EUROfusion

α-particle diagnostics for JET deuterium-tritium experiments

V G Kiptily and JET team

CCFE
CULHAM CENTRE FOR
FUSION ENERGY

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Introduction

Main fusion reactions

D + D → n (2.5 MeV) + ^{3}He (0.8 MeV)

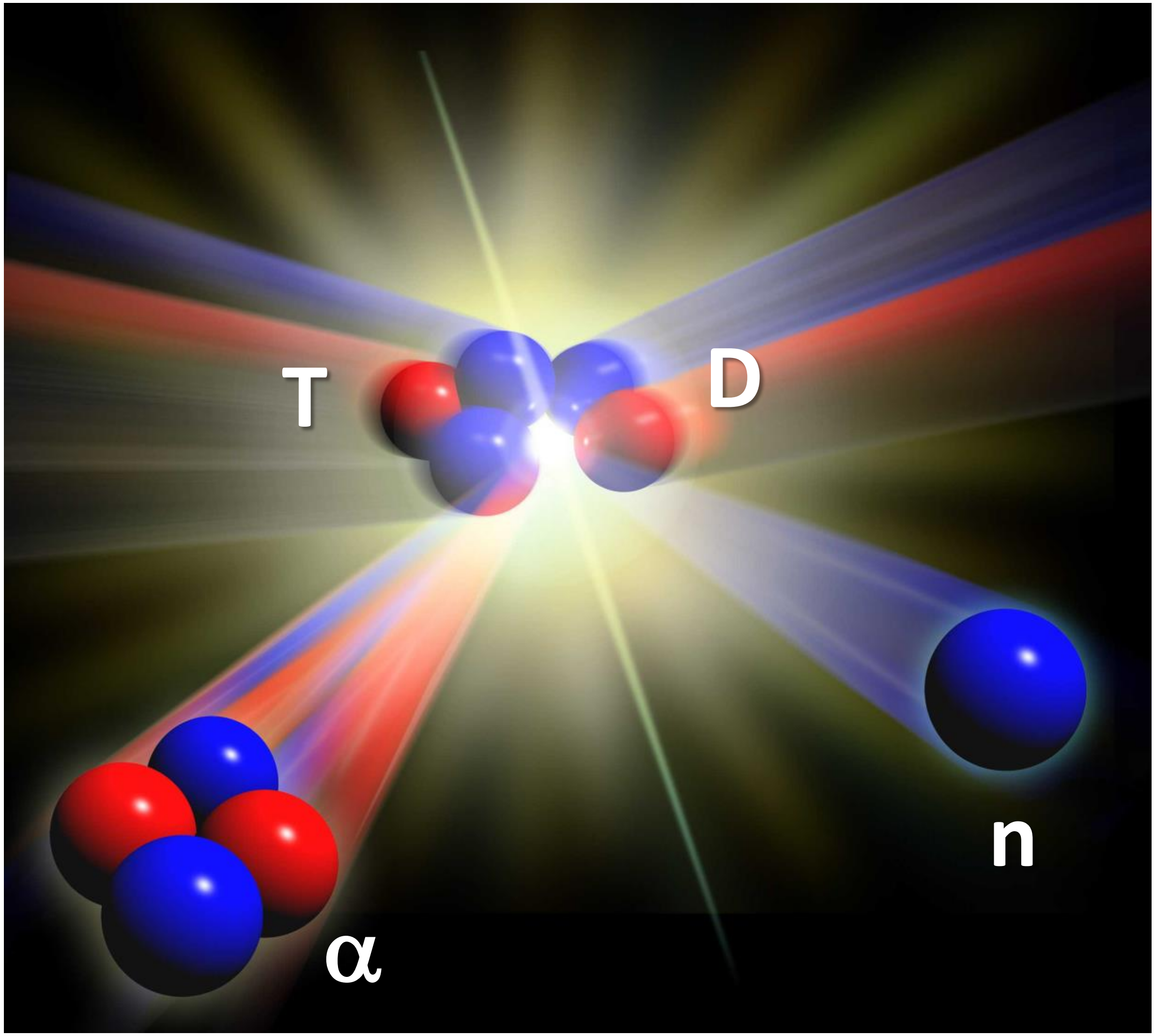
→ p (3.0 MeV) + T (1.0 MeV)

D + ^{3}He → p (14.7 MeV) + **^{4}He** (3.7 MeV)

D + T → n (14.1 MeV) + ^{4}He (3.5 MeV)

For sustained fusion need to be simultaneously maintained:

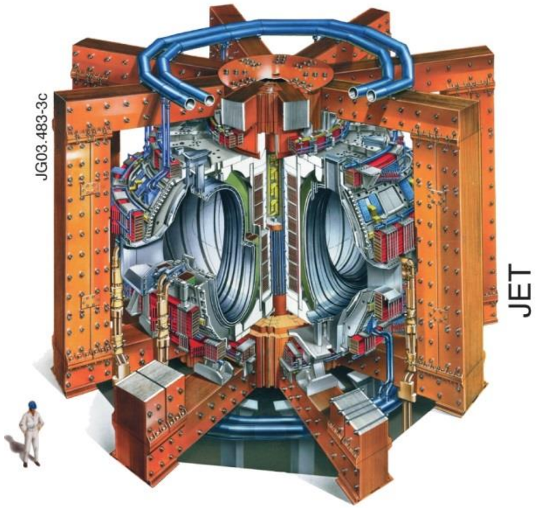
- T ~ 100-200x10^6 °C
- Energy confinement time ~ 4-5 s
- Plasma density ~ 1-2x10^{20} m^{-3}

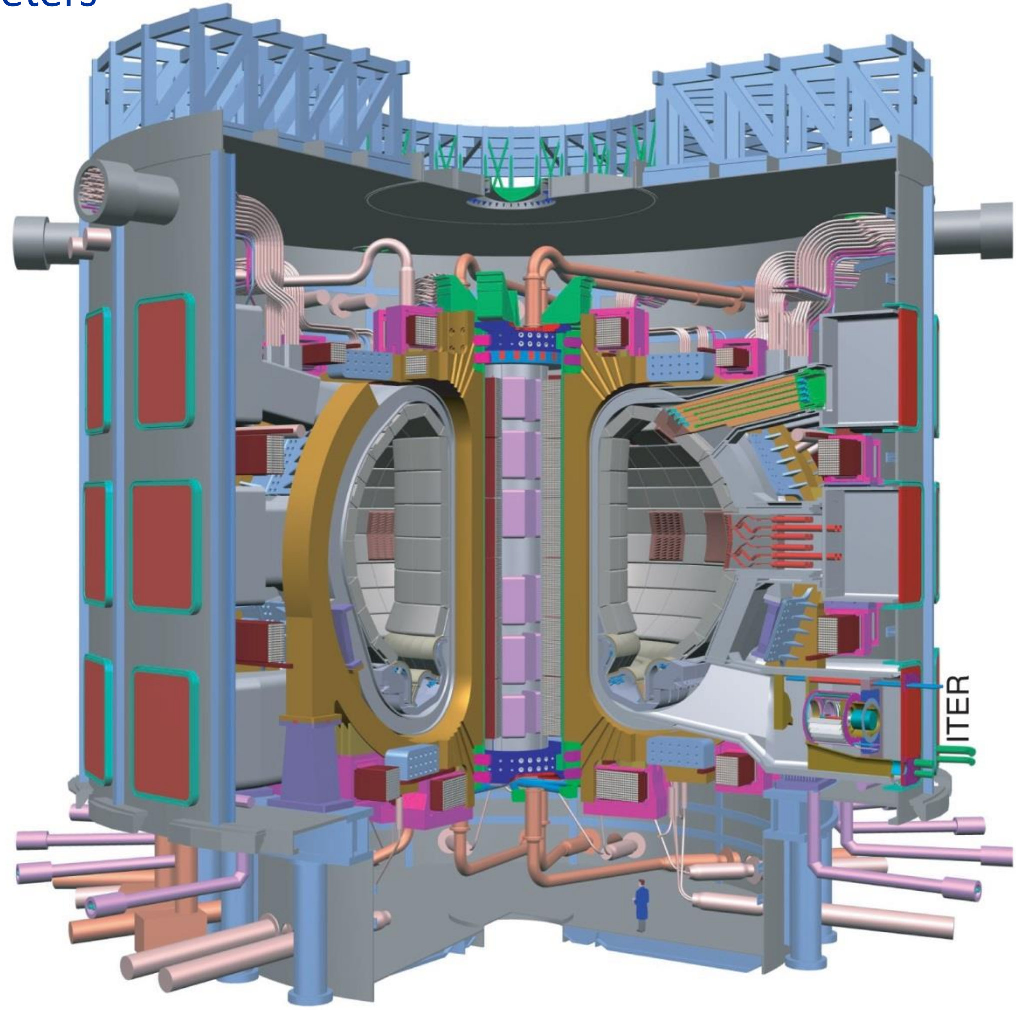


Fusion devices

JET is the tokamak closest to the ITER parameters with unique capabilities of tritium operation

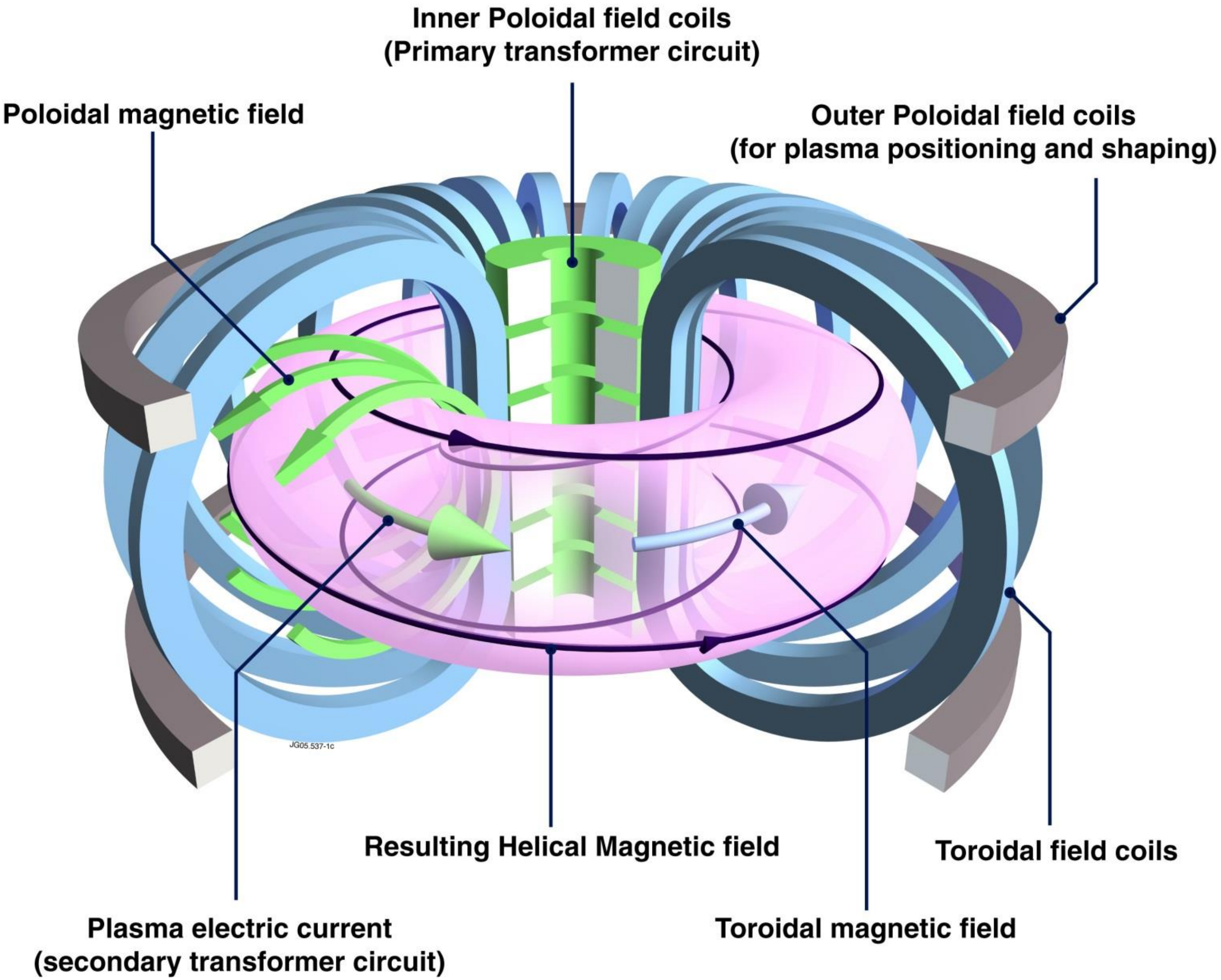
	JET	ITER
R, m	3.1	6.2
a, m	1.0	2.0
I_P, MA	up to 5	up to 15
B_T, T	up to 4	up to 5.3





