ITER DIAGNOSTICS

Compiled from material provided by T. Donné, Ch. Ingesson, A. Costley and many others, especially ITPA Diagnostics TG members
Content

- ITER parameters
- Diagnostics requirements
- Boundary conditions for diagnostics
- Specific problems
- Outstanding issues

Main systems:

- Magnetics (presented by JBL)
- Laser-aided systems
- Spectroscopy
- Radiated power
- Microwave systems
- Diagnostics for PWI
- Neutrons diagnostics
- Gamma ray diagnostics
- Lost alphas

Please note that this is only a very superficial overview, not all necessary systems can be presented. The amount of work going on for ITER diagnostics is phenomenal, see ITPA Diagnostics Topical group presentations: [www.rijnh.nl/ITPA](http://www.rijnh.nl/ITPA). Ask me for username and password (CRPP members only).
ITER objectives
(i) extended burn in inductively driven plasmas with $Q = \frac{P_{\text{fus}}}{P_{\text{heat}}} \geq 10$
(ii) steady-state operation using non-inductive current drive $Q \geq 5$
(iii) integration and tests of fusion technologies and reactor components

ITER operational parameters (1)
### Operational stages after construction

<table>
<thead>
<tr>
<th>Mile Stone</th>
<th>1st yr</th>
<th>2nd yr</th>
<th>3rd yr</th>
<th>4th yr</th>
<th>5th yr</th>
<th>6th yr</th>
<th>7th yr</th>
<th>8th yr</th>
<th>9th yr</th>
<th>10th yr</th>
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<tbody>
<tr>
<td>First Plasma</td>
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<tr>
<td>Full Field, Current &amp; H/CD Power</td>
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<td>Short DT Burn</td>
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<td>Q=10, 500 MW</td>
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<tr>
<td>Q=10, 500 MW, 400s</td>
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<tr>
<td>Full Non-inductive Current Drive</td>
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</table>

#### Operation

<table>
<thead>
<tr>
<th>Equivalent Burn Length (hr) with 500 MW</th>
<th>0.1</th>
<th>100</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence** (MWa/m2)</td>
<td>0.006</td>
<td>0.096</td>
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</table>

<table>
<thead>
<tr>
<th>Blanket Test</th>
<th>System checkout and Characterization</th>
<th>Initial Test</th>
<th>Performance Test</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Installation &amp; Commissioning</th>
<th>For activation phase</th>
<th>For high duty operation</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Installation &amp; Commissioning</td>
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</tbody>
</table>

*Average Fluence at First Wall (Neutron wall load is 0.56 MW/m² in average and 0.77 MW/m² at outboard midplane.*)
Several operating scenarios

Table 1. ITER parameters in inductive, hybrid and steady-state reg

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inductive</th>
<th>Hybrid</th>
<th>Steady-state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R/a$ (m/m)</td>
<td>6.2/2</td>
<td>6.2/2</td>
<td>6.35/1.85</td>
</tr>
<tr>
<td>Volume (m$^3$)</td>
<td>831</td>
<td>831</td>
<td>793</td>
</tr>
<tr>
<td>$B$ (T)</td>
<td>5.3</td>
<td>5.3</td>
<td>5.17</td>
</tr>
<tr>
<td>$I$ (MA)</td>
<td>15</td>
<td>13.8</td>
<td>9</td>
</tr>
<tr>
<td>$k_x/k_0$</td>
<td>1.85/1.7</td>
<td>1.85/1.7</td>
<td>2.0/1.84</td>
</tr>
<tr>
<td>$\delta_x/\delta_0$</td>
<td>0.48/0.33</td>
<td>0.48/0.33</td>
<td>0.5/0.4</td>
</tr>
<tr>
<td>$q_0/q_0/q_{\text{min}}$</td>
<td>3/1/1</td>
<td>3.3/1/1</td>
<td>5.2/3.4/2.4</td>
</tr>
<tr>
<td>$\rho_N$</td>
<td>1.8</td>
<td>1.9</td>
<td>2.56</td>
</tr>
<tr>
<td>$\langle n_e \rangle$ (10$^{20}$ m$^{-3}$)</td>
<td>1.01</td>
<td>0.93</td>
<td>0.67</td>
</tr>
<tr>
<td>$P_{\text{aux}}$ (MW)</td>
<td>40</td>
<td>73</td>
<td>68</td>
</tr>
<tr>
<td>$P_{\text{rad}}$ (MW)</td>
<td>47</td>
<td>55</td>
<td>38</td>
</tr>
<tr>
<td>$P_{\text{ fus}}$ (MW)</td>
<td>400</td>
<td>400</td>
<td>338</td>
</tr>
<tr>
<td>$P_{\text{net}}$ (MW)</td>
<td>87</td>
<td>114</td>
<td>110</td>
</tr>
<tr>
<td>$W_{\text{th}}/W_{\text{fast}}$ (MJ/MJ)</td>
<td>320/32</td>
<td></td>
<td>255/50</td>
</tr>
<tr>
<td>$Q$</td>
<td>10</td>
<td>5.4</td>
<td>5</td>
</tr>
<tr>
<td>$\tau_E$ (s)</td>
<td>3.66</td>
<td>2.73</td>
<td>2.32</td>
</tr>
<tr>
<td>$H_{\text{FP}}(\gamma,2)$</td>
<td>1</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>$Z_{\text{eff}}$</td>
<td>1.65</td>
<td>1.85</td>
<td>2.17</td>
</tr>
<tr>
<td>$\tau^*_\text{He}/\tau_E$</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$f_{\text{BS}}/f_{\text{CD}}$</td>
<td>0.16/0.08</td>
<td>0.25/0.17</td>
<td>0.48/0.52</td>
</tr>
<tr>
<td>Burn time (s)</td>
<td>400</td>
<td>1070</td>
<td>Steady-state</td>
</tr>
</tbody>
</table>

Inductive scenario: examples of transport modelling
-MMM ,-- empirical

by V.Mukhovatov et al, NF 43 (2003) 942

![Graph](image-url)
Diagnostics requirements

- **Machine control**
  - Discharge initiation, shape, stability, fuelling, MHD control, S-S scenarios...

