Acknowledgements

JET Neutron, Gamma & Particle Diagnostics

D.B. Syme¹, S. Popovichev¹, V. Kiptily¹, L. Giacomelli², S. Conroy³, P. Beaumont¹,
M. Santala⁴, G. Ericsson³, M. Weiszflog³, A. Hjalmarsson³, C. Hellesen³,
H. Henriksson³, G. Gorini², M. Tardocchi², R. Pereira⁵, A Fernandez⁵, M. Riva⁶, F. Belli⁶
and JET EFDA contributors*

¹brian.syme@ccfe.ac.uk, sergey.popovichev@ccfe.ac.uk
JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK

¹EURATOM-CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
²EURATOM-CNR Fusion Association, Istituto di Fisica del Plasma "Piero Caldirola", CNR, Milano, Italy
³EURATOM-VR Fusion Association, Department of Physics and Astronomy, Uppsala, Sweden
⁴EURATOM-Tekes Fusion Association, VTT Technical Research Centre, P.O. Box 1000, FI-02044 VTT, Finland
⁵EURATOM-IST Fusion Association, Instituto de Plasmas e Fusão Nuclear / IST
Av. Rovisco Pais, 1049-001 Lisboa Portugal
⁶Associazione EURATOM-ENEA sulla Fusione, C.P. 65, Frascati I-00044, Roma (Italy)

* See the Appendix of F. Romanelli et al, Proceedings of the 24th IAEA Fusion Energy
Conference 2012, San Diego, USA.
**Fusion power** has the potential to provide energy in the future in a sustainable way – reactions between hydrogen ions

- $^2\text{D} + ^2\text{D} \rightarrow ^3\text{He} (0.82 \text{ MeV}) + \text{n} (2.45 \text{ MeV})$ 50%
- $^2\text{D} + ^3\text{T} \rightarrow ^4\text{He} (3.5 \text{ MeV}) + \text{n} (14.1 \text{ MeV})$ 50%
- $^2\text{D} + ^3\text{He} \rightarrow ^4\text{He} (3.6 \text{ MeV}) + \text{p} (14.7 \text{ MeV})$
- $^3\text{T} + ^3\text{T} \rightarrow ^4\text{He} + 2\text{n} <11.3 \text{ MeV}>

D-T is favoured: - Best yield at lowest temperature (ion energy)

Need *containment* at high temperature and density
- In the Sun – Gravitational containment
- On Earth – Magnetic containment
- ‘Tokamaks’ like JET are now favoured

- **Maximise Fusion Product = ni.Ti.e**

**Arising points for Diagnostics**
- Neutrons measure the fusion yield – directly
- Same number of p, $^3\text{T}$ ions as n in a D,D plasma
- There are $^3\text{T}$ ions + 14 MeV neutrons, even in D,D plasmas
  - From Triton ‘burnup’
  - And tritium adsorbed in the walls
The present world leading machine is

**JET** (Joint European Torus), A European project, operated by Euratom

16 MW peak D-T fusion power and closest approach to break-even (Q~1) [1997]

Flexible machine with 25 years operation,

JET machine parameters and plasma conditions are nearest to those of the next step = ITER (now in build)

<NBI, ICRH & LH heating types, Be, Tritium facilities >
Neutron Diagnostics

Reactions in D-D and D-T research and power devices produce neutrons:

\[
\begin{align*}
2^D + 2^D & \rightarrow 3^He + n \quad 3.27 \text{ MeV} \\
\text{[} & \rightarrow 3^T + p \quad 4.03 \text{ MeV} \]\n
\begin{align*}
2^D + 3^T & \rightarrow 4^He + n \quad 17.6 \text{ MeV}
\end{align*}
\]

At a laboratory scale: neutrons are a diagnostic tool used for measurement of plasma parameters