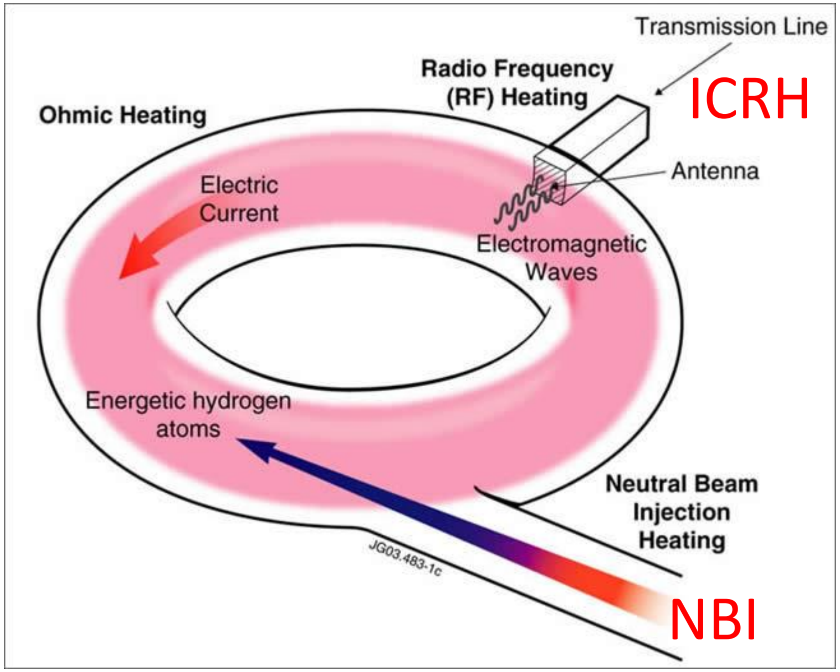
$V_{ITER} / V_{JET} \sim 10$

Tokamak basics



Plasma heating in tokamaks

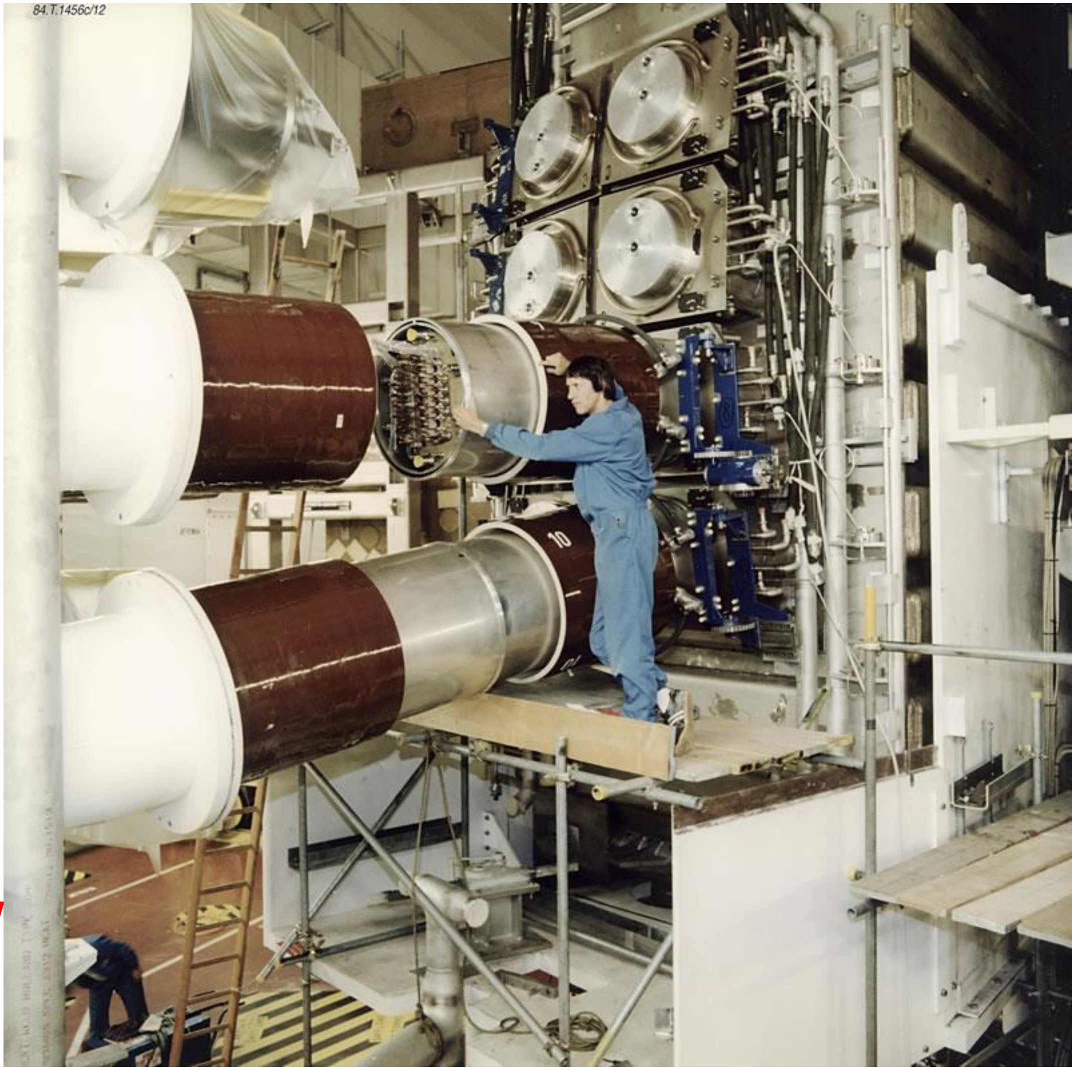
>8 MW



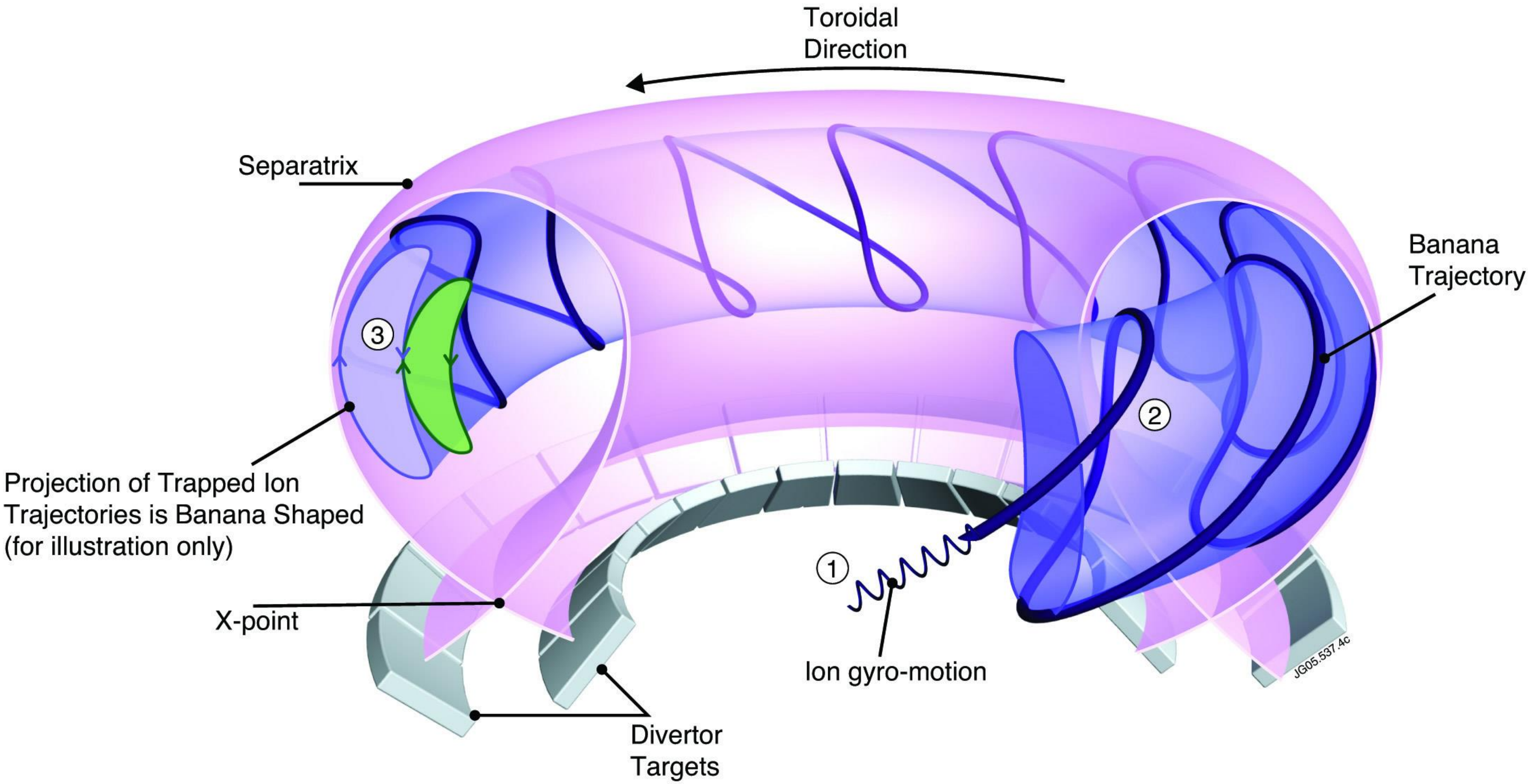
ICRH

NBI

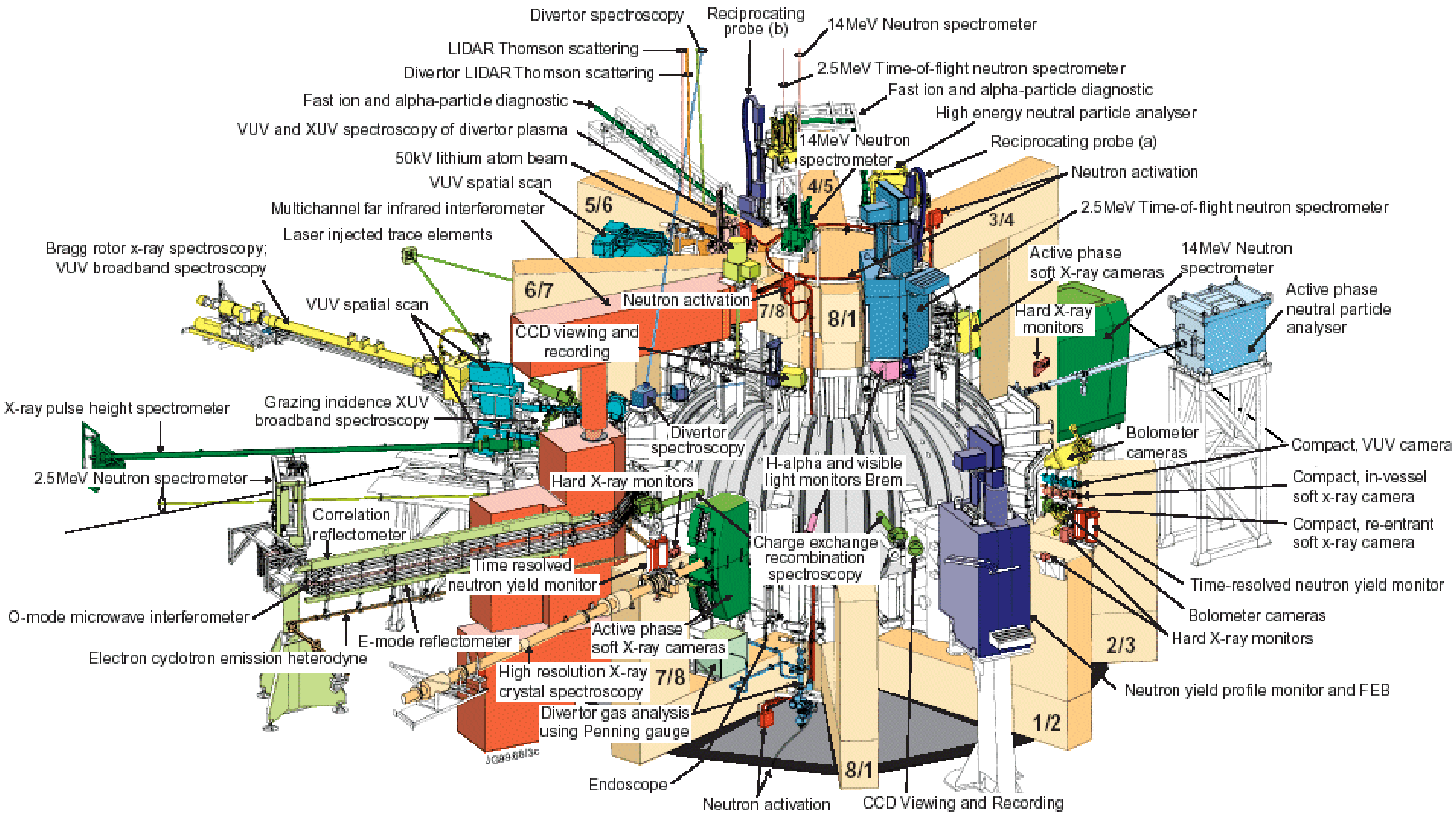
>23 MW



Fast ion orbits in tokamaks



Diagnostics



More than 90 diagnostics at JET

Why should fast alphas be studied?

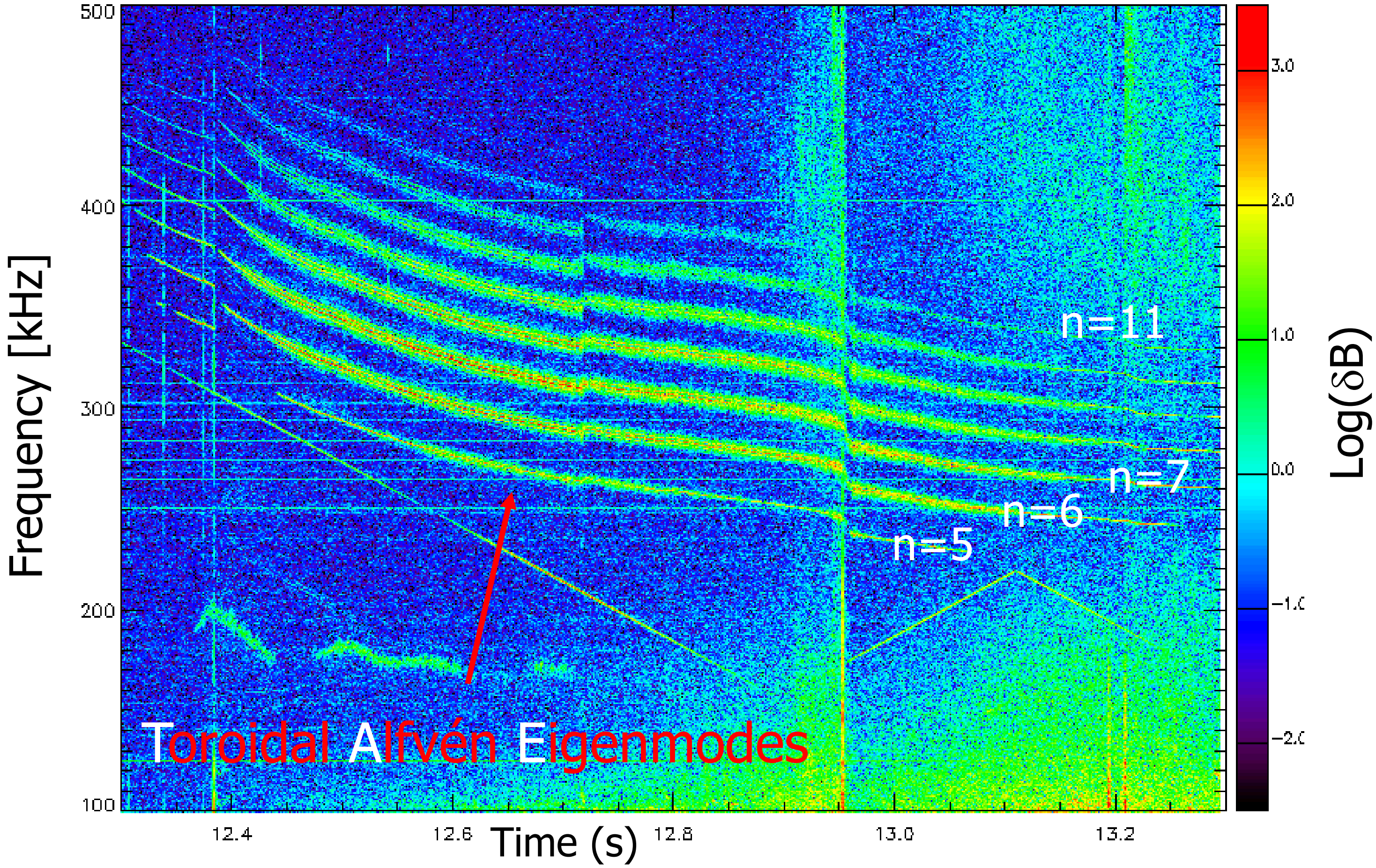
Fusion α-particles

- Reactor plasma is self-heated by fusion α-particles
- Up to now , fusion research was in sub-critical zone, without burn or with small burn (Q^{max}=0.61, JET in 1997)

  “Fusion gain" factor Q gives the ratio of *fusion power* to the external power (NBI, ICRH, …) needed to sustain the energetic equilibrium

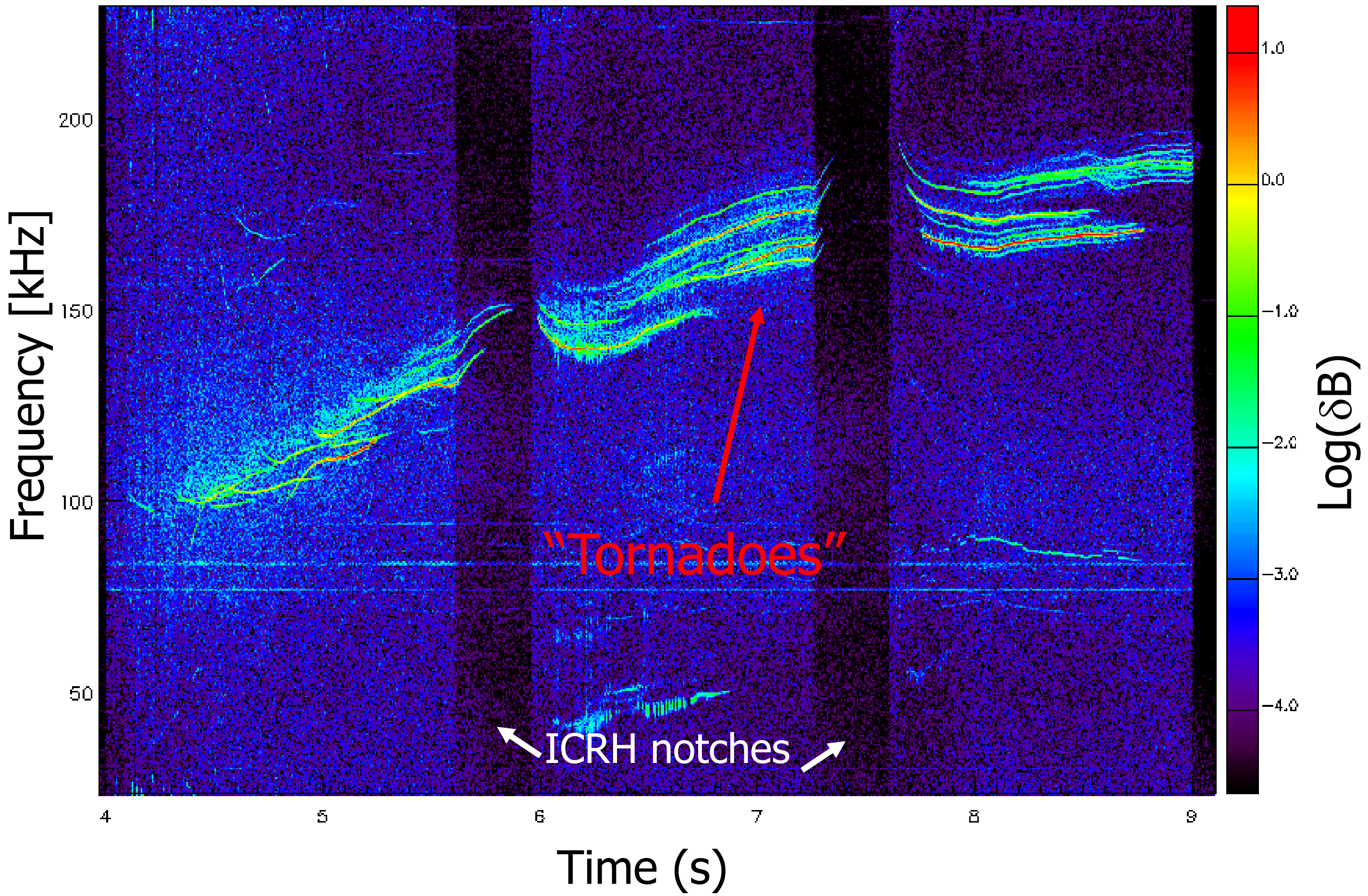
- Fast alphas may drive MagnetoHydroDynamic instabilities and can in turn be re-distributed and, in some cases, lost
- Loss of bulk plasma heating is unacceptable for an efficient power plant
  - May lead to ignition problems
  - Damage to first wall
- Can only tolerate fast alphas losses of a few % in a reactor