- **Machine protection**
  - Disruptions
  - Erosion
  - Local overheating
  - Radiation

- **Physics**
ITPA Diagnostic topical group

Created 1998 as ‘ITER Physics Expert Group on Diagnostics’. Changed to ‘International Tokamak Physics Activities’ (ITPA) … in 2001

Voluntary effort in support of BPXs, specifically ITER

Contributors worldwide, currently 8 specialist working groups

Collaborate closely with ITER team

www.rijnh.nl/ITPA  ask T Donné (or H.Weisen @ CRPP) for user & password

CHARTER (loosely summarised):

• Identify diagnostics requirements for BPXs (together with other ITPA groups)
• Make recommendations for ITER diagnostic specifications
• Identify potentially suitable techniques for BPX diagnostics
• Identify R&D needs and propose relevant research programme
• Advise on selection of techniques, their design & implementation in ITER
Example: requirements for $T_e$

- distinguish between core, pedestal and divertor: several systems
- different scenarios may have different requirements

<table>
<thead>
<tr>
<th>Operating Scenario</th>
<th>Range</th>
<th>Requirements for $T_e$-measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>H phase. Inductive Limited ELMY H Mode</td>
<td>r/a ≤ 0.9</td>
<td>0.5-30 keV</td>
</tr>
<tr>
<td></td>
<td>r/a &gt; 0.9</td>
<td>0.05-10 keV</td>
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<tr>
<td></td>
<td></td>
<td>0.3-200 eV</td>
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<tr>
<td></td>
<td>Div</td>
<td>a/20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 cm</td>
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<tr>
<td></td>
<td></td>
<td>10 ms</td>
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<tr>
<td></td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>D/T phase. Inductive ELMY H Mode</td>
<td>r/a ≤ 0.9</td>
<td>0.5-30 keV</td>
</tr>
<tr>
<td></td>
<td>r/a &gt; 0.9</td>
<td>0.05-10 keV</td>
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<td></td>
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<td>0.3-200 eV</td>
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<tr>
<td></td>
<td>Div</td>
<td>a/20</td>
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<tr>
<td></td>
<td></td>
<td>1 cm</td>
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<td></td>
<td></td>
<td>10 ms</td>
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<td></td>
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<td>10%</td>
</tr>
<tr>
<td>D/T Phase. Inductive ELMY H mode. High $\beta$</td>
<td>r/a ≤ 0.9</td>
<td>0.5-30 keV</td>
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<tr>
<td></td>
<td>r/a &gt; 0.9</td>
<td>0.05-10 keV</td>
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<tr>
<td></td>
<td></td>
<td>0.3-200 eV</td>
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<tr>
<td></td>
<td>Div</td>
<td>a/30</td>
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<td></td>
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<td>0.5 cm</td>
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<td>10 ms</td>
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<td></td>
<td></td>
<td>10%</td>
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<tr>
<td>Hybrid operation and steady state operation</td>
<td>r/a ≤ 0.9</td>
<td>0.5-30 keV</td>
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<tr>
<td></td>
<td>r/a &gt; 0.9</td>
<td>0.05-10 keV</td>
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<tr>
<td></td>
<td></td>
<td>0.3-200 eV</td>
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<tr>
<td></td>
<td>Div</td>
<td>a/30</td>
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<tr>
<td></td>
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<td>0.5 cm</td>
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<td></td>
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<td>10 ms</td>
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<td>10%</td>
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## ITER measurement requirements (2): parameters

<table>
<thead>
<tr>
<th>GROUP 1a</th>
<th>Measurements For Machine Protection and Basic Control</th>
<th>GROUP 1b</th>
<th>Measurements for Advanced Control</th>
<th>GROUP 2</th>
<th>Additional Measurements for Performance Eval. and Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma shape and position, separatrix-wall gaps, gap between separatrixes</td>
<td>Neutron and $\alpha$-source profile</td>
<td>Confined $\alpha$-particles</td>
<td>TAE Modes, fishbones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma current, $q(a), q(95%)$</td>
<td>Helium density profile (core)</td>
<td>$T_e$ profile (edge)</td>
<td>$n_e, T_e$ profiles (X-point)</td>
<td></td>
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<tr>
<td>Loop voltage</td>
<td>Plasma rot. (tor and pol)</td>
<td>$T_i$ in divertor</td>
<td>$T_i$ in divertor</td>
<td></td>
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<tr>
<td>$\beta_N = \beta_{tor}(aB/I)$</td>
<td>Current density profile ($q$-profile)</td>
<td>Plasma flow (divertor)</td>
<td>Plasma flow (divertor)</td>
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<tr>
<td>Line-averaged electron density</td>
<td>Electron temperature profile (core)</td>
<td>$n_T/n_D/n_H$ (edge)</td>
<td>$n_T/n_D/n_H$ (divertor)</td>
<td></td>
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<tr>
<td>Impurity and D,T influx (divertor, &amp; main plasma)</td>
<td>Ion temperature profile (core)</td>
<td>$T_e$ fluctuations</td>
<td>$T_e$ fluctuations</td>
<td></td>
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<tr>
<td>Surface temp. (div. &amp; upper plates)</td>
<td>Radiation power profile (core, X-point &amp; divertor)</td>
<td>$n_e$ fluctuations</td>
<td>$n_e$ fluctuations</td>
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<tr>
<td>Surface temperature (first wall)</td>
<td>$Z_{eff}$ profile</td>
<td>Radial electric field and field fluctuations</td>
<td>Radial electric field and field fluctuations</td>
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<tr>
<td>Runaway electrons</td>
<td>Helium density (divertor)</td>
<td>Edge turbulence</td>
<td>Edge turbulence</td>
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<tr>
<td>'Halo' currents</td>
<td>Heat deposition profile (divertor)</td>
<td>MHD activity in plasma core</td>
<td>MHD activity in plasma core</td>
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<tr>
<td>Radiated power (main pla, X-pt &amp; div).</td>
<td>Ionization front position in divertor</td>
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<tr>
<td>Divertor detachment indicator $(J_{Sat}, n_e, T_e$ at divertor plate)</td>
<td>Impurity density profiles</td>
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<tr>
<td>Disruption precursors (locked modes, $m=2$)</td>
<td>Neutral density between plasma and first wall $n_e$ of divertor plasma</td>
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<tr>
<td>H/L mode indicator</td>
<td>$T_e$ of divertor plasma</td>
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<tr>
<td>$Z_{eff}$ (line-averaged)</td>
<td>Alpha-particle loss</td>
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<tr>
<td>$n_T/n_D/n_H$ in plasma core</td>
<td>Low m/n MHD activity</td>
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<td>ELMs</td>
<td>Sawteeth</td>
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<tr>
<td>Gas pressure (divertor &amp; duct)</td>
<td>Net erosion (divertor plate)</td>
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<tr>
<td>Gas composition (divertor &amp; duct)</td>
<td>Neutron fluence</td>
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<td>Dust</td>
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Expect to meet meas. reqs; maybe/maybe not; expect not to meet meas reqs.

