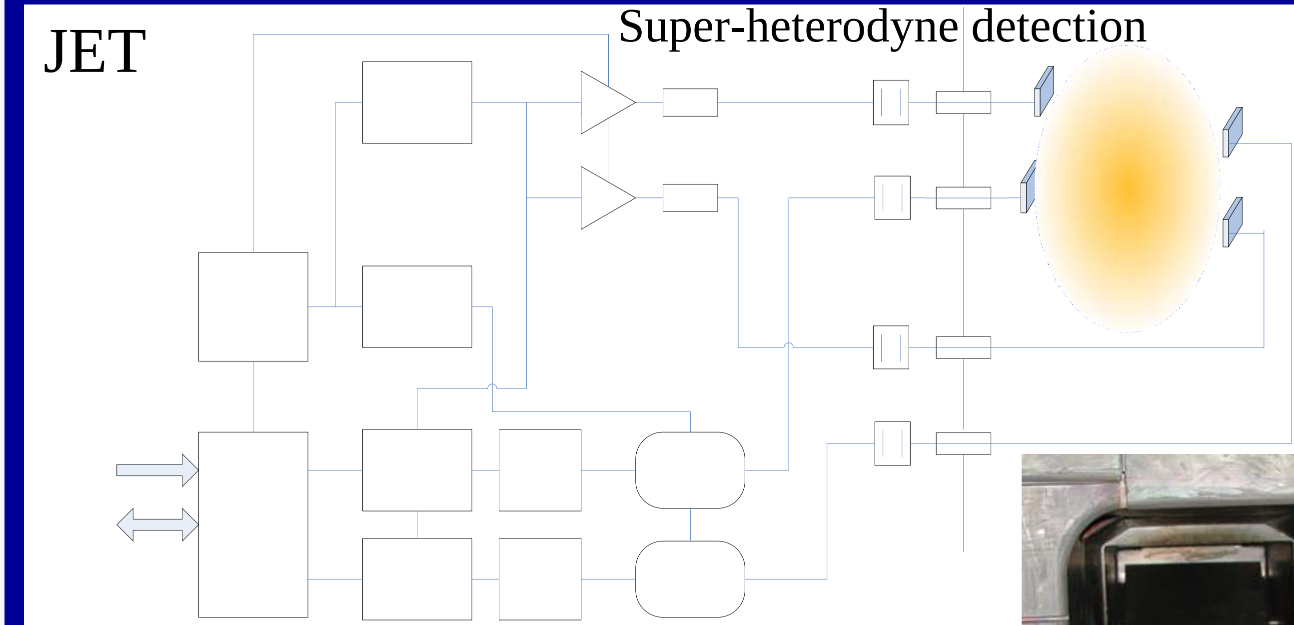
$f_1$ and $f_2$ electrons neutralised by each species (D and H)

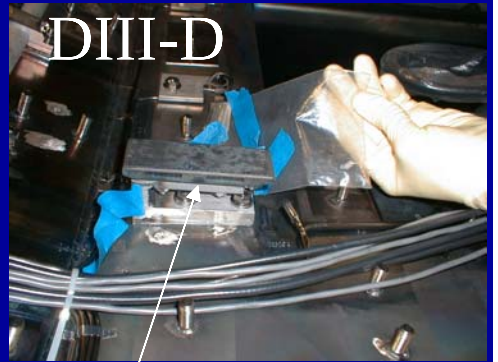
Measurements seem really feasible (support DIII-D)

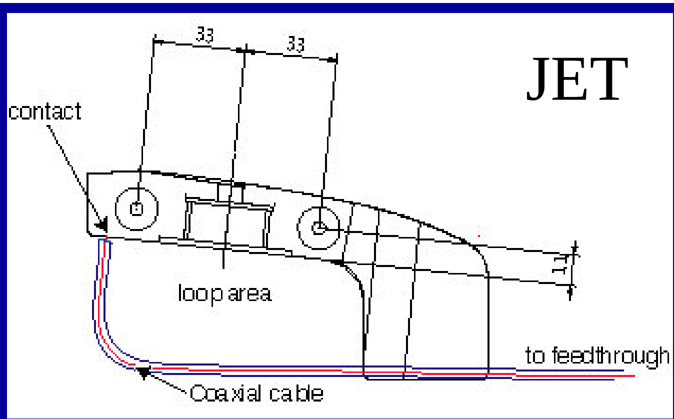
- In JET 10 W will be injected instead of 20 mW in DIII-D.
- More sophisticated detection foreseen.
- Simulations under way for propagation