MHD instabilities driven by fast-ions



MHD instabilities driven by fast-ions

Tornado modes (core localised TAE modes) are driven by the fast ^{3}He-ions accelerated by ICRH



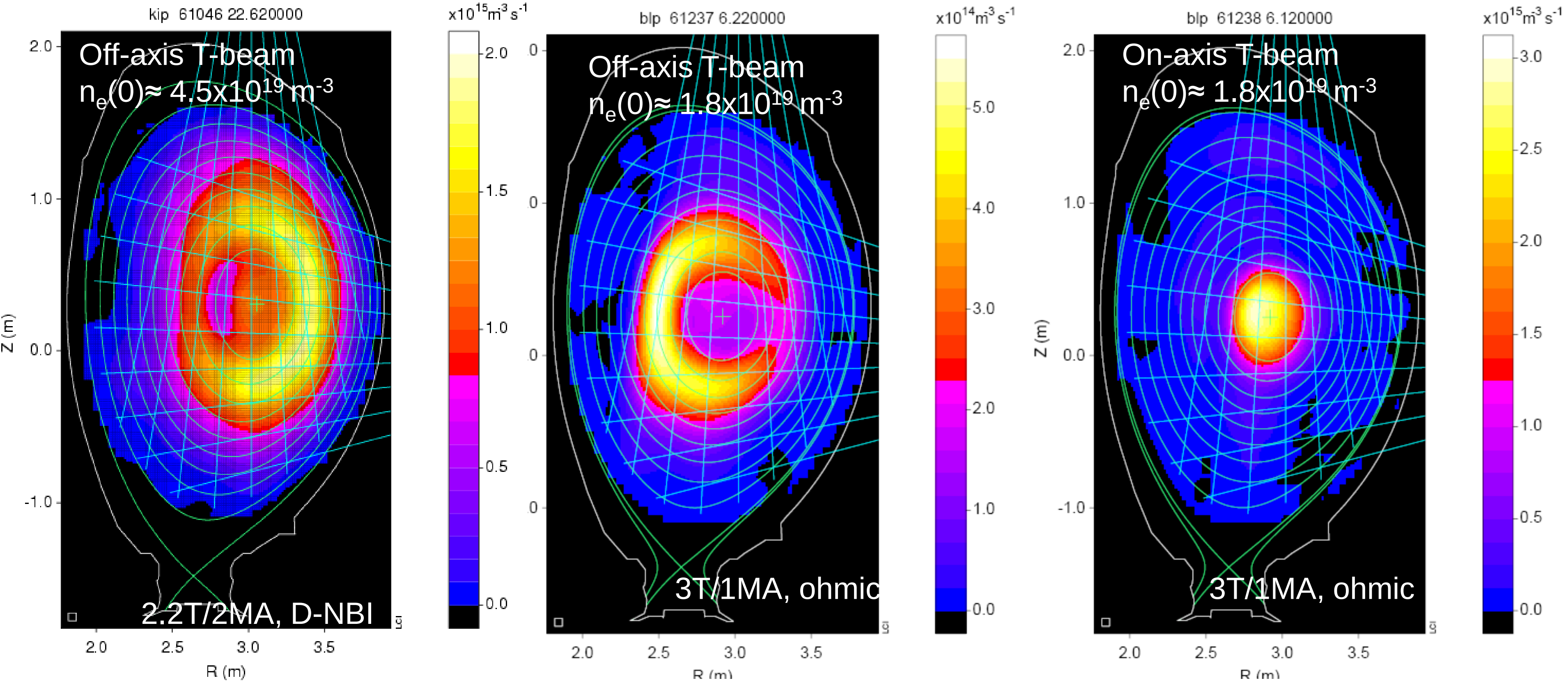
What to be measured
&
How to do it ?

Measurements in DT experiments

- Fusion α-particle source
- Spatial α-particle distribution & redistribution
- α-particle slowing down & energy distribution
- α-particle losses

Fusion α-particle source

14-MeV neutron profile measurements in the monotonic current discharges with T-NBI blips, during the Trace Tritium Experiments in 2003



Neutron & Gamma-ray Cameras

Vertical: 9 lines-of-sight

Horizontal: 10 lines-of-sight

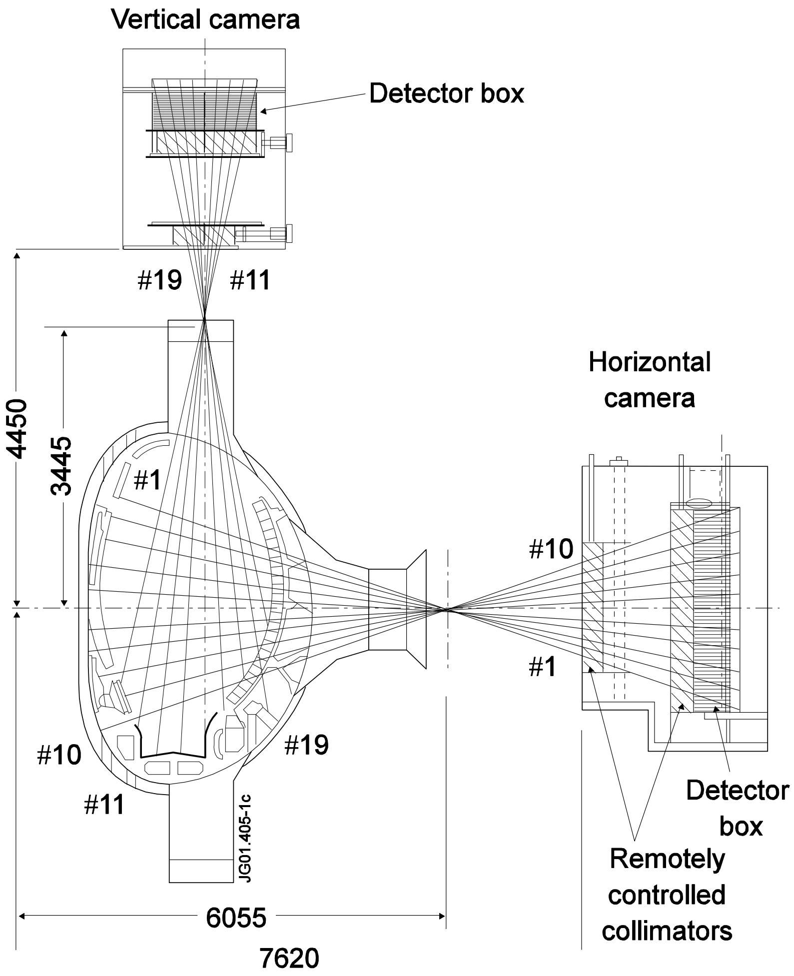
- Fan-shaped array of remotely adjustable collimators with two apertures (Ø10 & 21 mm)
- Space resolution: ~ 8 or ~ 15cm (in the centre)

Detectors:

- **NE213** liquid scintillators (2.5 & 14 MeV)
- **Bicron-418** plastic scintillators (14 MeV)
- **CsI(Tl)** photo-diodes (hard X-rays and γ-rays) to be replaced by **$CeBr_3$** - detectors
- Fast digital Data Acquisition system (DAQ)
- Pulse Height Analysis (PHA)
- Neutron and γ-rates in real time for all channels

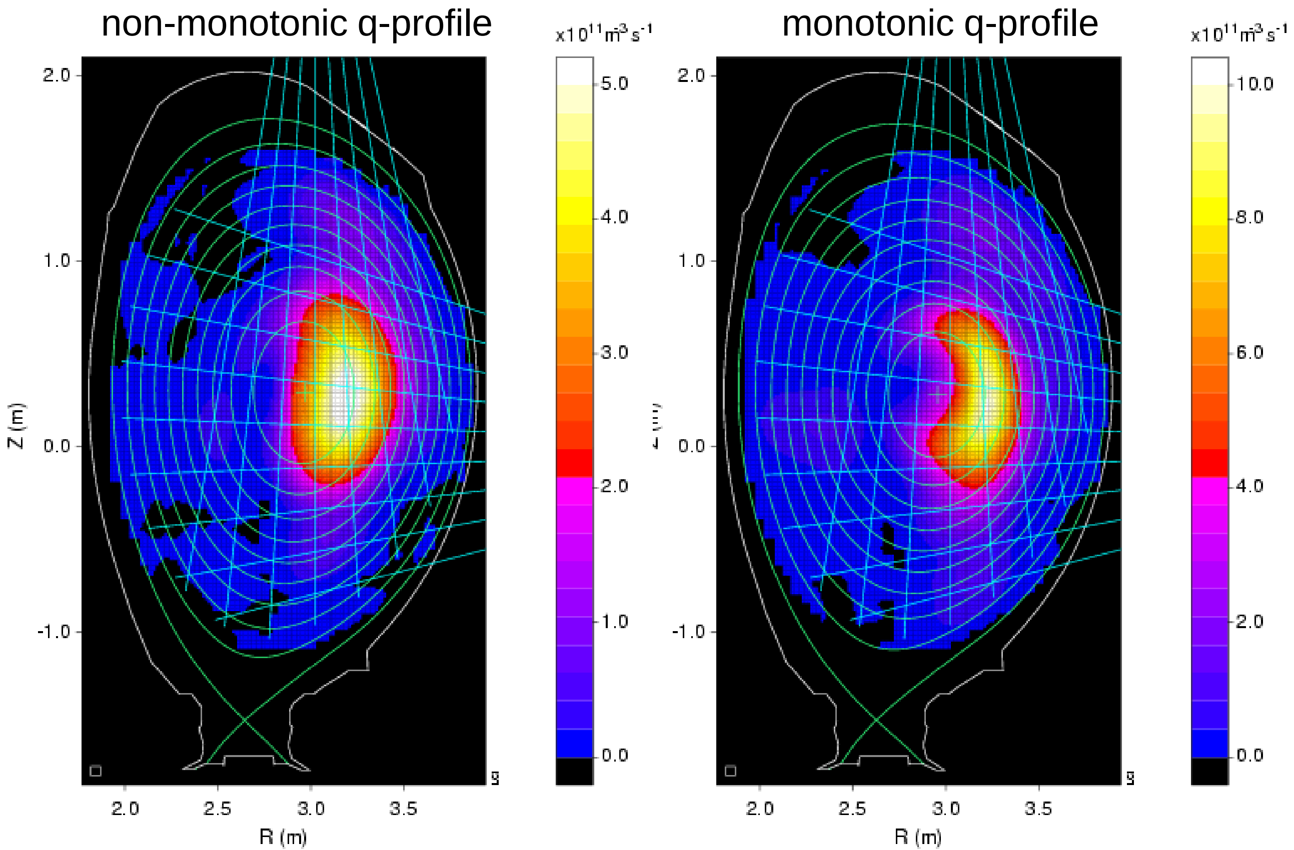
Notes :

$CeBr_3$ - fast scintillator: decay times ~ 20 ns; energy resolution $\Delta E/E \approx 3\%$; DAQ allows PHA with rate > 2 MHz



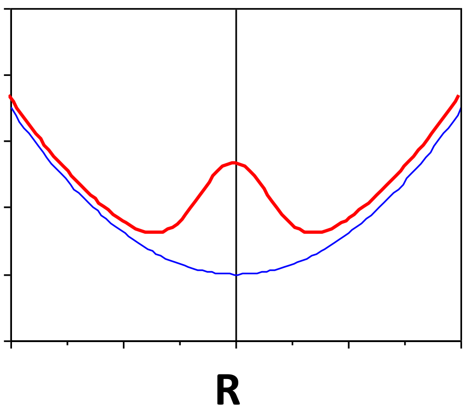
Spatial α-particle distribution / redistribution

^{4}He-beam acceleration: effect of magnetic field topology on γ-ray image of ^{4}He-ions in α-particle mimicking experiment



Safety factor

$q = rB_t / RB_p$



Kiptily et al NF 45 (2005) L21

Tomographic reconstructions of profiles measured in different q-profile phases of the plasma discharge in JET.
The monotonic q-profile had settled down after sawtooth crash.

Gamma-ray Cameras

Neutron attenuation is needed for measurements in DT experiments

Attenuation factors

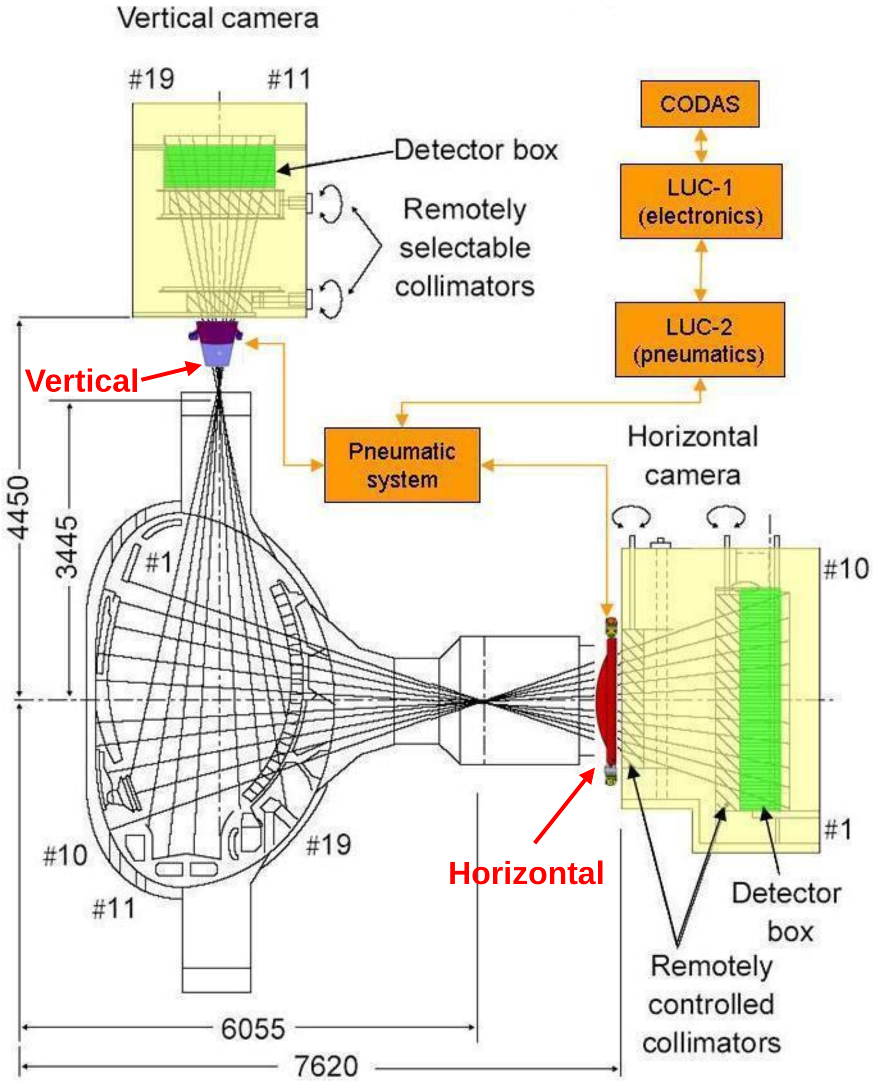
Neutron attenuator	Material	Neutron energy	
		2.45 MeV	14.1 MeV
Horizontal	H_2O	10^2	15
Vertical (normal)	H_2O	$10^{2\,(*)}$	15
Vertical (long version)	H_2O	10^4	10^2