Status April 2006
## Baseline Diagnostic Set (all credited)

<table>
<thead>
<tr>
<th>Magnetic Diagnostics</th>
<th>Spectroscopic and NPA Systems</th>
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<tr>
<td>Vessel Magnetics</td>
<td>CXRS Active Spectr. (based on DNB)</td>
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<tr>
<td>In-Vessel Magnetics</td>
<td>H Alpha Spectroscopy</td>
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<tr>
<td>Divertor Coils</td>
<td>VUV Impurity Monitoring (Main Plasma)</td>
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<tr>
<td>Continuous Rogowski Coils</td>
<td>Visible &amp; UV Impurity Monitoring (Div)</td>
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<tr>
<td>Diamagnetic Loop</td>
<td>X-Ray Crystal Spectrometers</td>
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<tr>
<td>Halo Current Sensors</td>
<td>X-Ray Cameras</td>
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<tr>
<td><strong>Neutron and Fusion Product Diagnostics</strong></td>
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<tr>
<td>Radial Neutron Camera</td>
<td>Beam Emission Spectroscopy</td>
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<tr>
<td>Vertical Neutron Camera</td>
<td>Neutral Particle Analysers</td>
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<tr>
<td>Microfission Chambers</td>
<td>MSE (based on heating beam)</td>
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<tr>
<td>Neutron Flux Monitors (Ex-Vessel)</td>
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<tr>
<td>Neutron Flux Monitors (Divertor)</td>
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<tr>
<td>Gamma-Ray Spectrometers (interfaces)</td>
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<tr>
<td>Neutron Activation System</td>
<td></td>
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<tr>
<td>High Resolution Neutron Spectrometer (interfaces)</td>
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<tr>
<td>Collective Scattering System (LFS front end)</td>
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<tr>
<td><strong>Optical Systems</strong></td>
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<tr>
<td>Thomson Scattering (Core)</td>
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<tr>
<td>Thomson Scattering (Edge)</td>
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<tr>
<td>Thomson Scattering/ LIF Interfaces (Divertor region)</td>
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<tr>
<td>Toroidal Interferom./Polarimetric System</td>
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<tr>
<td>Polarimetric System (Pol. Field Meas)</td>
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<tr>
<td><strong>Bolometric System</strong></td>
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<tr>
<td>Bolometric Array For Main Plasma</td>
<td></td>
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<tr>
<td>Bolometric Array For Divertor</td>
<td></td>
</tr>
<tr>
<td><strong>Microwave Diagnostics</strong></td>
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<tr>
<td>Neutron Flux Monitors (Ex-Vessel)</td>
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<tr>
<td>Neutron Flux Monitors (Divertor)</td>
<td></td>
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<td>Gamma-Ray Spectrometers (interfaces)</td>
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<td>High Resolution Neutron Spectrometer (interfaces)</td>
<td></td>
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<tr>
<td>Collective Scattering System (LFS front end)</td>
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<tr>
<td><strong>Plasma-Facing Comps and Operational Diag</strong></td>
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<tr>
<td>Neutron Flux Monitors (Ex-Vessel)</td>
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<tr>
<td>Neutron Flux Monitors (Divertor)</td>
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<tr>
<td>Collective Scattering System (LFS front end)</td>
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<tr>
<td><strong>Diagnostic Neutral Beam</strong></td>
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</tbody>
</table>

Different systems at different levels of convergence!

Machine Protection
Plasma Control
Physics Studies

Established Techniques
BPX / Reactor Relevance

Radiation Effects R & D
System Specific R & D

Engineering Requirements
Different systems at different levels of convergence!

Measurement Requirements and Justifications

Selected Diagnostic Techniques

System Conceptual Design

Integration on to Tokamak and with other Diagnostics

Performance Assessment Relative to Requirements

Yes

No

Detailed Design

Design meets Requirement?
ITER ENVIRONMENT

Relative to existing machines, on ITER the diagnostic components will be subject to (relative to JET)

- High neutron and gamma fluxes (up to x 10)
- Neutron heating (essentially zero)
- High fluxes of energetic neutral particles from charge exchange processes (up to x5)
- Long pulse lengths (up to x 100)
- High neutron fluence (> $10^6$ !)

- also larger amounts of materials eroded and repositioned
The ITER environment (2): radiation loads

Radiation loads (values corresponding to a fusion power of 700 MW):
- neutrons and gammas
- particles escaping plasma
- plasma radiation (synchrotron, bremsstrahlung, line radiation): x-rays–microwaves; mainly VUV

<table>
<thead>
<tr>
<th>Location</th>
<th>Typ. diagnostic components</th>
<th>Neutrons n/m²s</th>
<th>Dose rate Gy/s</th>
<th>Fluence (&gt;0.1 MeV) n/m²</th>
<th>Particle flux atoms/m²s</th>
<th>Plasma radiation (peak) kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>First wall</td>
<td></td>
<td>3×10^{18}</td>
<td>8×10^{17}</td>
<td>2×10^{3}</td>
<td>3×10^{25}</td>
<td>~5×10^{18}</td>
</tr>
<tr>
<td>Near blanket gap (on vacuum vessel)</td>
<td>magnetic coils, bolometers, retroreflectors</td>
<td>0.2×10^{16}</td>
<td>0.8×10^{16}</td>
<td>20 – 100</td>
<td>0.2 – 2×10^{24}</td>
<td>~10^{18}</td>
</tr>
<tr>
<td>Vacuum vessel (behind blanket)</td>
<td>magnetic loops</td>
<td>2×10^{16}</td>
<td>3×10^{14}</td>
<td>≤ 20</td>
<td>2×10^{23}</td>
<td>~0</td>
</tr>
<tr>
<td>Diagnostic block</td>
<td>First mirrors</td>
<td>1×10^{16}</td>
<td>9×10^{15}</td>
<td>20</td>
<td>1×10^{23}</td>
<td>~10^{17}</td>
</tr>
<tr>
<td>Labyrinth</td>
<td>Second mirrors, windows</td>
<td>2×10^{13}</td>
<td>3×10^{13}</td>
<td>10^{-2}</td>
<td>2×10^{20}</td>
<td>~0</td>
</tr>
<tr>
<td>Vacuum vessel (inboard TFC side)</td>
<td>magnetic loops</td>
<td>1×10^{14}</td>
<td>1×10^{12}</td>
<td>~0</td>
<td>~10^{21}</td>
<td>~0</td>
</tr>
<tr>
<td>Divertor cassette</td>
<td>First mirrors</td>
<td>1×10^{18}</td>
<td>3×10^{17}</td>
<td>1×10^{3}</td>
<td>~10^{25}</td>
<td>10^{17} – 10^{19}</td>
</tr>
<tr>
<td>Divertor port</td>
<td>Second mirrors</td>
<td>10^{13} – 10^{15}</td>
<td>10^{12} – 10^{14}</td>
<td>10^{-2} – 1</td>
<td>10^{18} – 10^{21}</td>
<td></td>
</tr>
</tbody>
</table>