<table>
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<tr>
<th>Technique</th>
<th>Apparatus</th>
<th>Measurement</th>
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<td>Elemental foils irradiation probes</td>
<td>(Y_n \text{ Yield} ) (N \text{ spectrum} )</td>
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<td>Neutron (rate) monitoring</td>
<td>Fission chambers, diodes, diamonds</td>
<td>(Y_n \text{ yield (t)} )</td>
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<td>Scintillators</td>
<td>(Y_n \text{ yield (t)} ) (n_{ion} \text{ profile} )</td>
</tr>
<tr>
<td>Spectrometry</td>
<td>eg Time-of-flight, Magnetic proton recoil &amp; CNS types</td>
<td>(N \text{ spectrum (t)} ) (T_{ion} \text{ (t)} )</td>
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</tbody>
</table>
Neutron Diagnostics measurements:
- Time resolved neutron yield
- Time integrated absolute neutron yield
- Radial profile of the neutron emission
- Neutron energy spectra.

+ recently a range of Fast Ion Diagnostics
- Fast ion loss detectors (FILD)
- Fusion gamma diagnostics
- Alfven Eigenmodes Antennas
- Neutral Particle Analysers

Measurement Challenges
- 10 s pulses/20 mins, N-yield range: $10^8$ - $10^{20}$
- Extended N source (Toroidal, R~3m, H~1-2m)
- Magnetic Fields, EM interference, Mechanical Vibrations
- High N, X & Gamma-ray backgrounds
- Radiation Damage levels, Restricted access
- [D,T equipment to be remotely handled]

Complementary Techniques are always required
[Different views, shielding, responses, sensitivities, +/-'s]
Time-resolved Total Neutron Yield Monitor
(2.45 MeV plus 14 MeV both included)

3 pairs of **fission chambers** - U\(^{235}\) & U\(^{238}\)
- Located around JET (on the limbs in Oct. 2, 8 and 6).
- Wide Range of neutron yields: \(10^{10}\) to \(10^{20}\) n/s
- Electronics: (All analogue)
  - HV, preamps, log amps, high linearity
- Absolutely calibrated to <10%, periodic verification

Time-resolved 14 MeV Neutron Yield Monitor

- Threshold \((n,p)\) and \((n,a)\) reactions in Si diodes & Diamonds
- Range: \(10^{13}\) - \(10^{18}\) n/s
JET Neutron Yield Monitors - Activation

JET Octant 3 Cross-section

(Octant 3 Upper) Irradiation End – I.E

JET Mechanical Support Structure

Vaccum Vessel (Double-walled)

Iter-Like Wall (Plasma-facing)

JET Activation System

- **8 Irradiation ends** located in 5 octants:

- **Capsules** containing sample foils are delivered and retrieved pneumatically

- **Conventional gamma-radiation measurements**
  Range: $10^{14}$ to $>10^{20}$ n/s
  most widely used reactions at JET:
  - **DD** - $^{115}$In(n,n')$^{115m}$In
  - **DT** - $^{28}$Si(n,p)$^{28}$Al, $^{63}$Cu(n,2n)$^{62}$Cu, $^{56}$Fe(n,p)$^{56}$Mn
  detectors: 3 NaI, HpGe (absolutely calibrated)

- **Counting of delayed neutrons** - Range $10^{14}$ to $>10^{20}$ n/s
  After N, fission reactions in ($^{235}$U, $^{238}$U, $^{232}$Th) foils
  Gives DD neutron yield, when $Y(DD)>> Y(DT)$
  detector system: 2 stations with six $^3$He counters

- **Accuracy typically ~ 8-10%**
  for both DD and DT neutron yields
  delayed neutron measurements can give 7%
Neutron Yield Monitors - Data

Typical time dependence of 7 sec pulse

Calibration of Fission Chamber vs Activation system

JET Neutron Yield per day (1984-2010)

Blue = Total Yield,
Red = D,T Yield
Need absolute measure of fusion rate

Need Absolute Calibration of Neutron Emission versus a calibrated neutron source in the torus, eg 252-Cf

- Last done in 1985-9, for the Fission Chambers only,
  <All-metal JET. No Divertor, Plasma Centre was lower by 30 cm.>
- Calibration extended by a succession of calculations, since then

1985/9 Method:

Pull a strong calibrated neutron source round the torus in a tube.