(*) Experimentally confirmed on a prototype

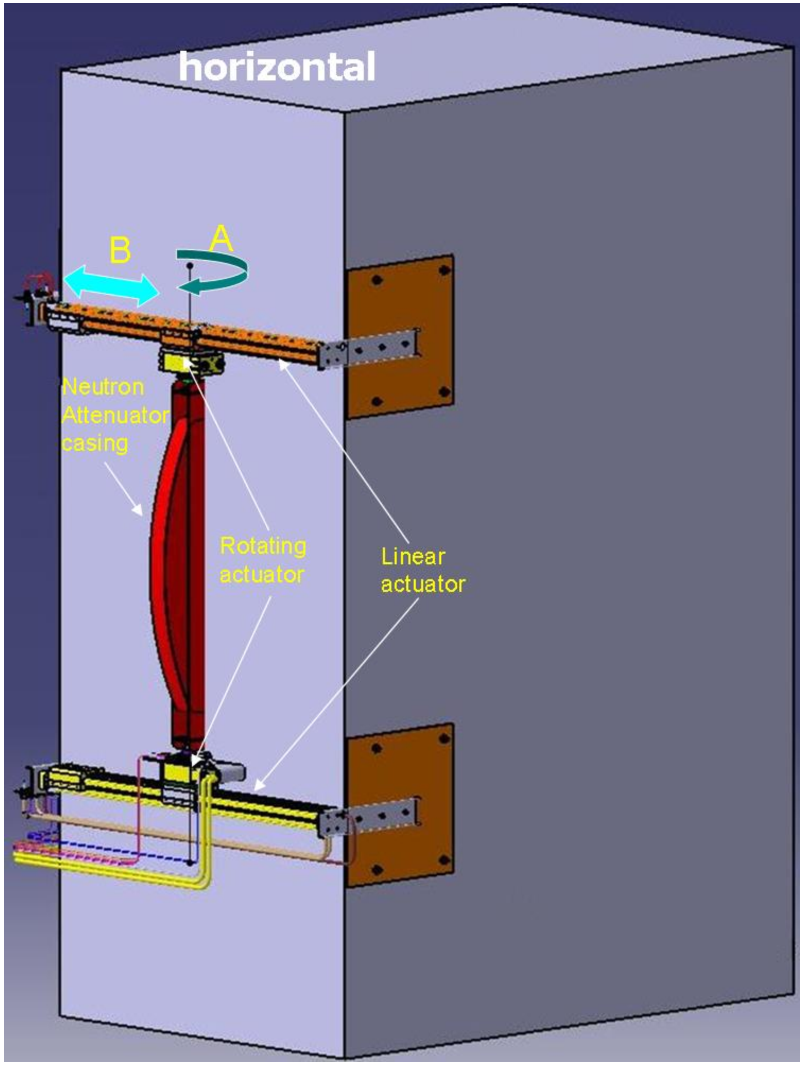
Zoita V. L. et al, Fus. Eng. Des. 84 (2009) 2052
Curuia M. et al, Fus. Eng. Des. 84 (2009) 2052

Notes:

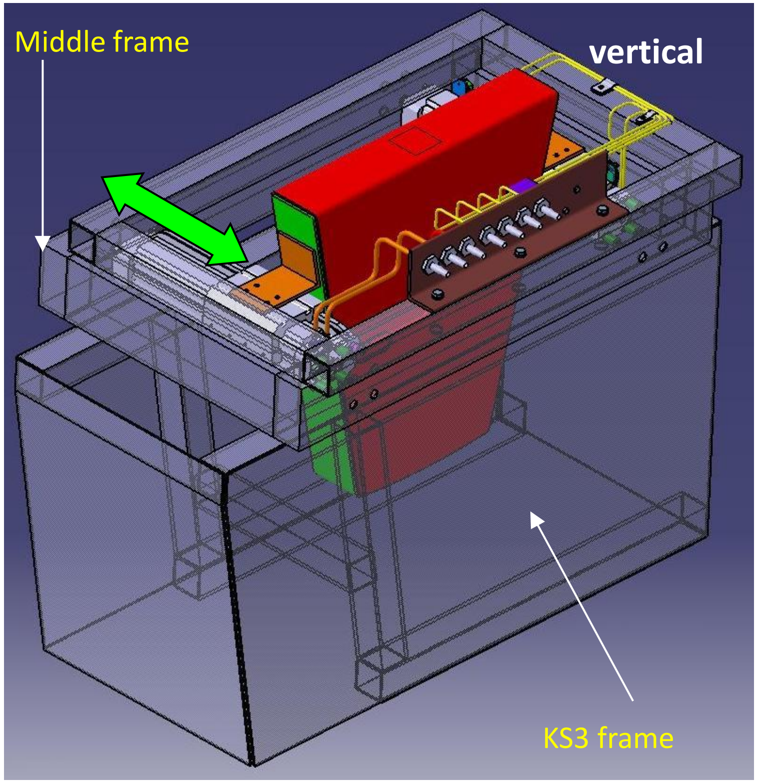
Vertical Camera can be used in DT discharges for γ-ray emission profile measurements with neutron rate up to $5 \cdot 10^{17}$ n/s !



Gamma-ray Camera neutron attenuators



A long version of the vertical neutron attenuator will be used to measure γ-ray profiles in some DT discharges (14-MeV neutron suppression ~ 100)



γ-ray spectrometry of fusion plasmas

Nuclear reactions

Confined fast ion studies with γ-diagnostics

protons

D(p,γ)^{3}He
T(p,γ)^{4}He
^{9}Be(p,γ)^{10}B
^{9}Be(p,p'γ)^{9}Be
^{9}Be(p,α γ)^{6}Li
^{12}C(p,p'γ)^{12}C

deuterons

^{9}Be(d,pγ)^{10}Be
^{9}Be(d,nγ)^{10}B
^{12}C(d,pγ)^{13}C

tritons

D(t,γ)^{5}He
^{9}Be(t,nγ)^{11}B
^{12}C(t,γ)^{15}N
^{12}C(t,nγ)^{14}N
^{12}C(t,αγ)^{11}B

^{3}He

D(^{3}He,γ)^{5}Li
^{9}Be(^{3}He,pγ)^{11}B
^{9}Be(^{3}He,nγ)^{11}C
^{12}C(^{3}He,pγ)^{14}N

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

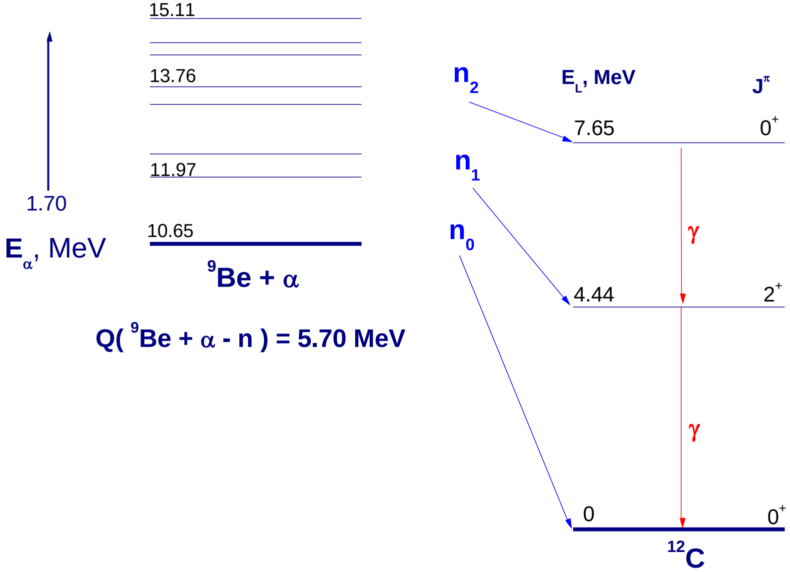
Notes:

- Currently, carbon is not a main impurity in JET (ITER-like wall)
- Some of this reactions can be used for studies of escaping alpha-particles and other fast ions (p, d, t and ^{3}He) in the MeV energy range

Kiptily V.G., Cecil F.E. and Medley S.S., Plasma Phys. Control. Fusion **48** (2006) R59-82

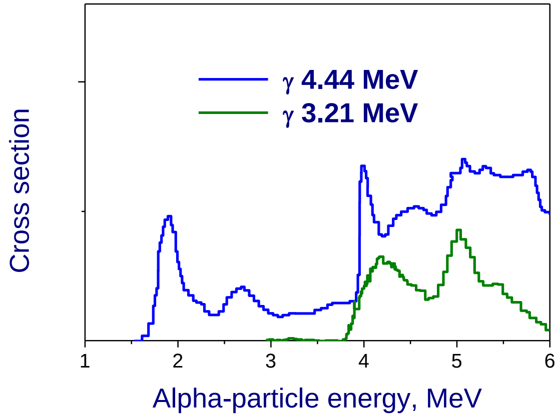
^{9}Be(α,nγ)^{12}C reaction for α-particle measurements

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



The nuclear reaction between fast α and ^{9}Be impurity leads to:

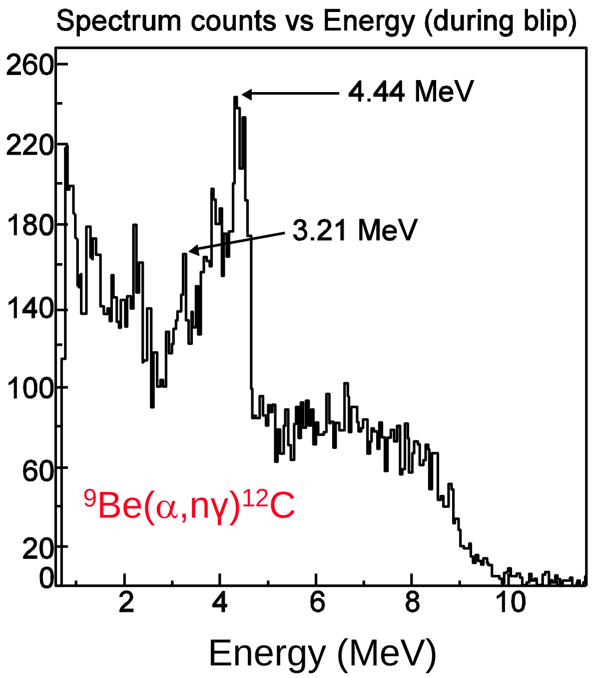
- ➢ Excitation of high-energy levels in ^{13}C* nucleus
- ➢ De-excitation by emitting neutrons with population of the low-lying levels in ^{12}C*
- ➢ Further de-excitation by γ3.21 MeV and γ4.44 MeV to the ground state of ^{12}C nucleus:
  - ✓ γ4.44 MeV (1st level) are produced by E_α > 1.7 MeV
  - ✓ γ3.21 MeV (2nd level) are produced by E_α > 4 MeV



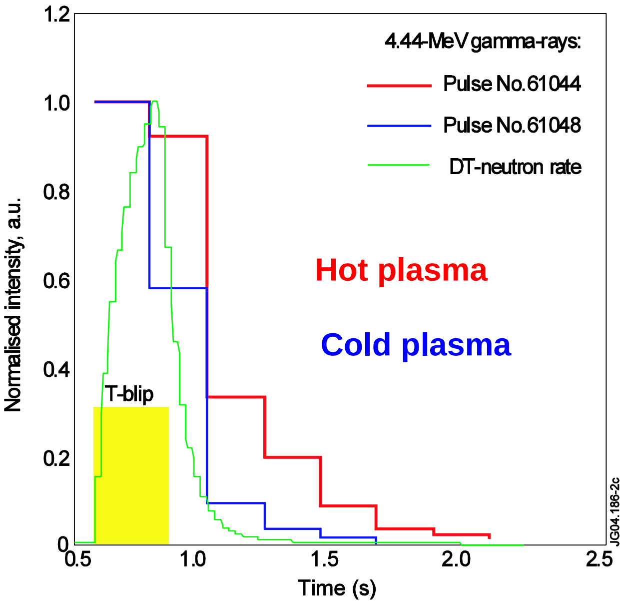
Kiptily V.G., Fusion Technology **18** (1990) 583

α-particle studies on JET

4.44-MeV γ-ray spectra measurements in plasma discharges with T-NBI blips in the Trace Tritium Experiments (2003)



4.44-MeV γ-ray spectrum recorded just after the T-blip

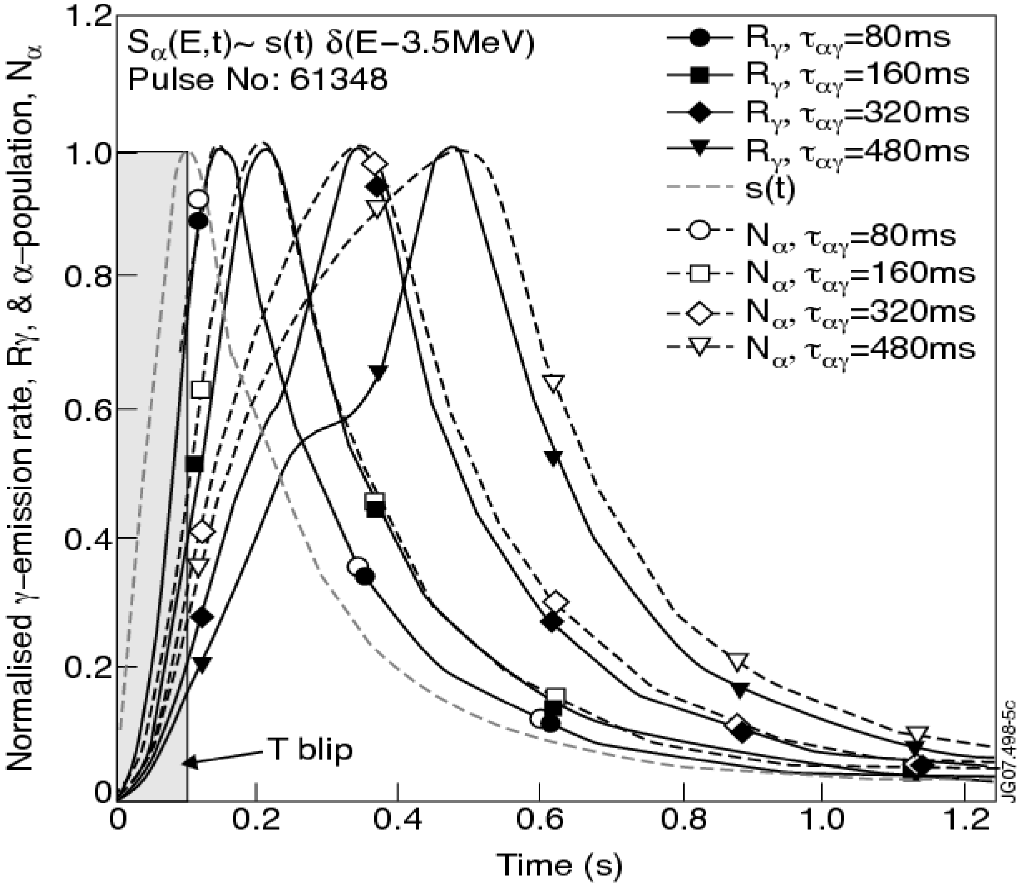


Relaxation of 4.44-MeV γ-ray intensity after the T-blip

Kiptily et al. Phys Rev Letter **93** (2004) 115001

α-particle modelling for TTE

Fokker-Planck modelling

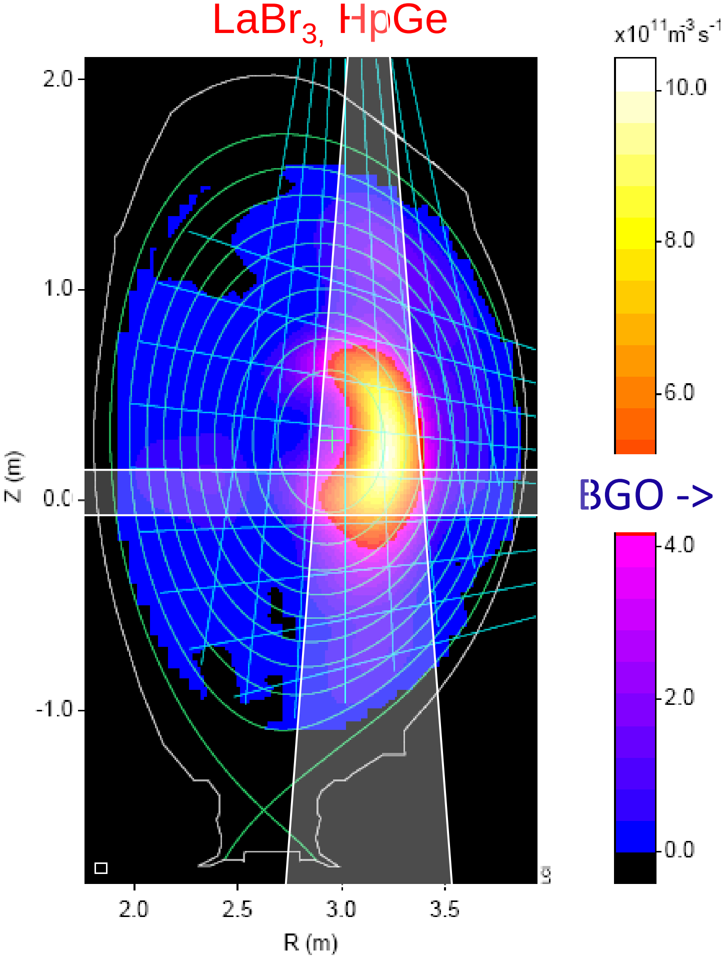


- Relaxation of 4.44-MeV γ-ray emission and fast alphas density (E_α >1.7MeV), depending on the value of the Spitzer slowing-down time
- Time resolution of γ-ray measurements: 50-ms or better is required for α-particle studies