1Gy (Gray) = 1J of ionising radiation/kg
Specific problems in BPXs

- Radiation-induced conductivity (RIC)
- Radiation induced electrical degradation (RIED)
- Radiation-induced electromotive force (RIEMF)
- Erosion and deposition
- Radiation induced absorption
- Radioluminescence
- Heating
- Change in other properties such as activation, transmutation and swelling

Moreover, the nuclear environment sets stringent demands on the engineering of the diagnostic systems – for example on neutron shielding, Tritium containment, vacuum integrity, RH compatibility.

Taken together this means that the development of diagnostics for ITER is the most difficult challenge ever undertaken in high temperature plasma diagnostic
Radiation effects on mineral insulated (MI) coaxial cable may be critical for in-vessel sensors, such as magnetic probes

**Radiation effects – prompt**

- **RIC: Radiation-Induced Conductivity**
  - Loads the signal but can be made negligible by careful choice of insulator and can be compensated.

- **RIEMF: Radiation-Induced EMF**
  - Radiation induces currents between the sensor wire and its surroundings.
  - Expected to generate < 100 nV signals across the ITER coils.

- **Nuclear Heating**
  - 0.1 – 1 W/cm³ cooled by conduction so special construction needed to reduce peak temperature to acceptable levels.

- **TiEMF: Thermally Induced EMF**
  - Seen in MI cable, possibly due to manufacturing non-uniformity.
  - Can cause spurious EMF arising from nuclear heating.

**Radiation effects – delayed**

- **RIED: Radiation-Induced Electrical Degradation.**
  - Not fully understood but maybe associated with metal colloid formation in insulator.
  - In ITER coils limits design electric field < 100 kV / m (cf. typical design values ~ 1 MV / m) and leads to rather large coils.

- **RITES: Radiation-Induced ThermoElectric Sensitivity.**
  - Nuclear heating supplies the temperature differences
  - A variety of effects can supply the material property changes that generate in turn thermocouples
Two prototype coils tested in Japan Materials Test Reactor

- Fast neutron & gamma fluences similar to ITER location for magnetic probes, leading to non-uniform temperatures similar to ITER

- Spurious coil current & voltage evolve during irradiation, voltage would lead to significant error on magnetics ($\psi = \int V dt$, with integrators: $5 \mu V \times 1000 s = 5 \times 10^{-3}$ Wb)

- Voltages return near starting values when reactors stops and coil cools down

- Suggest random internal thermocouple effects (RITES) due to inhomogeneities/defects induced by radiation and to lesser extend, pre-existing.

- Improvements: uniform flux conditions & T, low sensitivity alloys (Cu with few 0.1% Ni)
  
  Internal stresses in MI cables: avoid MI cables altogether? $\rightarrow$ ceramic coated wire?
Alternatives to MIC?

- Radiation induced electrical effects may be due to damage produced during MIC manufacture
- Normal copper wire shows none
- R&D explores usage of ceramic coated wire + ceramic filler
Radiation effects on optical components

Radiation-induced absorption (RIA)
- Atoms can be displaced by proton, neutron or electron impact
- $\gamma$-rays can cause displacement by creating Compton electrons
- Defects lead to states & absorption bands between valence and conduction bands in insulators

Radiation induced luminescence (RIL)
- Glass behaves like scintillator: slowing down charged particles (knock-on nuclei, Compton electrons) excite transitions or, if fast enough (i.e. electrons), may produce Cerenkov radiation

Lens before & after exposure to $\gamma$-rays
Radioluminescence in optical fibers

SiO$_2$ fibre irradiation in fission reactor
from B. Britchard, Nuclear Belgian Research Centre
H$_2$-treatment drastically reduces the 2 eV RIA band formation in all type of fibres

Fission-reactor irradiation of High OH silica fibres

- H$_2$ delays the 2 eV RIA band formation
- 2 eV RIA band re-increases when the “H$_2$ reservoir” is exhausted

Pre-loading with H and ways to continuously supply H to fiber are under study
Several other types of fibers may be acceptably radiation hard, active R&D

1Gy (Gray) = 1J of ionising radiation/kg
Plasma-facing (first) mirrors

- Optical diagnostics need light to be relayed by mirrors before it can be coupled through windows or into fibers.

- Plasma facing mirrors subject to:
  - Erosion (energetic ion/neutral impact)
  - Deposition (mostly molecules)
  - Radiation induced changes (swelling due to He accumulation)

- Effects depend on location, temperature, mirror substrate, wavelength and are polarisation dependent.

- Active R&D
Radiation damage due to energetic He ions
keV-range He ions/neutrals 1 ITER shot ~1-3 \(10^{21}/\text{m}^2\)

Evolution of Surface Damage at R. Temp. by Low Energy He\(^+\)

- **1E21**
  - light brown
  - Formation of fine He bubbles around the projected range.
  - Weak influence on Surface roughness

- **1E22**
  - brown
  - Formation of blisters ⇒ large scale roughening
  - Fine bubbles near the surface ⇒ fine scale roughening.

- **3E22**
  - dark brown
  - Due to the sputtering erosion, the covers of blisters disappear.
  - Due to the balance of formation of bubbles and sputtering erosion, dense fine bubbles always exist in the area between the surface and the projected range. Porous surface
  - He bubbles beneath the surface cause the fine scale surface roughening.