Observe response from external Fission Chambers per source neutron => calibration

How it has been set up in 1985/9
The JET Experiment - Changing since 1983

JET 1985

JET 1991

March 2010 - During Shutdown

Inside JET 1985

Inside JET 1994

2011 JET ITER-Like Wall

D. B. Syme et al, EIROForum May 2013
R-H Deployment Environment

Safe source storage
- TCTF Tent
- Operational Shield
- Auxiliary Shield In ISO container

Source loading & deployment
- Transport Flask In Loading Bay
- Oct5 Boom Tent
- Mascot

Contingency Provisions
- Normal Operations

11 m Port to Port
Direct calibration of JET neutron monitors, versus a standard 252Cf source in-torus

Deployment plan on right

Improves old JET calibration

Precursor to JET D,T Calibrations

Addresses many questions relevant to ITER Calibrations

eg Corrections for –

Non symmetric sources

Scattering effects, eg source holder & support structure

Point vs 3D calibrations

Torus practicalities

JET Neutron Source Calibration - 2013

a) 40 steps round vessel in plasma centre locations
b) 1 set of radial & vertical scans at a port
c) Scan under Irradiation End – First direct calibration
d) Basket scan: 40 steps x 5 rings round vessel - with +/- 50 cm in Z, R
e) Direct Comparison of Activation and Fission Chamber methods for 252Cf
Progressive reduction of Raw FC neutrons observed per JET neutron as JET ports regions became congested and Limiters were added.

Note: No information from this on the effect of recent torus inner wall changes, as there was no neutron calibration in the earlier ‘carbon wall’ period.
Two cameras:
Vertical: 9 lines-of-sight
Horizontal: 10 lines-of-sight
Fan-shaped array of remotely adjustable collimator with two apertures.
Space resolution: \(\sim 8\) (or \(\sim 15\)) cm (in the centre)

Detectors:
- NE213 liquid scintillators (2.5 and 14 MeV) + PSD
- Plastic Bicron418 scintillators (14 MeV)
- CsI(Tl) photodiodes (Hard X rays and \(g\) emission \(0.2 < E_g < 6\) MeV).

DAQ: Recently converted from analog to digital

Neutron detectors are absolutely calibrated
Covers both DD and DT regimes of operation
Plasma coverage allows 2D pseudo - tomography

KN3 Basic Data –
Neutron Yield Profile as Line Emission Profiles
See variations in position and peaking of the neutron emission (profile of fusion ‘burn’)

Data can be -
- Used as: plasma N emission profile vs time
- Compared with: models of plasma emissivity, fast ion distributions, etc.
- Converted to: pseudo-tomographic images

Vertical camera has demonstrated asymmetries in the neutron emission profiles for some experiments
- large orbit trapped ions can produce neutrons

Profile Monitor - Recent Results - Digital DAQ

#82723 (NBI = 21 MW), KN3N

Raw Data, not yet corrected for variations in detector efficiency, etc
Digital DAQ by ENEA association
Spectrometry Principles for Neutrons

Measurement of neutron energy - by transfer of momentum/energy from neutron to recoil proton

a) Measurement of recoil proton momentum in dispersive magnetic spectrometer (MPR)

b) Timing of recoil neutron (TOF) from scattering detector to 2nd detector (TOFOR)

b’) Direct measurement of recoil proton energy from thin foil - in SSD detector (not shown)

c) Proton absorption by scintillator - proportional conversion to light, then to an electronic signal, amplification & DAQ processes - ‘compact neutron spectrometer’

Fig. Giacommeli et al, Nucl. Fusion 45 (2005)
**D,D Neutrons - Time of Flight Spectrometer - <TOFOR>**

Vertical Line of sight

Sited in Roof Laboratory above Oct 8

Range: $10^{14}$-$10^{17}$ n/s

*Diagnostics by VR association (Sweden)*
D,T (D,D) neutrons - Magnetic Proton Recoil spectrometer <MPRu>

Horizontal - Tangential LoS,
Looking from Oct 4 to Oct 7
Sited in a Separate Shield in the Torus Hall

Plasma self-heated thermal peak (top)
- Peak width – ion temperature
ICRF-Heated D,T Plasma (bottom)
- Broadened Thermal peak - Ion Temperature
- and High Energy Neutrons

Diagnostics by VR association (Sweden)
Compact Neutron Spectrometer - <CNS>
For D,D & D,T Neutrons

Horizontal - Tangential LoS,
Looking from Oct 7 to Oct 2
Sited in Bunker Outside Torus Hall

Range: $10^{14}$-$10^{17}$ n/s
Ne213 Spectrometer (left) and Stilbene Scintillators, sharing an annular neutron field in a JET bunker.