Yavorskij et al NF **50** (2010) 025002

JET gamma-ray spectrometers

$LaBr_3$, HpGe



BGO ->

$CeBr_3$
$LaBr_3$

Goal: provide time resolution < 50 ms for 4.44-MeV γ-rays at MHz count-rate

$LaBr_3$: energy resolution - ΔE/E ≈ 3%,
Decay times ~ 20 ns,
DAQ allows up to 5 MHz PHA,
30-cm ^{6}LiH neutron attenuator

Chugunov et al. Nucl. Fusion **51** (2011) 083010
Nocente M et al. IEEE Trans. Nucl. Sci. **60** (2013)

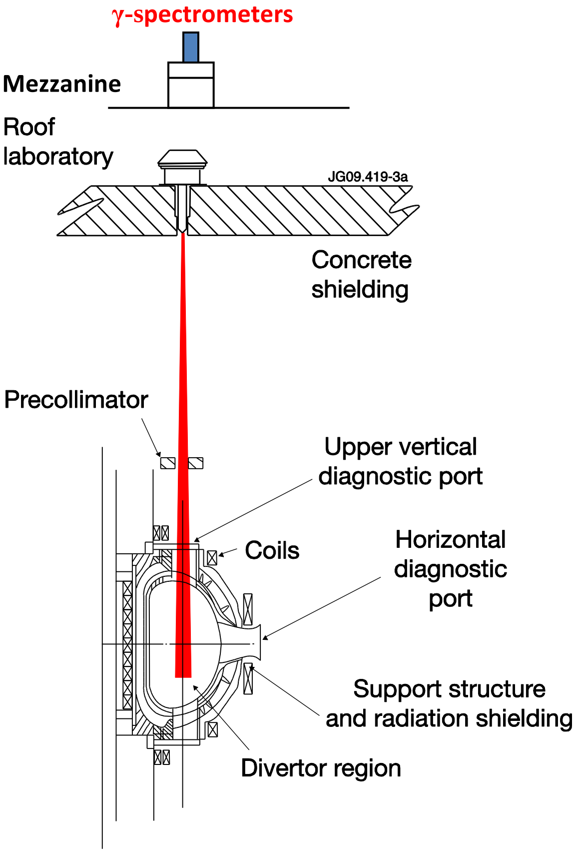
BGO : energy resolution - ΔE/E ≈ 14%
Best detection efficiency!
Slow: decay time ~ 300 ns (pile-up!)

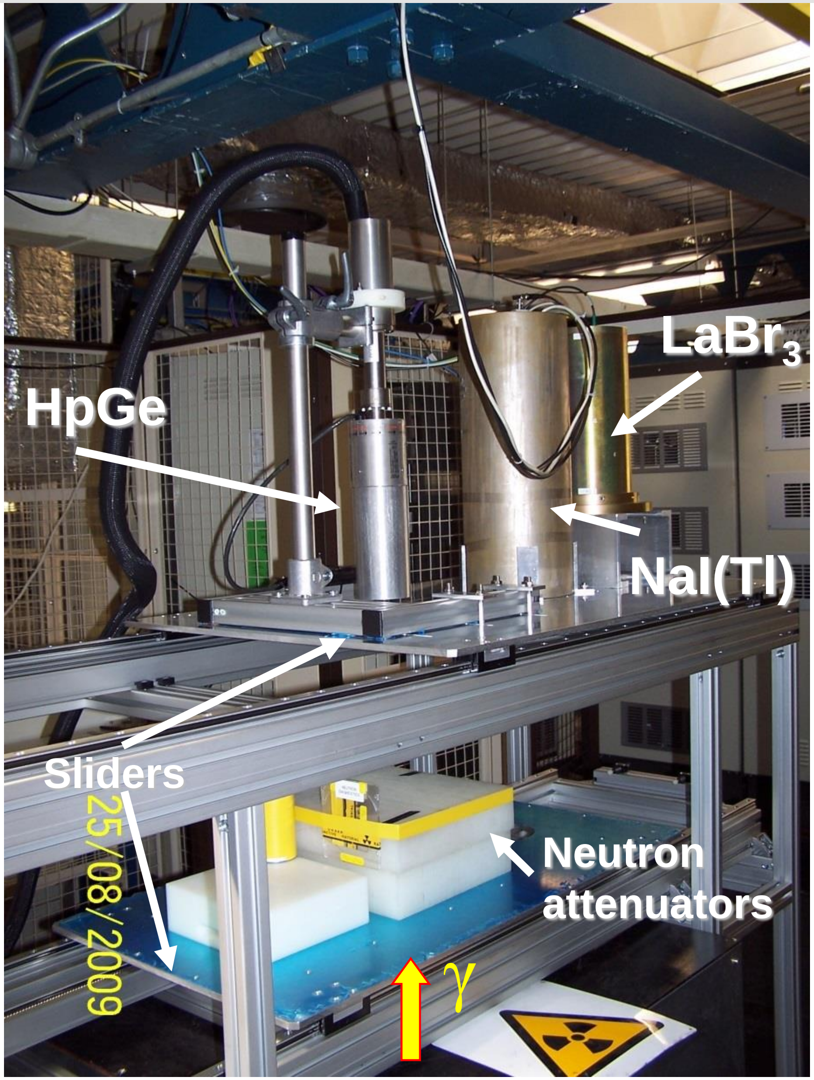
HpGe: ΔE/E ≈ 0.3% - Doppler broadening of γ-lines;
DAQ allows up to 0.5 MHz PHA

Notes:

- BGO-detector to be replaced by fast $CeBr_3$ / $LaBr_3$
- Fast digital DAQ
- Additional neutron/gamma shielding
- LiH-attenuators for horizontal LoS

Vertical γ-ray spectrometers



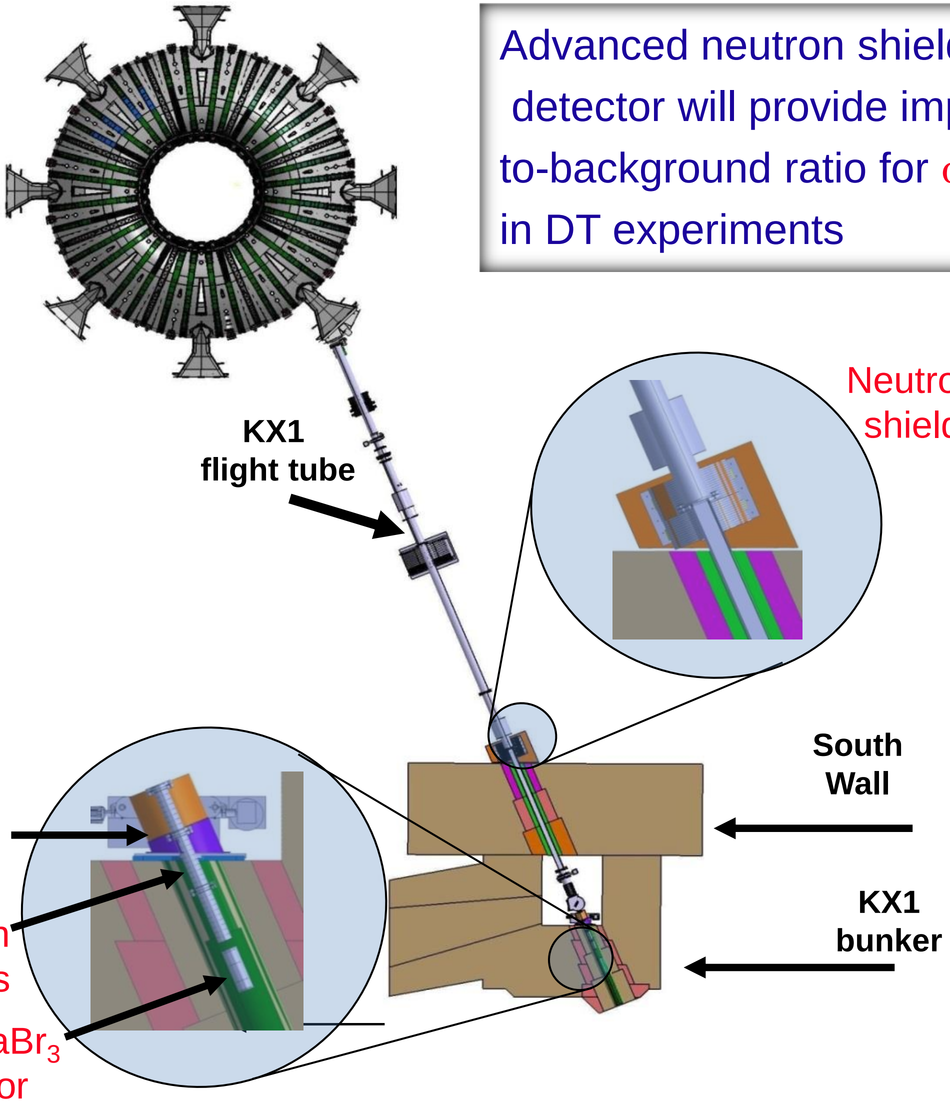


Neutron attenuators are needed to reduce γ-ray background

Neutron attenuators: polyethylene for DD and ^{6}LiH for DT measurements will be used

Horizontal γ-ray spectrometer

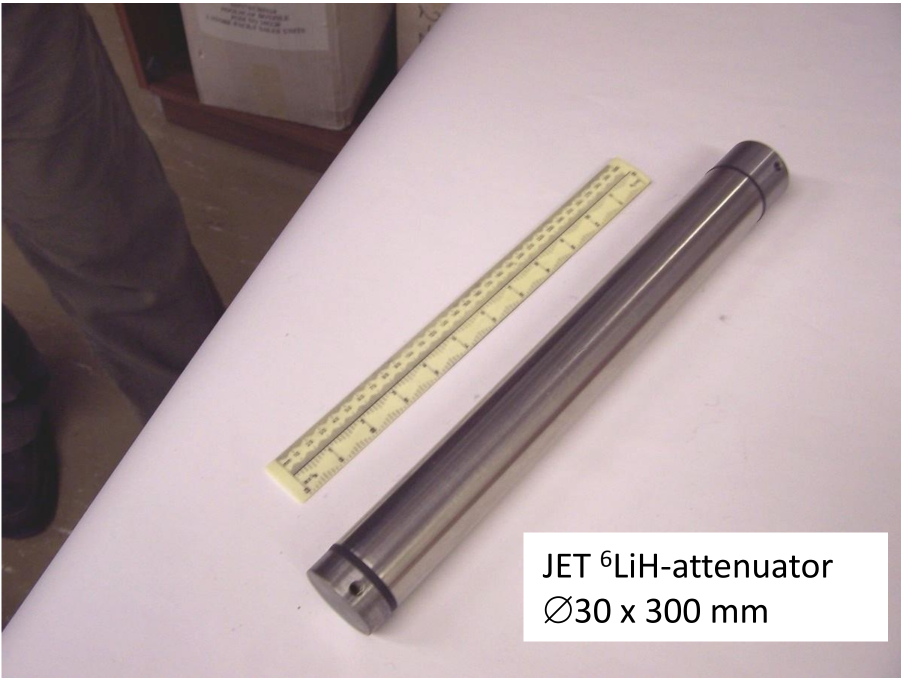
Advanced neutron shielding of $CeBr_3$ or $LaBr_3$ detector will provide improvement of the signal-to-background ratio for α-particle measurements in DT experiments

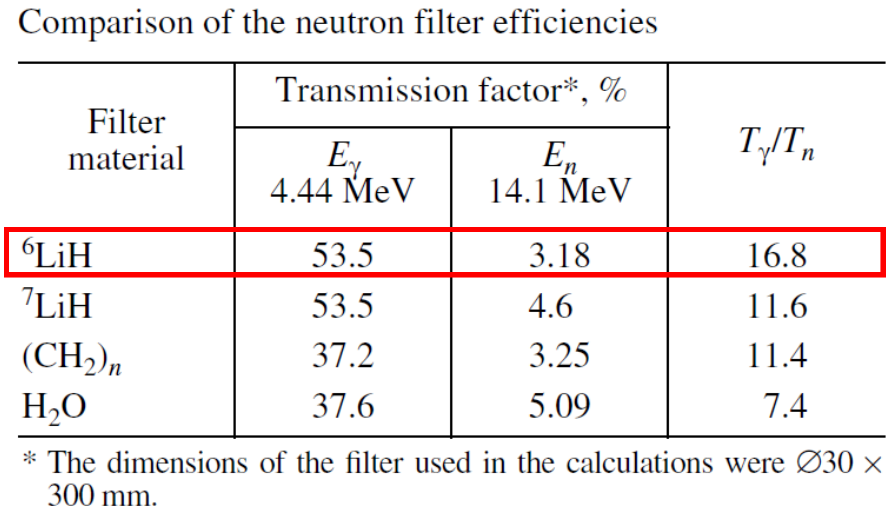


Neutron attenuators

Neutron attenuation is a key issue for measurements of γ-rays in DT experiments

^{6}LiH based neutron attenuator is most efficient one


JET ^{6}LiH-attenuator
∅30 x 300 mm

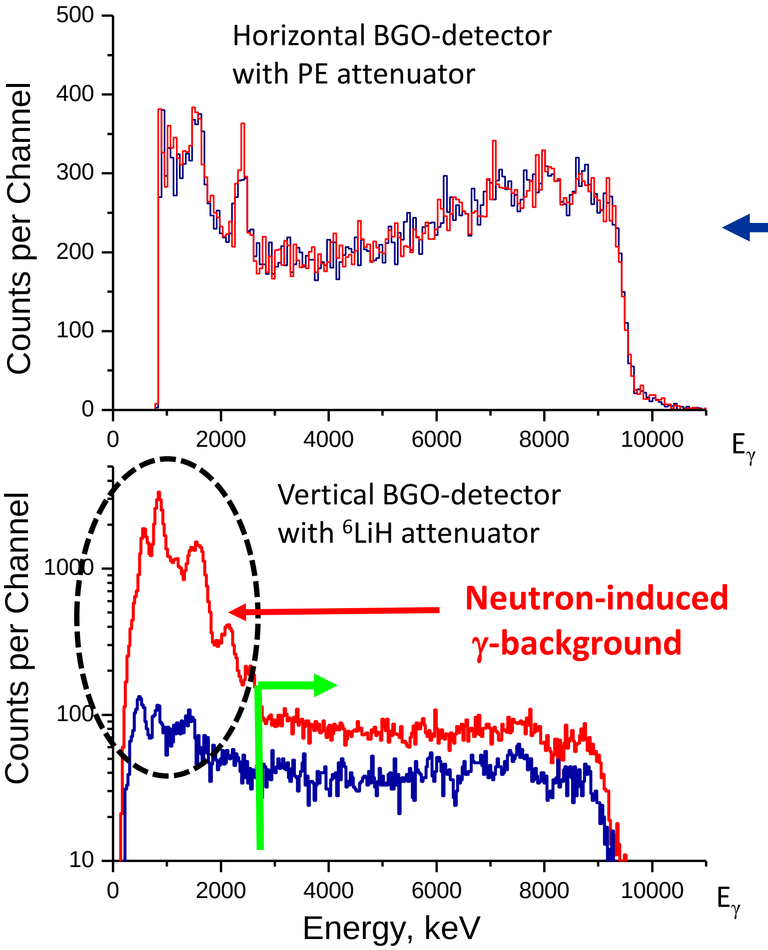

Comparison of the neutron filter efficiencies

Filter material	Transmission factor*, %		T_γ/T_n
	E_γ 4.44 MeV	E_n 14.1 MeV	
^{6}LiH	53.5	3.18	16.8
^{7}LiH	53.5	4.6	11.6
$(CH_2)_n$	37.2	3.25	11.4
H_2O	37.6	5.09	7.4

* The dimensions of the filter used in the calculations were ∅30 × 300 mm.