Fluence

N Yoshida, Kyushu University
We have been performing the experiments of helium irradiation to W target. They were primarily for the demonstration of divertor material. Thus, the surface temperature is higher (>1000 K) than the operation condition of mirror. However, the results may provide important common phenomena.
Reflectivity reduction enhances with incident ion energy

Optical reflectivity is measured with He-Ne laser (λ=632.8nm).

Reduction in reflectivity enhances with incident ion energy.

Fiberform nanostructure is observed in cases of W2, W3, while holes are observed on the surface in case of W1.

Incident ion energy would be a key factor.

W. Sakaguchi, submitted to JNM.
Erosion

Erosion due to low energy ions/neutrals leads to reflectance decrease due to roughening
Single crystal mirrors with planes // surface maintain reflectance despite high erosion

(V. Voitsenya, IPP, Kharkov)
Deposition on ‘first’ mirrors

- Absorption in deposited layer ($\lambda$-dependent)
- Interference effects in deposited layer (depends on N of layer, of substrate, on thickness, $\lambda$, incident polarisation)
- Deposition depends on plasma composition (chemical & energy distribution), substrate material & temperature. Depending on conditions, a surface may be either have net deposition or net erosion.
- R&D to avoid deposition
- R&D for possible in situ cleaning …
- Work at CEA, KFZJ, RRC, DIII-D … and Uni Basel/CRPP
Laboratory experiments (Uni Basel)

- Exposure of metallic mirrors to a low temperature deuterium plasma with controlled partial pressures of methane in the gas mixture

- 2 substrate materials: copper and stainless steel prepared in IPP Kharkov, Ukraine

U = -200 V
Water cooled sample holder
\[ f_{CH_4} = 0 / 1.8 / 3.5 \% \]

Samples characterization:

In situ measurement of the reflectivity using laser reflectometry (532 nm)

Weight measurement: determination of the eroded/deposited depth

SEM: surface morphology

Total and diffuse reflectivity (250-2500 nm); Spectroscopic ellipsometry (350-2300 nm)
Reflectivity during plasma exposure

Stainless steel

For $f_{\text{CH}_4}=3.5\%$, appearance of interferences typical from the growth of a:CH layer
No carbon on the other samples (EDX measurements)

Copper

Strong correlation between the carbon content in the plasma and the degradation rate of R
All samples are "carbon free"
Reflectivity after exposure

- Reflectivity measured with a UV-Vis-NIR spectrophotometer equipped with an integrating sphere.

Copper

Degradation of the reflectivity due to an increase of the surface roughness.

Stainless steel

Degradation of the reflectivity due to absorption of light in the deposited layer.
Evolution of the surface morphology

Stainless steel

\[ f_{CH_4} = 0\% \]
\[ Ra = 4nm \]

\[ f_{CH_4} = 1.8\% \]
\[ Ra = 6nm \]

\[ f_{CH_4} = 3.5\% \]
\[ Ra = 26nm \]

No significant effect of physical sputtering
Carbon protection effect

Copper

\[ f_{CH_4} = 0\% \]
\[ Ra = 7nm \]

\[ f_{CH_4} = 1.8\% \]
\[ Ra = 26nm \]

\[ f_{CH_4} = 3.5\% \]
\[ Ra = 70nm \]

Deterioration of the reflectivity by an increase of the roughness
Appearance of the crystallographic grains
Erosion/deposition measurements

- Eroded/deposited depth estimated both from mass loss measurements and profilometry

![Graph showing the comparison of surface thickness change against \( f_{\text{CH}_4} \) for stainless steel and copper. The graph illustrates different behavior towards erosion and deposition for both substrates.]

Different behaviour of both substrates towards erosion/deposition

Uni Basel
Reflection of polarized light (800 nm)

Stainless steel

- Virgin mirror
- $D_2$ pure
- $f_{CH4}=1.8\%$
- $f_{CH4}=3.5\%$

Polarization of the light strongly affected by the carbon layer.

Copper

- Virgin mirror
- $D_2$ pure
- $f_{CH4}=1.8\%$
- $f_{CH4}=3.5\%$

A drastic increase of the surface roughness has only a slight effect on the polarization.

Deposition of impurities appears to be a more serious problem for diagnostics using polarized light.

Rs reflection coefficient for polarisation $//\ to\ surface,\ Rp\ for\ \perp\ to\ surface$
Si and Mo mirror tests on TCV

Sample exposures were integrated over short campaign periods of 2-3 weeks, including He glow discharge conditioning

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Material</th>
<th>Distance below the tile surface (mm)</th>
<th>Number of shots</th>
<th>Glow discharge (hrs)</th>
<th>Deposited thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Mo</td>
<td>50</td>
<td>223</td>
<td>24.5</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Si</td>
<td>50</td>
<td>223</td>
<td>24.5</td>
<td>15.89</td>
</tr>
<tr>
<td>5</td>
<td>Mo</td>
<td>50</td>
<td>820</td>
<td>90.5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Si</td>
<td>50</td>
<td>820</td>
<td>90.5</td>
<td>24</td>
</tr>
</tbody>
</table>

Strong dependence on substrate material!
Strategies for 1st mirrors/(windows)

- The mirrors closest to plasma are exposed to harshest conditions
- In locations of net erosion: choose correct single crystal orientation and most resilient materials/coatings (ex: Molybdenum, Rhodium)
- Where deposition expected:
  - Choose material with lowest sticking coefficient
  - Active cleaning measures:
  - Keep mirror hotter than surroundings (facilitates erosion of deposit)
  - Gas puff in front of mirror
  - Laser cleaning
Laser cleaning of the window deposited in HL-2A

Y.Zhou  L. Zheng Y.G.Li  L.C.Li  G.Zhao

- Laser cleaning of the impurity film on fused quartz deposited in HL-2A was performed by Nd:YAG laser.

- The irradiation threshold for multi-pulse is about 0.25J/cm², for single pulse is about 2.8J/cm².

- The time for one ECE diagnostic window (diameter of 60 mm) full area cleaning using one shot laser ablation is about 5 min.