The NE213 response function was measured at PTB, in an ENEA project.

NE213 scintillator detector (BC501A) with a 207Bi γ source for long term stability monitoring & LED for short-time PM gain corrections.

Digital DAQ for PSD, Pulse Height analysis, and event time stamping.
Simultaneous Energy Spectra (ex Pulse Height Distributions)
From 2.5 MeV Neutrons (D,D)
And 14 MeV neutrons (D,T)

Unfolded broad NBI-induced neutron energy spectrum (D,D)
## Summary: Current JET Neutron Diagnostics Systems

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<th>JET Detection</th>
<th>Capabilities</th>
<th>Neutron range</th>
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<td>Time-resolved total emission</td>
<td>All En: fission counters</td>
<td>dYn/dt: Wide range, fast response, Redundancy, MHD, T Burnup, n_D/n_E</td>
<td>10^{10} to 10^{20} n/s</td>
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<tr>
<td>(rate)</td>
<td>14 MeV: Si diodes, CVD</td>
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<tr>
<td>Time-integrated emission</td>
<td>Foil activation &amp; count Gamma or neutron</td>
<td>Absolute N yields, Yield Calibration in D,D &amp; D,T</td>
<td>10^{14} to &gt;10^{20} n/s</td>
</tr>
<tr>
<td>N Profile Monitor (2D-cameras)</td>
<td>Liquid scintillators NE213 Plastic scintillators BC418 CSI Scintillators for Gamma-Camera</td>
<td>dYn/dt(R, Z), Total N yield, N Emission Tomography, n_D/n_E, T Burnup, Fast particle confinement</td>
<td>10^{15} to &gt;10^{17} n/s</td>
</tr>
<tr>
<td>Spectrometers</td>
<td>TOFOR (VR) NE213 (and Stilbene) Magnetic proton recoil (VR)</td>
<td>Neutron emission Spectra, Ion Temperature (Ohmic), NBI - Thermal &amp; Beam-plasma yields, Hot ions in ICRH heating, n_D/n_E in D,D - or n_fuel/n_e in D,T</td>
<td>10^{14} to &gt;10^{17} n/s</td>
</tr>
</tbody>
</table>
Fast ions occur in the plasma from:

- fusion products: p (3 & 15 MeV), T (1 MeV), $^3$He (0.8 MeV), $\alpha$ (3.5 MeV)
- ICRH-accelerated [Fuel and product] ions: H, D, T, $^3$He, $^4$He

$\gamma$-ray emission is produced by fast ion nuclear reactions with bulk ions and impurities in the plasma (mainly C, Be)

Gamma-ray ‘fingerprint’ identifies fast ions $>$ key energies, eg:

- $\alpha$-particle diagnosis at JET is based on the $^9$Be($\alpha,n\gamma$)$^{12}$C reaction
- Fast deuteron detection in the old JET was based on the $^{12}$C(d,p$\gamma$)$^{13}$C reaction - now Be reactions, mainly Be(d,n$\gamma$) and Be(d,p$\gamma$)

NaI & BGO detectors previously used, (plus CsI in the profile monitor)

Recent additions: LaBr$_3$ & HpGe
γ-ray spectrometers - Lines of Sight

Original Capabilities: (Analog DAQ)

**NaI(Tl):** energy resolution, $\Delta E/E \approx 8%$
Slow: decay time $\sim 250 \text{ ns}$
Recent RF DAQ system allows up to 1 MHz Pulse Height Analysis