Kiptily et al, Tech. Phys. **43** (1998) 471

^{6}LiH neutron attenuator test



Reference γ-rays spectra

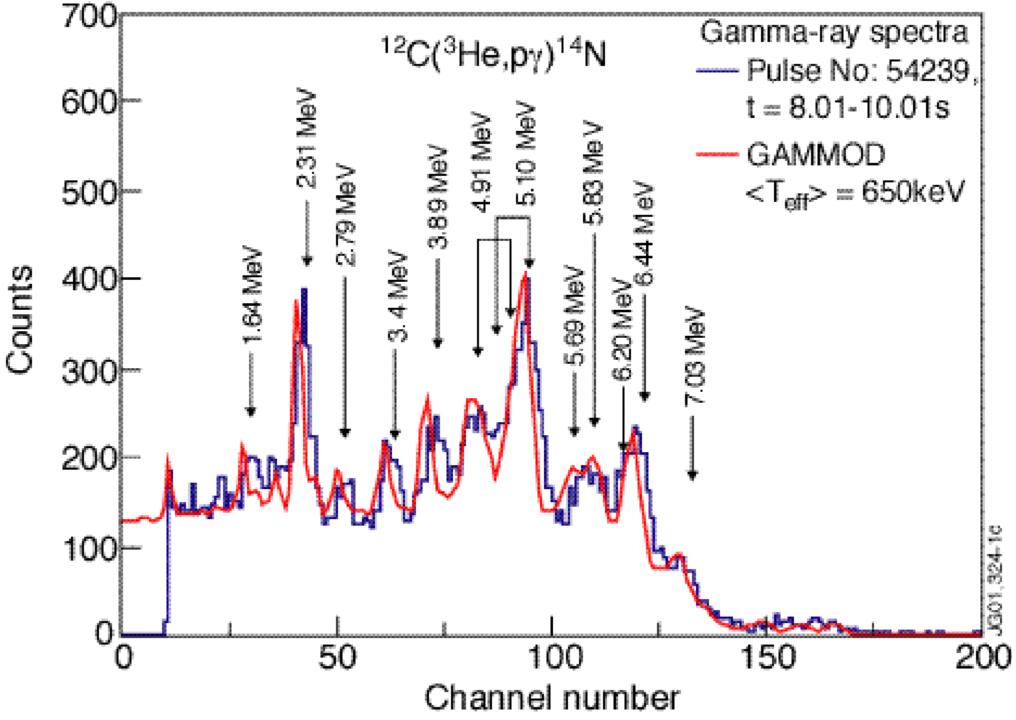
Neutron-induced gammas in the range $E_\gamma < 3$ MeV (inelastic nuclear scattering in detector) suppressed with ^{6}LiH attenuator by a factor of ≈ 100

Gamma-rays with $E_\gamma > 3$ MeV suppressed with ^{6}LiH attenuator by a factor of ≈ 2

Chugunov et al, Instrum. and Exp. Techniques **51** (2008) 166

JET γ-ray spectra

A typical γ-ray spectrum recorded during ICRH with ^{3}He-minority



Spectrum analysis based on GAMMOD code:

- The program is based on known reaction cross-section data (hundred γ-ray transitions)
- The program includes spectrometer response function, calculated *a priori*
- Natural background spectrum
- Input parameters: time-averaged temperatures, injected power, fuel and low-Z impurity densities
- Energy distributions of the fusion products are approximated by the classical distribution functions
- Maxwellian energy distribution is chosen to describe the line-of-sight averaged ICRF-driven ions' distributions

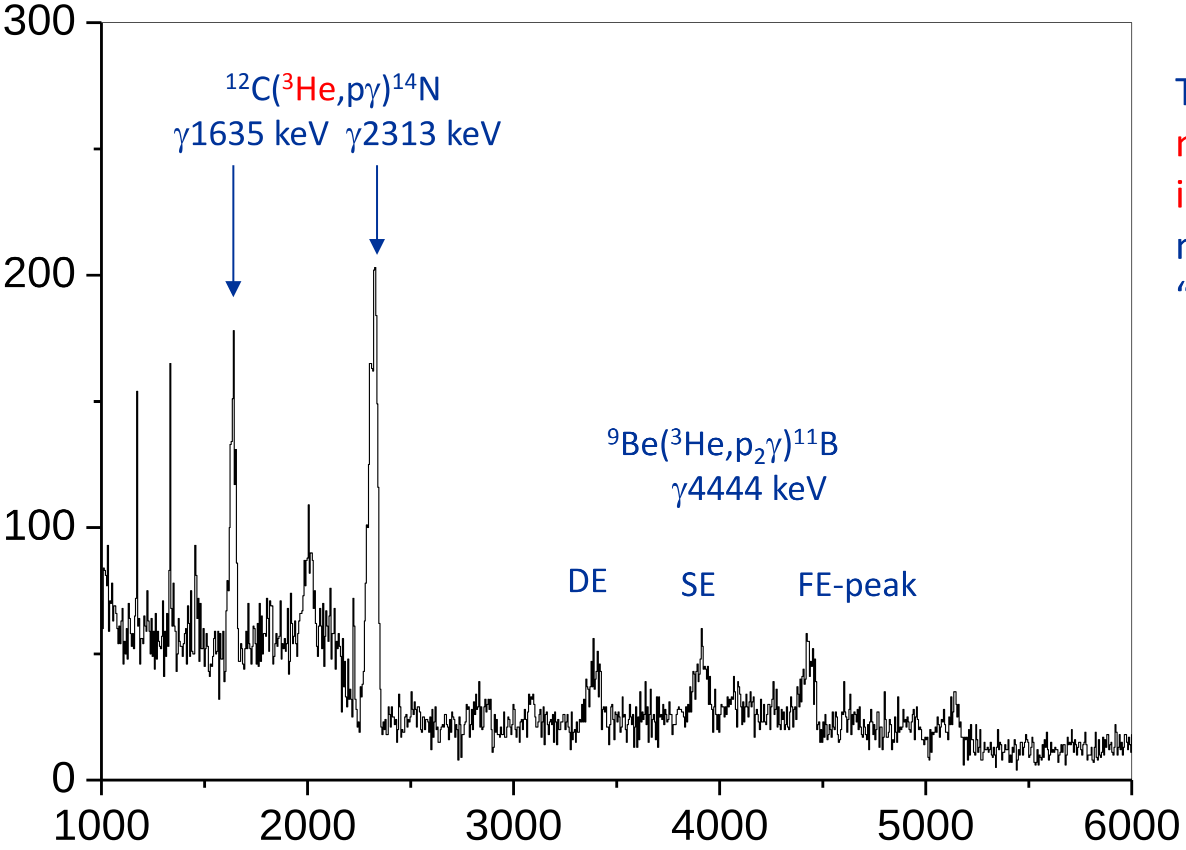
GAMMOD gives

- an effective fast ion temperatures,
- relative fast ions' concentrations and
- a contribution to the neutron yield made by the ICRF-heated fast particles
- an average accuracy of the effective tail temperature ~ 30%

Kiptily et al NF **42** (2002) 999

Novel technique: Doppler broadening γ-lines

^{3}He-ions accelerated during ICRH



The Doppler broadening due to nuclear reactions between ^{3}He-ions and Be impurity has been measured for assessment of an "effective temperature" $<T_{3He}>$:

$$\Delta E_\gamma \approx E_{\gamma 0}(V_R/c)\cos\theta$$

V_R – recoil velocity, which depends on the ^{3}He-ion velocity

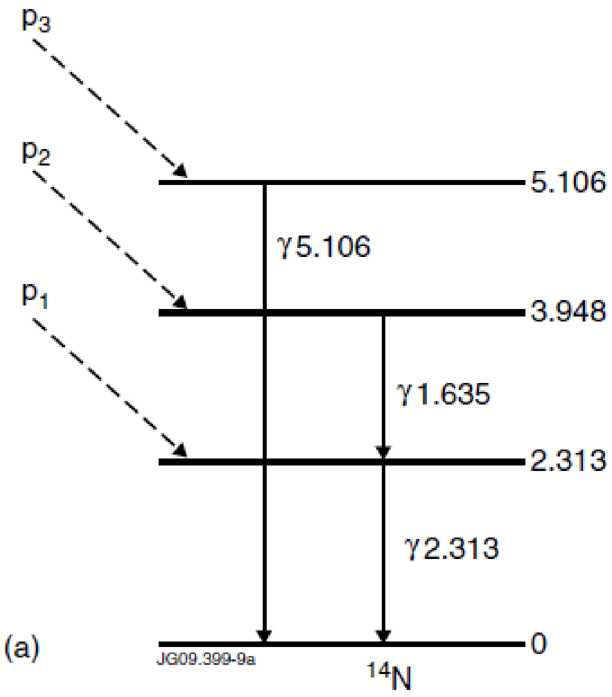
Notes:

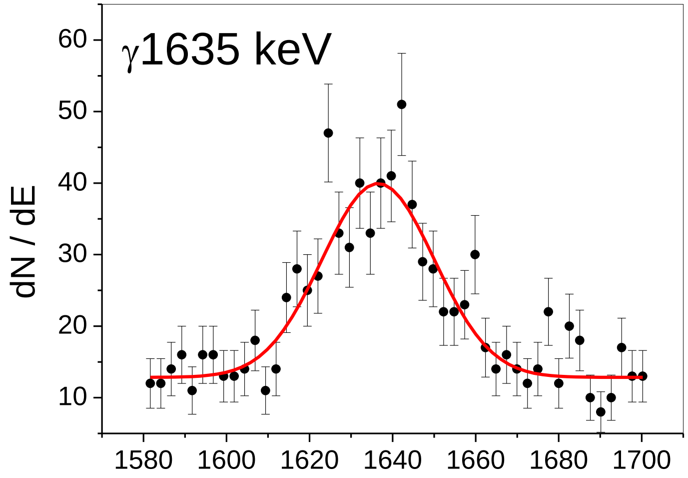
HpGe-detector could be used in DT experiments with an efficient neutron attenuator

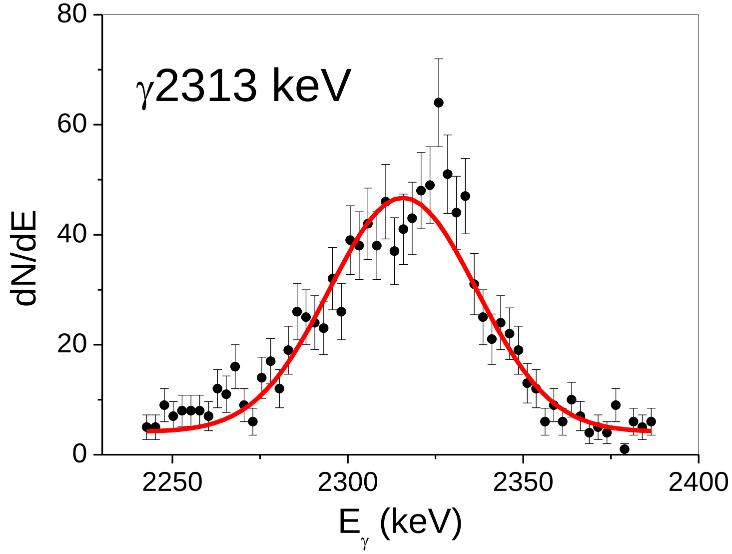
Kiptily et al NF **50** (2010) 084001
Tardocchi et al PRL **107** (2011) 205002
Nocente et al NF **52** (2012) 063009

Fast ion temperature measurements

$^{12}C(^{3}He,p\gamma)^{14}N$



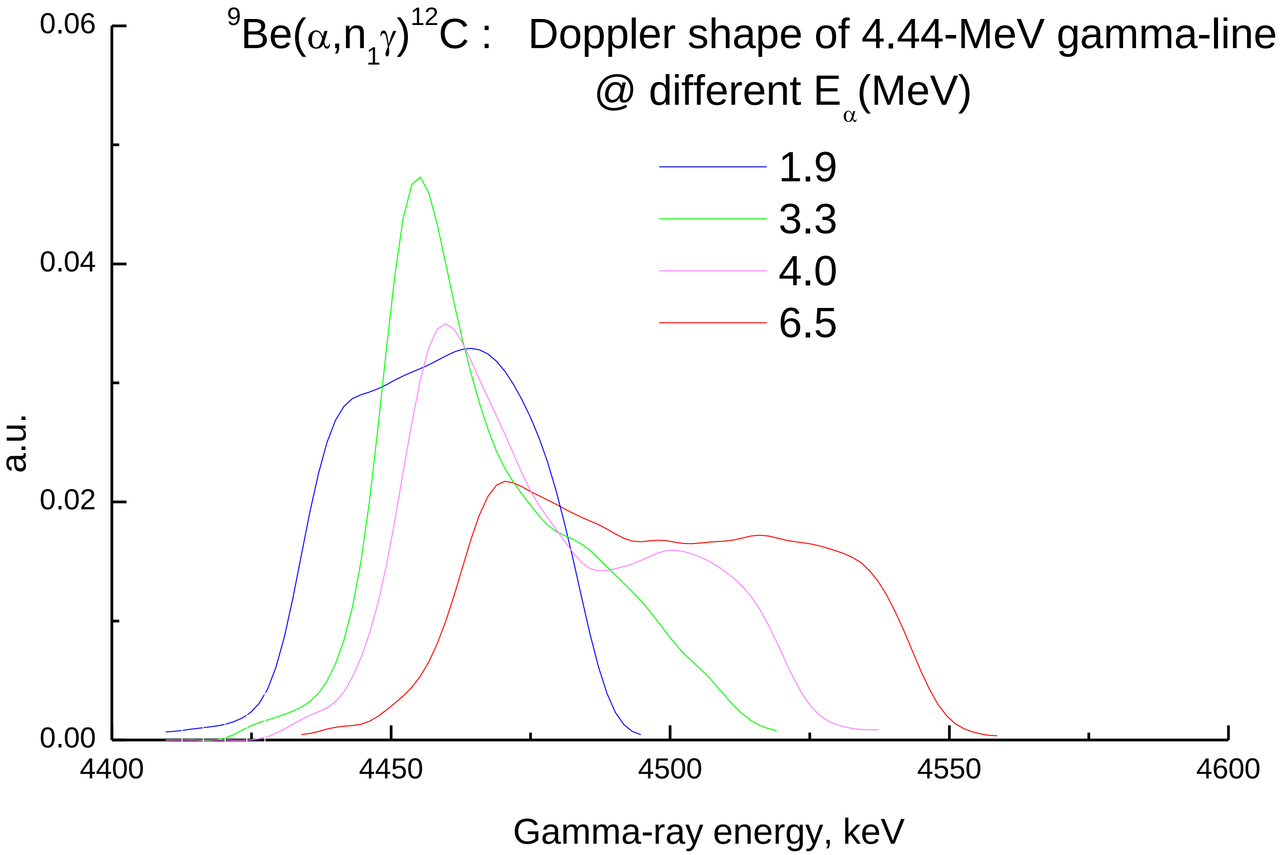




Assessed effective temperature ~ 350 keV

Fusion α-particle measurements

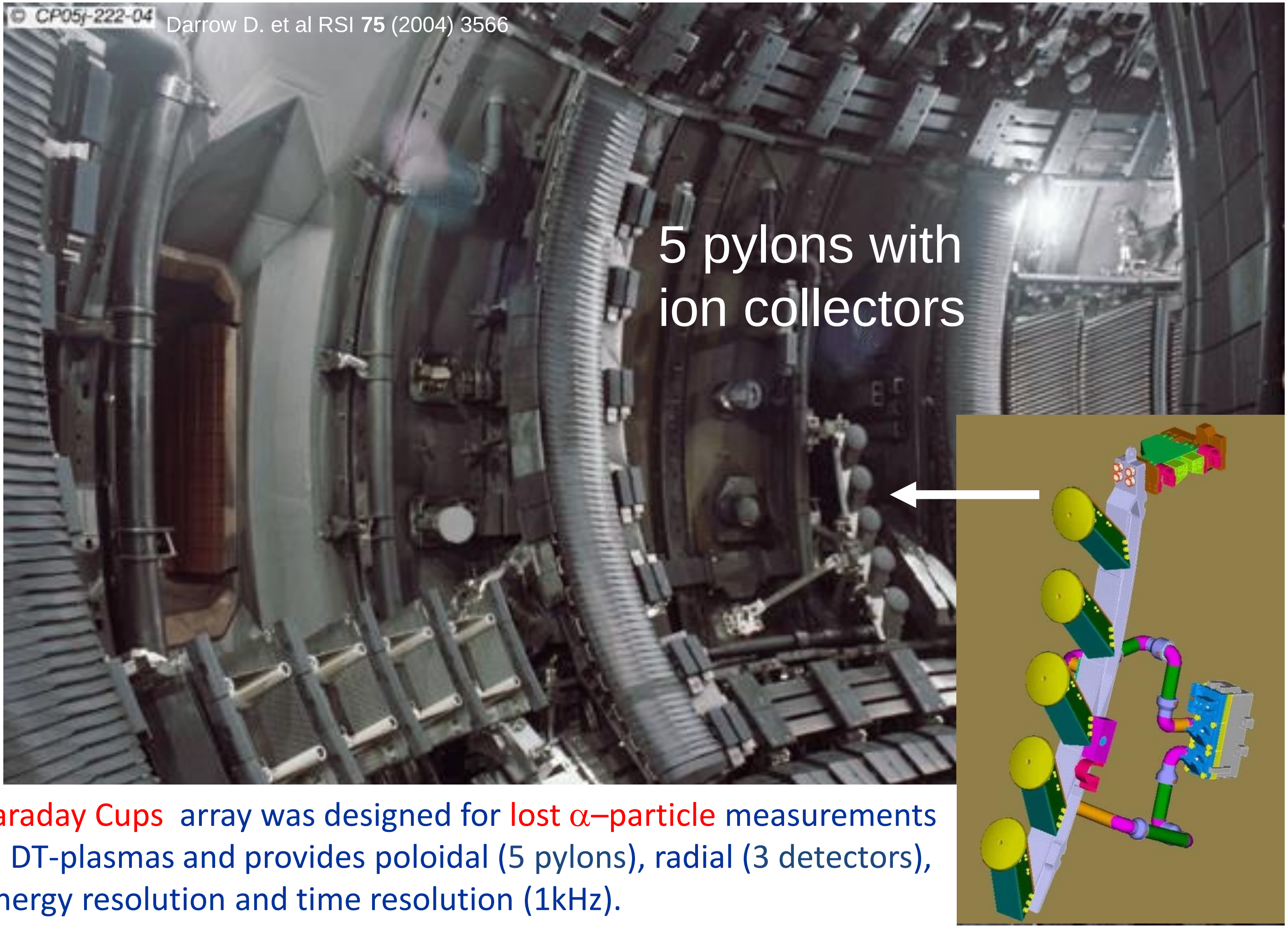
γ-emission from a thin Be-target recorded on accelerator