- The transmission improved significantly after laser cleaning.
‘Second’ mirrors

- Conditions less stringent after first mirror (no deposition/erosion)
- Dielectric multilayer mirrors may be acceptable: reflectivity near 100% in design wavelength band
- Must still be tested for radiation hardness

Calculated Spectrum of TiO$_2$/SiO$_2$ (27 layers) Dielectric Mirror

Part of the spectrum of TiO$_2$/SiO$_2$ DM

K. Vukolov - Kurchatov Institute, Moscow
DUST!

- Erosion and redeposition leads to dust formation, in ITER W, Be, C dust

- Dust hazard 1: **explosion**
  - Water+hot dust $\Rightarrow$ oxides + H$_2$
  - Air + H$_2$ $\Rightarrow$ explosion
  - Max pressure 2 bar limits tolerable quantity of dust, corresponding to 2.4kg of H$_2$ or 6 kg of W,Be and C

- Dust hazard 2: **release of activated dust** in case of breach of vessel integrity $\Rightarrow$ max 1000kg W

- Dust hazard 3: **release of Tritium** trapped in dust in case of breach of vessel integrity. Not clear from presentations I’ve seen how serious this is. However co-deposition of T with W,Be,C will reduce the available T inventory (1kg) and may limit D-T operation, if T cannot be completely recovered.
DUST MONITORING

- Erosion and redeposition leads to dust formation, in ITER W, Be, C dust
- Dust hazard 1: **explosion**
  - Water+hot dust → oxides + H₂
  - Air + H₂ → explosion
  - Max pressure 2 bar limits tolerable quantity of dust, corresponding to 2.4kg of H₂ or 6 kg of W,Be and C
- Dust hazard 2: **release of activated dust** in case of breach of vessel integrity ⇒ max 1000kg W
- Dust hazard 3: **release of Tritium** trapped in dust in case of breach of vessel integrity. Not clear from presentations I’ve seen how serious this is. However co-deposition of T with W,Be,C will reduce the available T inventory (1kg) and may limit D-T operation, if T cannot be completely recovered.
- see e.g. S. Pitcher, 16th ITPA Diag TG meeting
In ITER, it is assumed that:

- Dust size: between 100 nm and 100µm
- Dust mass-median diameter: 2 µm
- Except dust from disruption: 0.1 µm
- Dust will be made of C, Be, W, and metallic (St. St.) impurities
Dust measurement diagnostics still need to be developed

• Influx spectroscopy (W, Be, Cl, etc)
  Resonable estimate of main chamber erosion? ELMs? disruptions?

• Divertor plate net erosion monitor—Should be reasonably accurate.

• Dust monitors (several, perhaps in the divertor cassettes)
  – Simple, size of a fist, e.g. capacitance technique
  – Require test on existing tokamaks
  – Find optimal locations

• In-Vessel measurements (manned access or RH tool)
  – Net erosion (mechanical caliper)
  – dust collection (vacuum cleaner)

• Long-term samples (manned access or RH tool), e.g. cups
  (Dust and T removal techniques also need to be developed)
Two ideas for dust measurements, among many others

**Capacitive diaphragm gauge** measures weight of material on diaphragm via change of its capacitance due to deformation of diaphragm. May be installed under divertor. Materials can be chosen as to have a long life under neutron bombardment. Counsell G et al, REVIEW OF SCIENTIFIC INSTRUMENTS 77, 093501 2006

**Speckle interferometry** provides equal height fringes of image of surface. Need two different wavelengths to extend range to expected erosion depths (thousands of wavelengths) and to resolve ambiguities. Doré P, Gauthier E, Journal of Nuclear Materials 363–365 (2007) 1414–1419
ITER diagnostic systems
Note: Blanket design under review (2009), may impact diagnostics integration
Port plugs & divertor cassettes are designed for remote handling

Equatorial port with polarimetry and LIDAR TS relay optics
Access distribution (top level)

1. MSE
   Neutron Act syst ($^{16}$N)

2. H-alpha spectroscopy (inner edge)
   Position Reflectometry

3. Neutron Camera

4. CXRS (poloidal rotation, linked to DNB)
   Wide angle viewing/IR (1 of 5)

5. Neutron Camera
   Neutron Act syst ($^{16}$N)

6. Neutron Camera
   Neutron Act syst (foil)

7. Neutron camera
   Wide angle viewing/IR (2 of 5)

8. Bolometry
   Main plasma Reflectometry (1 of 2)

9. H-alpha spectroscopy (upper edge)

10. H-alpha spectroscopy (outer edge)
    VUV, X-ray Crys spectroscopy
    Neutron Act syst (foil)

11. Edge Thomson scattering
    Wide angle viewing/IR (3 of 5)

12. In-vessel diagnostic wiring

13. Wide angle viewing/IR (4 of 5)
    Main plasma Reflectometry (2 of 2)

14. Bolometry (matches equ. port 16 & div 16)
    Soft X-Ray (matches equ. port 16)

15. Wide angle viewing/IR (5 of 5)
    Visible spectroscopy
    (div port 15, outer leg)
Access distribution (equatorial level)

3 Wide angle viewing/IR
   CXRS (with DNB)
   MSE (with heating NB)
   H-alpha /Vis. spectroscopy
   DNB

4 Obscured port

7 Wide angle viewing/IR
   Neutron flux monitor

8 Wide angle viewing/IR
   Tor./Interfer. polarimeter
   ECE
   Fast Wave Reflectometry

9 LIDAR Thomson Scattering
   Polarimeter

11 X-ray Cryst spec
   NPA
   VUV (main & div.)
   Reflectometry

12 Wide angle viewing/IR
   H-alpha spectroscopy (edge)
   Visible continuum array

13 Wide angle viewing/IR
   Radial Neutron Camera
   Bolometry
   Soft x-ray array
   Visible spectroscopy
   (div port 15, inner leg)

15 RH plus Limiter
   Neutron flux monitor
   Neutron Act syst (foil & $^{16}$N)

Unassigned:
   Collective scattering
   Laser Induced Fluorescence
Access distribution (divertor level)

- 3 Reflectometry, Interferometry, Magnetics, Langmuir Probes
- 4 Langmuir Probes, Thermocouples
- 9 Reflectometry, Interferometry, IR Thermography, Bolometry, Magnetics, Pressure Gauges
- 12 X-point LIDAR, Div. Thomson Scattering, Bolometry, Magnetics
- 15 Visible Div. Impurity Monitor, Bolometry, Magnetics, Pressure Gauges
- 16 Bolometry, Langmuir Probes
- 18 VUV Impurity Monitor, Magnetics, Thermocouples, Pressure Gauges