**BGO:** energy resolution, $\Delta E/E \approx 12%$
Best detection efficiency!
Slow: decay time $\sim 300 \text{ ns} \Rightarrow 1 \text{MHz PHA}$

Recent Upgrades: CNR & IST led

- **HpGe:** $\Delta E/E \approx 0.1\%$, DAQ to 1 MHz
  Neutron Sensitive → specific tasks

- **LaBr$_3$** (or BrilLanCe): $\Delta E/E \approx 3\%$
  Decay times $\leq 20 \text{ ns}$
  DAQ allows up to 2 MHz PHA

- **Quasi-tangential BGO-spectrometer:**
  front and rear collimators to improve S/B ratio

- **Gamma Camera:** 19 LoS indicated:
  Energy Windows, now Spectrometers

- **DAQ:** Upgraded from Analog - Digital

BGO, NaI(Tl), LaBr$_3$, HpGe

a link to results with carbon wall

The image contains a diagram of BGO, NaI(Tl), LaBr$_3$, and HpGe spectrometers. The original capabilities are highlighted, featuring NaI(Tl) with an energy resolution of $\Delta E/E \approx 8\%$ and a decay time of $\sim 250 \text{ ns}$. The BGO spectrometer has a better detection efficiency with $\Delta E/E \approx 12\%$, and its decay time is $\sim 300 \text{ ns}$, allowing up to 1 MHz Pulse Height Analysis. Recent upgrades include HpGe with $\Delta E/E \approx 0.1\%$ and DAQ to 1 MHz, LaBr$_3$ (or BrilLanCe) with $\Delta E/E \approx 3\%$, and decay times of $\leq 20 \text{ ns}$, allowing up to 2 MHz PHA. The quasi-tangential BGO-spectrometer uses front and rear collimators to improve the S/B ratio. Additionally, the Gamma Camera indicates 19 LoS with energy windows now as spectrometers, and the DAQ has been upgraded from analog to digital.
3 Detectors and 2 neutron filters on sliders - Choose 1 & switch into the N/G beam

BGO or LaBr3 above $^6$LiH Filter in 2nd vertical path (not shown)
3rd IC harmonic $^4$He-beam ion acceleration experiments

Kiptily V.G. et al 2002 Nucl. Fusion 42 999


Gamma-ray spectra measured by the NaI(Tl) detector: red line - spectrum recorded in discharge with 70 and 110 keV $^4$He-beam injectors; blue line - spectrum recorded in a discharge with two 70 keV $^4$He-beam injectors.

Tomographic reconstructions of 4.44 MeV $\gamma$ -ray emission from the reaction $^9$Be($^4$He, $n\gamma$)$^{12}$C and 3.09 MeV $\gamma$ -ray emission from the reaction $^{12}$C(D, p$\gamma$)$^{13}$C deduced from simultaneously measured profiles.
**γ-ray emission profile from Gamma Camera**

(From spectroscopic data obtained with the new digital DAQ)

Be-profile is needed to obtain the spatial distribution of energetic ions

Digital DAQ by IST Association

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D. B. Syme et al, EIROForum May 2013
**4He-acceleration experiments**

4He-beam ions was accelerated by ICRF in the 4He-plasma

The Doppler broadening due to nuclear reactions between 4He and Be impurity has been measured for assessment of effective “temperature” $<T_{4He}>$:

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

$V_R$ – recoil velocity which is depend on the 4He-ion velocity

Kiptily et al NF 50 (2010) 084001
$\gamma$-ray spectrum from HpGe-detector: fast a-particle beam

$E^* = 6 \text{ MeV}$

$E_\alpha = 3 \text{ MeV}$

Shape does change with $E^*$

Limited by statistics

$K_p$ in agreement with values found from analysis of peaks from $^{12}\text{C}(d,p\gamma)^{13}\text{C}$

M. Tardocchi et al, proceeding of EPS conference, Dublin, June 2010
M. Nocente et al, Nuclear Fusion 52 (2012)022001

D. B. Syme et al, EIROForum May 2013
Fast Ion Loss Detectors (1) Faraday Cups

Multifoil Faraday Cups with energy resolution for lost alphas at 5 poloidal positions (promising 4He results)