Kiptily Fusion Technology 18 (1990) 583
Kiptily et al. RSI 74 (2003) 1753

Escaped alpha-particles

JET Faraday Cups

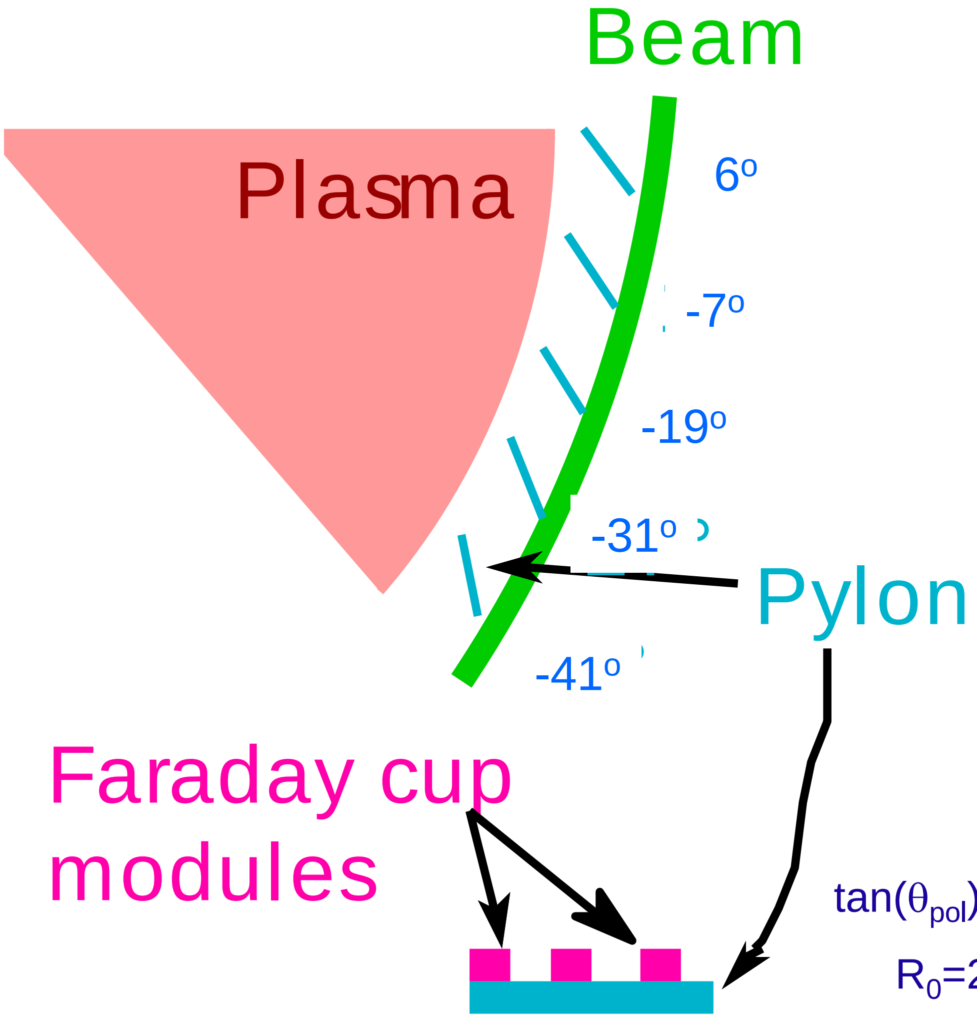


Darrow D. et al RSI **75** (2004) 3566

5 pylons with ion collectors

Faraday Cups array was designed for lost α–particle measurements in DT-plasmas and provides poloidal (5 pylons), radial (3 detectors), energy resolution and time resolution (1kHz).

JET Faraday Cups set-up

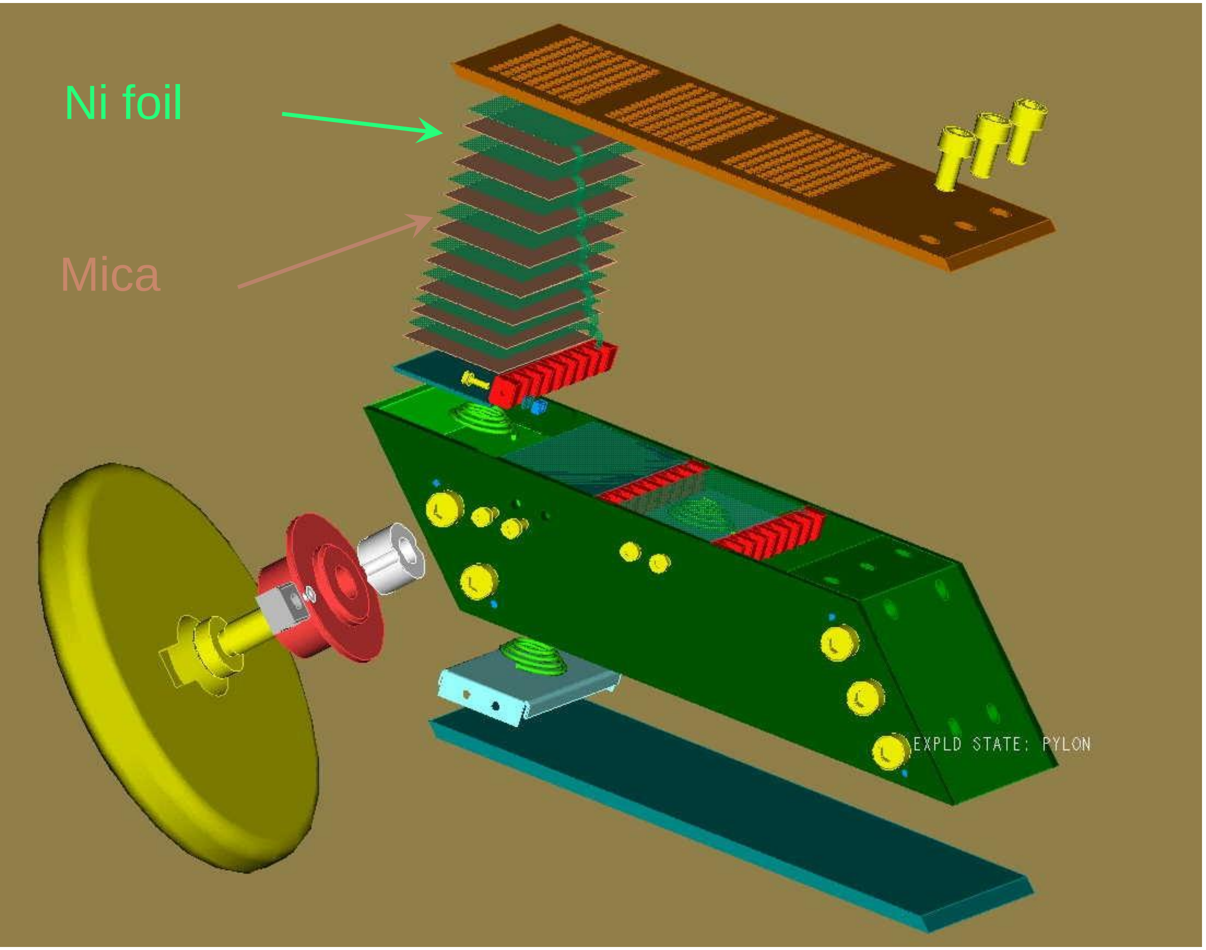


- Curved beam mounted on the vessel wall below mid-plane
- 5 “Pylons” mounted on the beam – poloidal resolution
- Each pylon contains up to 3 Faraday Cup modules – radial resolution
- But, no pitch angle resolution

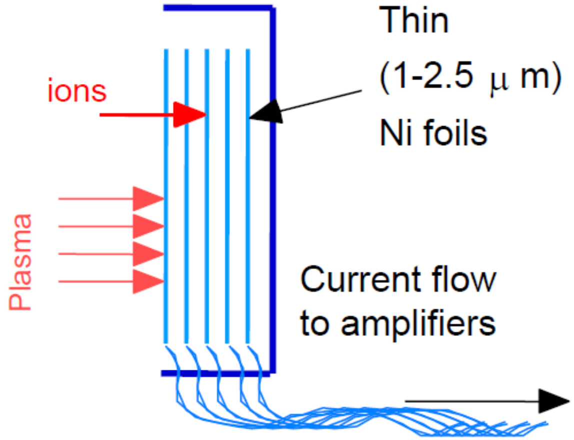
$\tan(\theta_{pol})=(Z-Z_0)/(R-R_0)$

$R_0=2.96\text{m}, Z_0=0$

JET Faraday Cups detectors

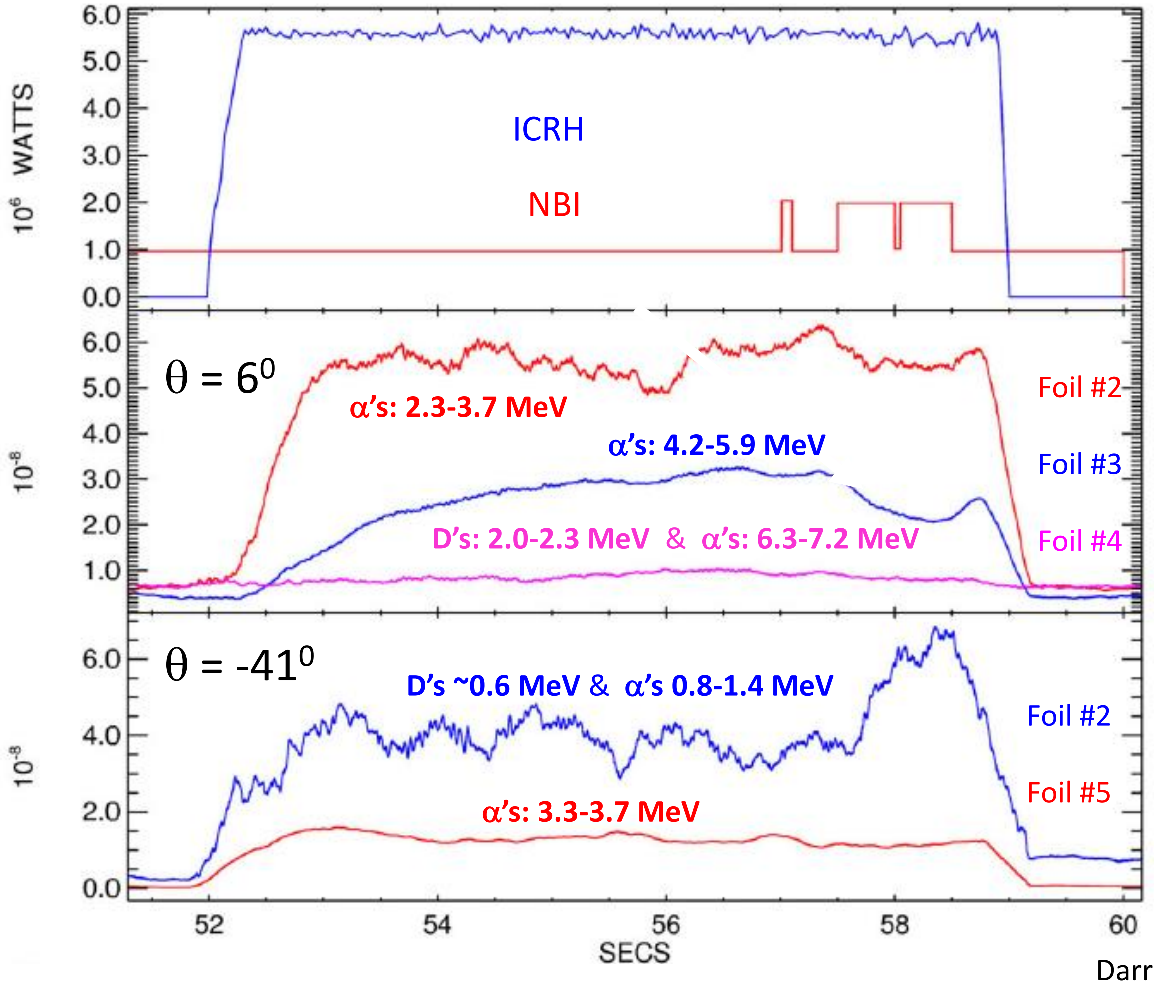


- Stack of alternating Ni foils and mica insulating sheets
- Terminal block
- Perforated cover to admit ions
- Ion current measured for each foil individually
- Ion energy determines deposition depth
- Current vs. depth gives energy distribution (dE~10–50%)



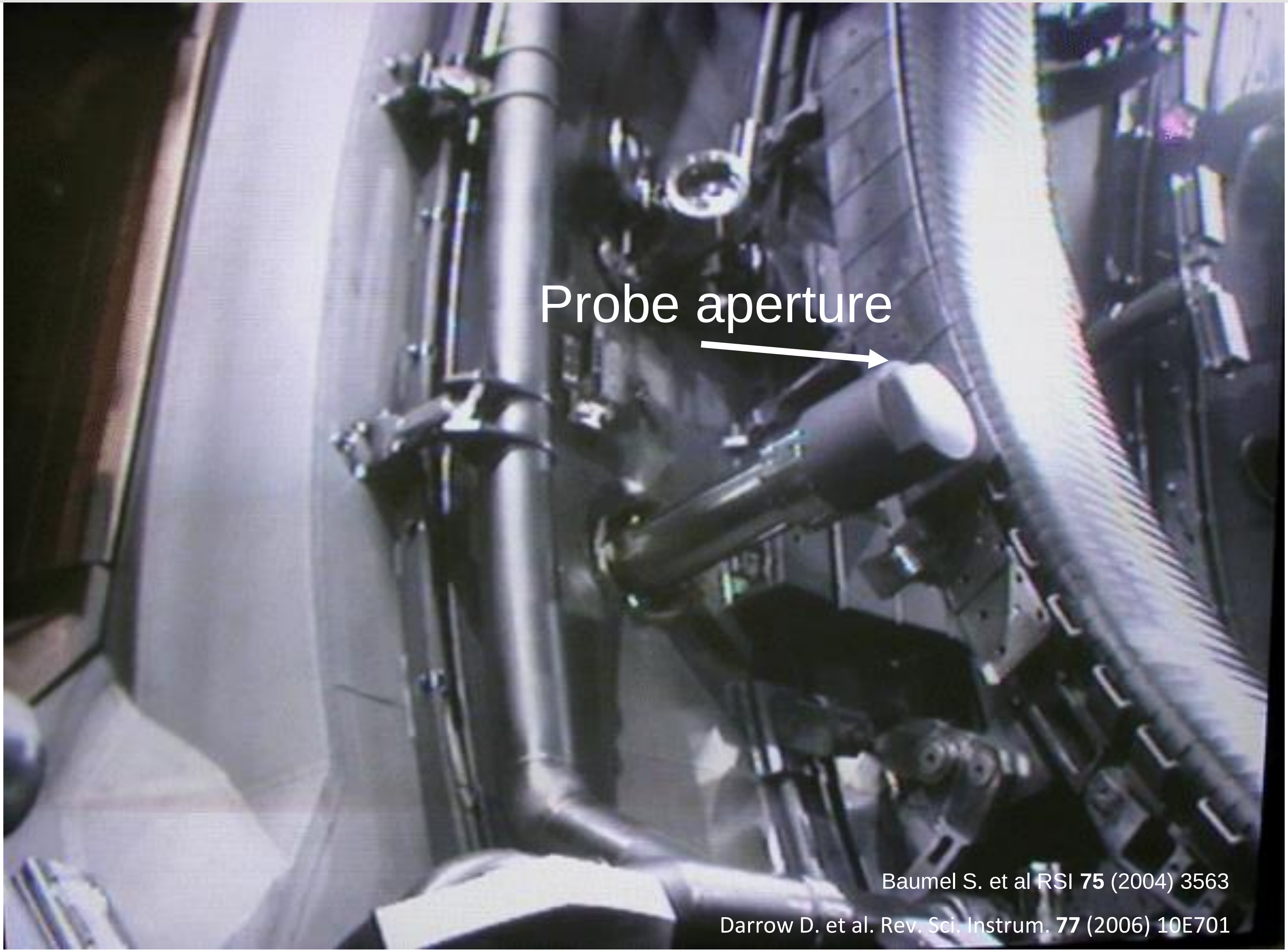
JET α-particle measurements in ^{4}He-plasma