Diagram showing access distribution with sectors labeled from 01 to 18, indicating different instrumentations and locations.
Magnetic diagnostics
(see lecture by J.B. Lister, ITERMAG consortium)

- sets of pick-up coils, saddle loops and voltage loops on the inner wall of the vacuum vessel;
- sets of pick-up coils and steady state sensors on the outer surface of the vacuum vessel;
- continuous poloidal (Rogowski) loops on the TF coil case;
- sets of coils in the divertor diagnostic cassettes;
- a diamagnetic system comprising poloidal loops on the inner wall of the VV and compensation circuits inside and outside the vessel;
- Rogowski coils mounted around earth straps of the blanket/shield modules and divertor structures for measuring the 'halo’ currents.
Approx. 1000 probes & loops
MHD saddle flux loops

Halo Rogowski around blanket connections measures currents passing from disrupting plasma to blanket module to vessel
Towards steady state magnetic measurements

- Coil signal is $U = -d\phi/dt$, but we want $\phi$.
- Low drift integrators for $>1000$ s demonstrated (ok for ITER, but not for reactor)
- Active research on non-inductive magnetic sensors, such as Hall effect probes
- Radiation-tolerant Hall probes under development at Magnetic Sensor Laboratory, Lviv, Ukraine
- Existing Hall probes suitable for use outside VV
- Slow radiation degradation, to be regularly recalibrated using integrated calibration coils

![Diagram of magnetic sensor and coil setup]

1 – Hall Sensor
2 – Coil
3 – Substrate
4 – Pins
Thomson scattering

- Core LIDAR Thomson scattering from equatorial port. (EU)
- Edge TS (classical) from top or eq. port (?)
- Divertor Thomson scattering from divertor port (RF)

Core system has strongly relativistic spectra, must be modelled for correct measurement

Optical labyrinth with shielding blocks for neutron shielding
R&D needed for high repetition rate Alexandrite laser
Dual wavelength (10.6 & 5.3 μm) 5-chord tangential polarimeter - interferometer

- Dual wavelength allows vibration compensation for interferometer.
- Faraday angle is backup for fringe loss, depends mostly on $n_e$ since $B_{||}$ well known
- ‘Dispersion interferometer’ at same wavelengths also proposed.
Poloidal polarimeter

Wavelength 118 μm

Large Faraday angles, density obtained by Cotton-Mouton effect (elliptisation)

Challenge: survival of inner wall retro-reflectors
Microwave systems

- Relativistic broadening limits access
- LFS O1 & X2 ECE look ok
- Two cooled equatorial antennae at different Z
- X and O mode analysed separately
- Two Michelson broadband spectrometers
- Two heterodyne multichannel receivers
- Implications for coherent Thomson scattering for alpha particle measurements: ECE pollution from 65 GHz to few hundred GHz
- 60 GHz X-mode CTS system planned
Fast ion CTS

• For measuring fast alpha particle distribution function (spatial and velocity resolution)

• Assessment of options at 60GHz, 170GHz & 3THz concluded to superiority of former (Bindslev et al)

• Back-scatter geometry shown

• Forward scatter somewhat better, but requires HFS mirror or launcher

• 1 MW gyrotron required
CTS, backward scattering, 60 GHz

Calculated scattered spectrum

Simulated fast particle distribution fct

Expected accuracy of measurements

1-D fast ion distribution

Fast Ion CTS for ITER,  H. Bindslev et al.  ITPA 6 (sub), San Diego
Spectroscopy
VUV, X, Divertor, CXRS

- VUV spectrometers, crystal X-ray spectrometer and NPA grouped because require torus vacuum all the way to the detector
- Placed in secondary vacuum chamber for safety reasons
- Tungsten atomic physics data poorly known, become priority for collaborating atomic physicists
Charge exchange spectroscopy

- Measures Ti, v, impurity densities
- Dedicated 100keV 4MW (?) H diagnostic beam because 1MeV heating beams have very low CX cross section
- Core and edge systems with different requirements for resolution
- Poor penetration: ok for r/a > 0.4
- Optical relays to outside VV, then optical fibre arrays to VIS spectrometers
Bolometry

- Total radiated power measurement, tomography
- No lack of ambition here!
- Traditional type with Au as in TCV, AUG not radiation hard (Au→Hg!)
- Alternative with Pt on ceramic substrate ok at 0.01dpa
Divertor diagnostics

- Bolometry (radiated power)
- Thermography (tile temperatures)
- Impurity spectroscopy
- ECE (pressure), reflectometry
- Thomson scattering (Te, ne)
- Erosion monitor
- Mirrors mostly under dome, erosion & deposition issue!

IR Thermography

Impurity monitoring
Fusion products

- **Neutrons**
  - measure of fusion power, alpha birth profile, Ti, n_D/n_T

- **Gammas**
  - indirect measure of alphas, T & D densities

- **Alphas**
  - confined: CTS
  - lost: monitors on first wall

\[
D + T \rightarrow ^{4}\text{He} \ (3.5 \text{ MeV}) + n \ (14.1 \text{ MeV}) \\
D + D \rightarrow ^{3}\text{He} \ (0.8 \text{ MeV}) + n \ (2.5 \text{ MeV}) \ 50\% \to T \ (1 \text{ MeV}) + H \ (3 \text{ MeV}) \ 50\%
\]

\[
T + T \rightarrow ^{4}\text{He} \ (3.8 \text{ MeV}) + 2n \ (7.6 \text{ MeV}) \\
D + ^{3}\text{He} \rightarrow ^{4}\text{He} \ (3.6 \text{ MeV}) + H \ (14.7 \text{ MeV})
\]

\[T + ^{3}\text{He} \rightarrow ^{4}\text{He} + 3 \text{ possibilities} \approx 12-15\text{MeV} \]

and many $\gamma$ reactions (some minor branchings of above reactants)
Global neutron flux measurements

- **Aim:** measure total neutron rate, hence fusion power
- **Specs:** $10^{14}$-$10^{21}$n/s, $\Delta t=1$ms, $\Delta R_n/R_n \leq 10\%$
- **Method:** $^{235}$U fission chambers in VV behind blanket & larger fission chambers outside VV
- **Responses adjusted for large dynamic range by position, moderators and amount of $^{235}$U.**
- **Response from neutron transport calculations and calibration by neutron source moved around torus**
Activation measurements

- **Aim:** Global measurement of neutron production with low time resolution.