USA (PPPL, CSM), JOC

Darrow et al. RSJ 77 (2006) 10E70
Faraday Cups array provides good poloidal and time resolution

- Time resolution: 1 kHz
- Multiple poloidal positions (5)
- Multiple radial locations (max 3)
- BUT, no pitch angle resolution

Also

Moderate Energy Resolution (max 8 bins)

- Detector composed of multiple thin metal foils separated by mica foils
- Ion energy determines deposition depth
- Ion current measured for each foil individually
- Current vs depth gives energy distribution ($\Delta E \approx 30\% - 50\%$)
Fast Ion Loss Detectors (2) Scintillator Probe

Location: Octant 4 lower limiter guide tube

USA (PPPL, CSM), JOC
Ion selection is defined by slit-geometry and field
- energy range selection
- pitch-angle range selection

Particle energy is linked to gyroradius of fast ions:

\[ r \propto \sqrt{mE_{\perp}} / B_T Z \]

Observation of lost ions:
- particles hit surface of the scintillating material
- light emission allows
- to use fast CCD and PMT detectors
- 20 kHz camera, 5 kHz P.M.

Scintillator probe provides 2D lost-ion images (pitch-angle & gyroradius)

Entrance aperture: 1-µ Au foil stops low energy ions
H, D < 150 keV; He < 250 keV
Scintillator Probe (2) – Main project activities

- General probe design / physics
- Probe shaft / structural analysis
- Heat protection / CFC cup and cooling
- Beam ion suppression by thin foil
- Optic design
- Software / interface to CODAS / PPF
DD tritons & protons: first orbit loss measurements
D\(^0\) and T\(^0\) distributions

Low-energy NPA measures simultaneously the energy distribution function of neutral H, D and T in the energy range 5 – 740 keV.

- D / T ratio measurements in the plasma core
- ICRH heating efficiency
High-Energy NPA measures the energy distribution function of neutral H, D, T, $^3$He and $^4$He in the energy range 0.3 – 4 MeV.

Si-detectors now installed for better distinguishing D and α’s!
How NPA works

- Neutralisation in plasma
- Ionisation by carbon foil (~30 nm)
- Acceleration (horizontal)
- Momentum-energy separation (B, E)
- Detection (in 2D array of CsI or Si)
- Data acquisition

$E$ deflection is used to select the particle

Diagram shows:
- C foil
- HV
- JET
- Atoms
- CsI(Tl) scintillator + PMT detectors
Overview of recent NPA upgrade

Detectors

UHV Flange

Preamplifiers

16 pair cable

thin thick

J1T CODAS

PPF

Chain1

After pulse

1.5 GB

BAD2

16 pair cable
Raw Data from the NPA Si detectors

Vertical: Energy,  Horizontal: Time through JET pulse (3 conditions)

Bottom 2 Plots are Power in the pulse (NBI & ICRH) and Neutron output
### Summary: Current JET Fast Ion Diagnostics Systems

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<td>Faraday cups</td>
<td>Fast Ion losses: fast response, low E resn,</td>
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<td>particle analysers</td>
<td>Multifoils, 5 Poloidal angles</td>
<td>&gt;300/850 keV, H,D/He</td>
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<tr>
<td>Scintillator Probe</td>
<td>TG-Green, CCD &amp; PM arrays</td>
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<td><strong>Fast Ion losses:</strong></td>
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<tr>
<td>vs E range &amp; pitch angle</td>
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<tr>
<td>&gt;300/850 keV, H,D/He</td>
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<td>Fluxes of neutrals by:</td>
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<tr>
<td>particle analysers</td>
<td>NPAs: C, ExB, CsI</td>
<td>Energy, Species</td>
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<td>**Fast Ion energy</td>
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<tr>
<td>distribution:**</td>
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<td>(NBI and ICRH heating)</td>
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<tr>
<td>&gt;50/900/1700 keV for H,D/3He/4He</td>
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<td>**Fast Ion spatial</td>
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