^{4}He-beam ion accelerated with ICRF (JET, 2009)



Darrow D et al RSI **81** (2010) 10D330

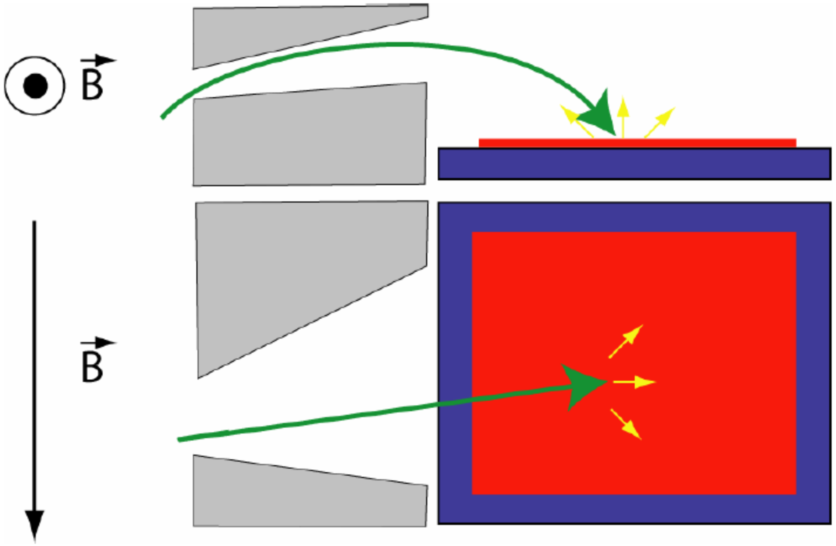
Scintillator Probe in JET vessel



Baumel S. et al RSI **75** (2004) 3563

Darrow D. et al. Rev. Sci. Instrum. **77** (2006) 10E701

Scintillator Probe: basic principals



- Gyromotion of fast ions
- Particle selection by slits
- Light emission by scintillator

Gyro-radius: $$\rho \propto \frac{mV_{\perp}}{ZB}$$

Pitch-angle: $$\theta = \cos^{-1}\frac{V_{II}}{V}$$

Species:	ρ(B=3T)
α(3.5 MeV)	9.0 cm
P(3.0 MeV)	8.3 cm
T(1.0 MeV)	8.3 cm
^{3}He(0.82 MeV)	3.8 cm

JET Scintillator Probe set-up

Scintillator: TG-Green, 0.5 μs decay

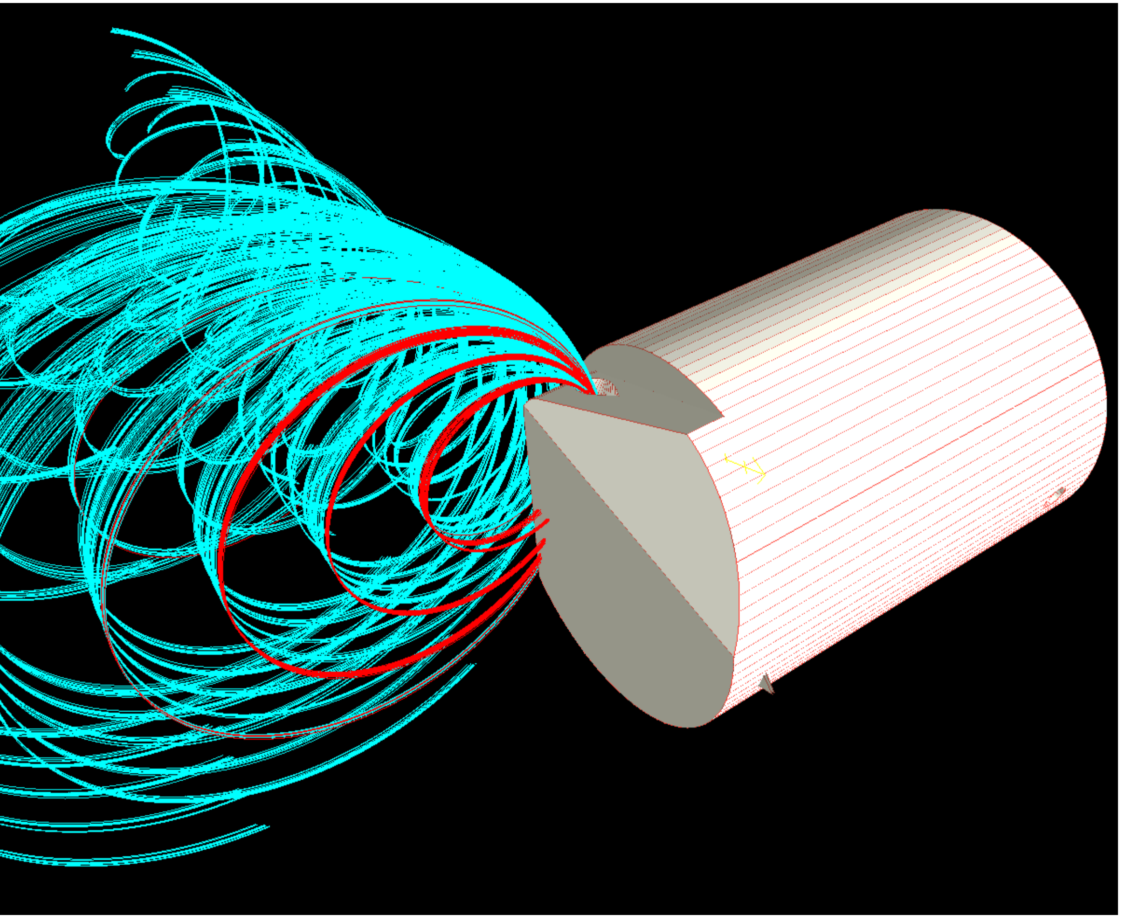
CCD camera: 128x256 pixels, 20 kHz

Fast PMT: 4x4 array (ADC 200 kHz or 2 MHz)

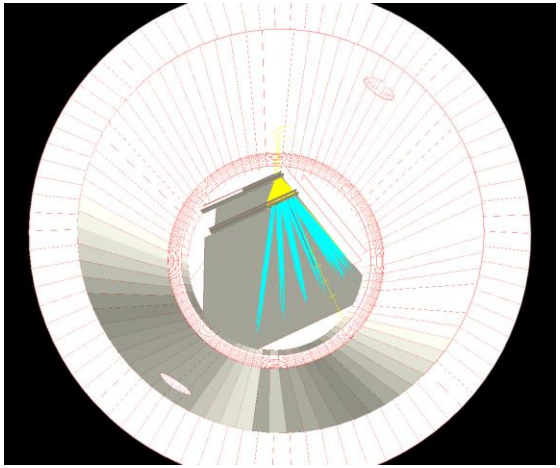
Notes :

Electrically-heated hose (up to 200^0) for fibre optic bundle will be installed before DT campaign. It will not be degraded by nuclear irradiation up to a total dose of 10^8 rad

Scintillator Probe: ion orbits simulation



View along tube axis



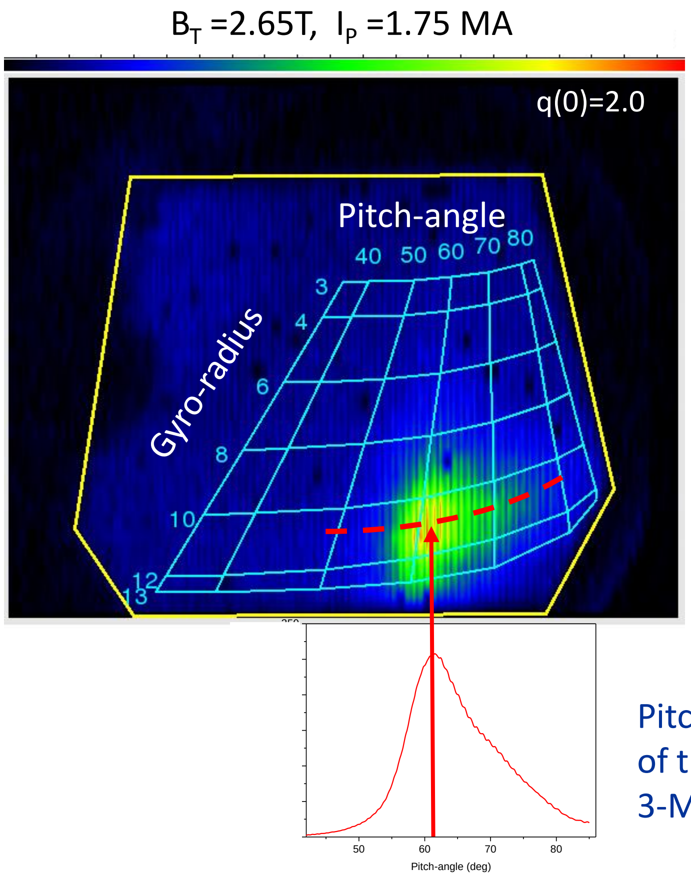
SP detects ions with

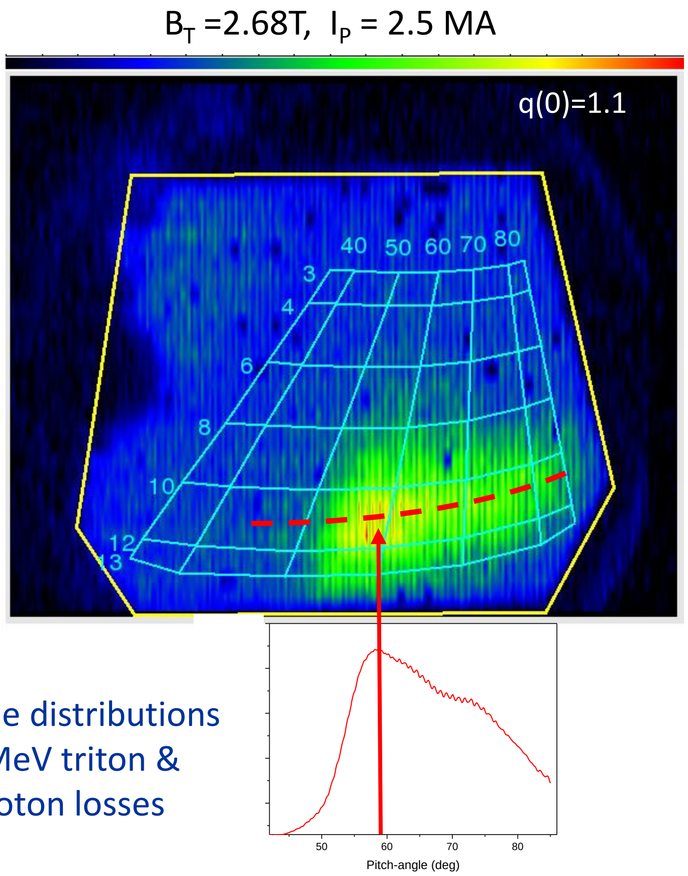
gyro-radius from *3 cm* to *14 cm*

pitch-angle from *35^0 to 85^0*

JET Scintillator Probe data

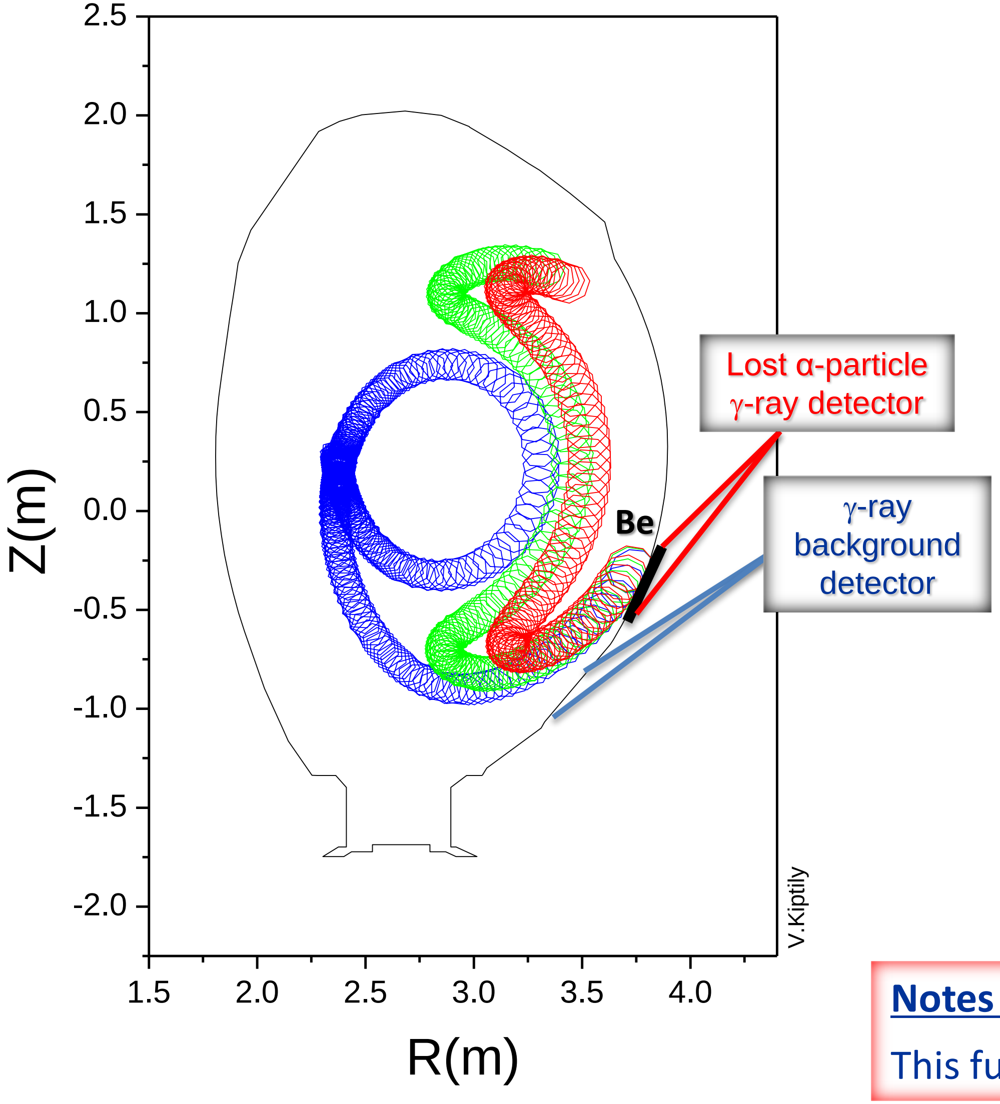
Footprints of the lost 1-MeV tritons and 3-MeV protons at different q(0)


B_T =2.65T, I_P =1.75 MA


B_T =2.68T, I_P = 2.5 MA

Pitch-angle distributions of the 1-MeV triton & 3-MeV proton losses

Novel technique: Lost Alphas γ-ray Monitor



- Escaped alphas strike a thick **Be-target**
- **Be-target** is placed in the field of view of a gamma-detector, avoiding plasma observation
- Measurements of gammas from the $^{9}\text{Be}(\alpha,n\gamma)^{12}\text{C}$ reaction
  - α-particles with $E_\alpha > 1.7$ MeV give rise to γ4.44-MeV;
  - α-particles with $E_\alpha > 4$ MeV give rise to γ3.21-MeV & γ4.44-MeV
- A separate detector for background measurements is needed

Kiptily et al Fusion Technology 22 (1992) 454

Notes :

This fusion alpha loss diagnostic is under R&D

Summary

- An overview of JET fusion alpha-particle diagnostics with examples of recent experimental results has been presented
- During the period 2015 – 2017, several diagnostics will be upgraded in the preparation of the DT operation
- Presented set of diagnostics will play important role for the fast alpha-particle studies in DT-experiments
- Some of these diagnostics could be used in future DT-reactors ITER and DEMO

JET, operating with DT plasmas, will provide the opportunity to obtain full information on the feasibility and capability of the developed alpha-particle diagnostics for future experiments on ITER