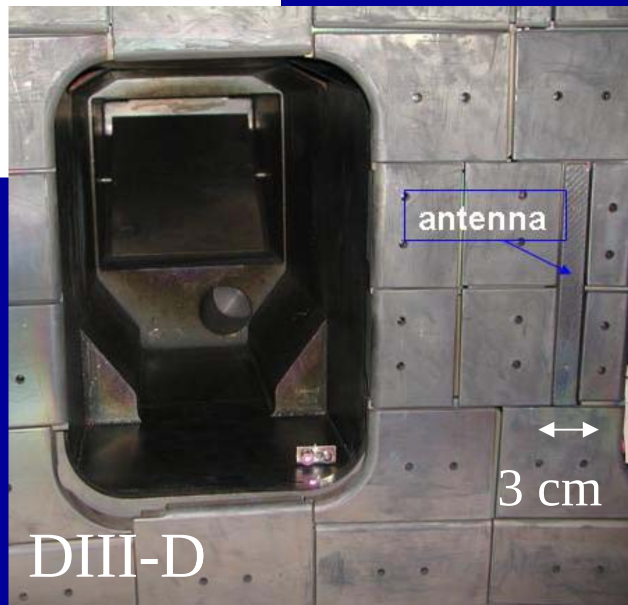
The system could not only be tested but also contribute to trace campaign (RF heating with 10 % T for example)

# Fast Wave Reflectometer: project for JET




Demanding installation but LFS version still acceptable for JET and important **proof-of-concept for ITER**

# Summary

**JET** is presently the best machine to test Burning Plasma diagnostics in a **ITER like environment**

**Consistent progress** has been made to improve the diagnostic capability on JET (Neutrons, γ-rays, Helium ash, Tritium retention)

**Improvements** are underway:
Electronics for neutron and γ-ray detectors
Neutron attenuation (LiH/Water), …

**New Concepts** will be tested:
Compact spectrometers (CVD Diamond detectors,…)
Fast Wave reflectometry (Fuel Mixture)
New NPA detectors

Strong commitment to provide key enhancements on **Diagnostics for ITER Scenario development** and **ITER prototypes**

But budgets limitations do exist!

## Neutronics

# A continuous and coherent progress…

### JET EP (2001-2005)

**Magnetic Proton Recoil (MPR)**
neutron emission spectrometer (NES) diagnosis of both D and DT plasmas.

**TOFOR Project (TOF)**
time-of-flight neutron spectrometer

### Small Enhancements (2005-2006)

**Digital Pulse Discriminators**
neutron/gamma ray digital pulse shape discrimination (DSPS): prototype (one channel)

**NE213 Liquid Scintillators**
improvements of the spectrometer by optimising the geometry and photomultiplier of the scintillation detector for the specific measurement conditions at JET

**CVD Diamond detectors for neutron and UV detection**
polycrystaline CVD diamonds both as 14 MeV neutron monitor and 14 MeV neutron spectrometer.

**Stilbene detector and digital signal processing electronic (RF)**
Organic scintillation detector coupled to PMT and pulse-shape discriminator to study DD neutron fluxes and energy distributions. Digital data acquisition

**Natural Diamond Neutron Detectors (NDD) for neutron flux dynamics studies (RF)**
Upgrade of the NDD based neutron flux monitors in JET (torus hall, behind the neutron precollimators and the proton recoil telescope)

### JET Programme in support of ITER (2005-2008)

**MPR-F**
total neutron yield and also fusion power.

**Development of fast electronics for TOFOR**

**Fast electronics for neutron and gamma diagnostics**
improved transient recorder and time digitizers modules for neutron diagnostics: Increased resolution and acquisition .

**Development of compact spectrometers**
with NE213 Organic scintillators: detectors completed characterized, digital electronics and photomultiplier with high count rate, small magnetic interference and improved linearity

**Development of compact spectrometers**
Monocrystaline CVD diamond detectors for neutron measurements. Insensitive to radiation damage.

Single Crystal **CVD diamond detectors for UV** measurements; Insensitive to radiation damage;Develop UV detectors for ITER

**Micro Fission chambers (MFC)**
Neutron monitors for the measurement of the neutron emission/yield for the determination of fusion power

# A continuous and coherent progress…

## Gamma-ray

**JET EP (2001-2005)**

**Small Enhancements (2005-2006)**

**New detectors for the gamma ray camera**
bigger CsI detectors (20 mm diameter) to increased sensitivity with the aim to improve accuracy and time resolution

**LiH attenuator (RF)**
Installation of LiH attenuator (under Loan Agreement with RF) on the collimator of the gamma-ray spectrometer (one channel)

**JET Programme in support of ITER (2005-2008)**

**Upgrade of gamma-ray spectroscopy**
Compact/radiation-resistant detectors for fusion reactors
HPGe spectrometer
Heavy Scintillators: LaBr3:Ce,LYSO:Ce,LuAP
energy resolution of 0.2-0.4% in the MeV range (10-20 x better than present spectrometers)
TER relevant if proved to work in D-T operation.

**Fast electronics for gamma detectors**

**LiH/Water attenuators**
Neutron background suppression.
Allow the use of cameras in all JET scenarios and even DT-plasmas

## Alpha particles

**Lost alphas project (LAP)**
replacement of the existing detector head with two separate detectors assemblies:
Faraday Cup
Scintillator probe

**Activation probe for particle losses**
Fast ion flux monitors inside vessel

**NPA upgrade**
Develop ultra-thin silicon 3D detectors optimized for the use in the NPAs.
Improved signal-background separation at high neutron count rates
Improved ability to measure ions at low energies
Improved capability to identify ions, especially alphas and deuterons