- **Method 1.** Encapsulated foils (Fe, Al or Ti) transferred by pneumatic tube system from VV to counting stations outside bioshield. \( \Delta t \sim 100\text{s} \)

- **Method 2.** Water loop flow system from blanket to counting station and reservoir outside bioshield.

- Uses \(^{16}\text{O} + n \rightarrow p + ^{16}\text{N}\) reaction
  \( E_n > 10.24 \text{ MeV} \)

- \(^{16}\text{N}\) half-life time = 7.13 s

- Beta decay of \(^{16}\text{N}\) produces 6.13 & 7.11 MeV \( \gamma \)'s

- \( \gamma \)'s detected by scintillators

- Tested at JAERI, \( \Delta t \sim 0.1\text{s} \)
Neutron cameras

- Radial and vertical cameras
- Weighted sum over vertical or horizontal channel signals provides total fusion power
- Tomography: neutron source $n_D n_T < \sigma_{DT} v >$ & together with other diagnostics, $T_i$ profile.
- Channels equipped with ‘compact spectrometers’ – scintillators allowing limited resolution after PHA & deconvolution

**Total Neutron Flux and Emission Profile**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total neutron flux</td>
<td>$10^{14}$ - $10^{20}$ n s$^{-1}$</td>
</tr>
<tr>
<td>Neutron/α source</td>
<td>$10^{14}$ - $4 \times 10^{18}$ s$^{-1}$ m$^{-3}$</td>
</tr>
<tr>
<td>Fusion power</td>
<td>$\leq 1$ GW</td>
</tr>
<tr>
<td>Fusion power density</td>
<td>$\leq 10$ MW m$^{-3}$</td>
</tr>
</tbody>
</table>
detectors for RNC

✓ NE213 & stilbene
  - Ø 1-2 cm (ex-vessel) & 2-4 cm (in-vessel), 1 cm thick, 2.5 MeV efficiency ~ 0.3, 14 MeV efficiency ~ 0.1
  - flux measurements in DD and DT with required spatial and time resolution and accuracy
  - energy threshold (bias) can be set suitably
  - pulse height spectra available (energy spectra with unfolding)
  - in case radiation resistance is a problem, also in-vessel detectors are removable now (cassettes)
  - n/γ separation (DPSD)
  - fast electronics: possibility of real time control

✓ diamonds (ND and CVD)
  - lower efficiency for neutron detection but higher radiation resistance

• Simulations show good accuracy for neutron tomography with integration times down to 1ms (Esposito et al, ENEA)
Gamma spectroscopy

- Development of new $\gamma$ scintillators & detectors
- To be integrated into neutron cameras, making use of same collimation
- Need neutron moderator (80cm long $^6$LiH) to remove neutron background signal
- Potential:
  - Fuel densities/ratios using
    - $D+T \rightarrow ^5He+\gamma(17\text{MeV})$ *
    - $T+H \rightarrow ^4He+\gamma(20\text{MeV})$
    - $D+D \rightarrow ^4He+\gamma(24\text{MeV})$ *
  - Alpha particles using
    - $^9\text{Be}+^4\text{He} \rightarrow n+12\text{C}+\gamma(4.44\text{MeV})+\ldots$

* These have $\sigma \sim 10^{-4}$ of those of main fusion reactions, $^5\text{He}$ decays in $6 \times 10^{-24}\text{s}$, releasing 0.6 MeV
• Threshold reactions provide information on fast particles

• \( E_{\text{min}} \approx 1.7\text{MeV} \) for
\[
9\text{Be} + 4\text{He} \rightarrow n + 12\text{C} + \gamma(4.44\text{MeV}) + \ldots
\]
good for partly slowed-down alphas

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**Figure 5.** Excitation functions of the 4.44 and 7.65 MeV levels of \(^{12}\text{C}\) in the reaction \(^9\text{Be}(\alpha, n\gamma)^{12}\text{C}\).
Gamma tomography using JET neutron cameras reveals fast particle distributions from minority heating in JET.

+90° antenna phasing

-90° antenna phasing

\[^9\text{Be} + ^3\text{He}\] and \[^{12}\text{C} + ^3\text{He}\]
More…

- Lost alpha detectors
  Ceramic scintillators on wall, view from behind or with in-vessel camera
- Motional Stark effect for q profile.
  Based on heating beams
- In vessel IR and visible cameras
- Plasma position reflectometry
- Erosion monitors
- Dust monitors
- Monitors for deposition
- …?
- ITER Physics Basis: Diagnostics, NF 2006 (?) special issue
crpplocal/~weisen/ITER_diagnostics/ITERPhysBasDiag.pdf
  also ITPA Diagnostics website
Thank you for your attention!
PY-11 Plasma diagnostics
Exam date to be decided with the participants, 2nd half of September
Exam questions below. We recommend, as a preparation, that you create, for each of the questions below a personal memo of about 1 page containing keyword answers, obtained from the course & exercise material. The memo should simply reflect what you want to present at the exam in about 10-15 minutes for each question. You'll draw 3 questions at random, discard one and get 30 minutes to prepare answers for the two you keep. You are not allowed to bring notes or course material to the preparation, but you may use the notes written during the preparation for your presentation at the blackboard.

LIST OF QUESTIONS, some more to follow on lectures given by R Behn, Ch. Hollenstein, JBL, S.Coda, Ivo Furno, see website

2) Magnetic diagnostics
   2.1 Explain the measurement principles for inductive magnetic diagnostics. Formally, using multiple probe or flux measurements how can a discrete filament representation of the plasma current be calculated? For a cylindrical current carrying plasma, relate the measurements using magnetic probes placed around it to the plasma position (ex.2.1.4).
   2.2 Explain diamagnetism and paramagnetism in a fusion plasma (chapter 2, section 3 – Equilibrium properties)

3a) Broadband radiation diagnostics
   3.1 Broadband X-ray measurements and bolometry. Detection principles and diagnostics applications. Relate the local emissivity (W/m³) to the power incident on a detector element of area A₀, viewing the plasma through a pinhole of area A₀ placed a distance d in front of it.
   3.2 Relate the local emissivity (W/m³) to the power incident on a detector element of area A₀, viewing the plasma through a pinhole of area A₀ placed a distance d in front of it (ex.3.2). Explain how the total radiated power can be estimated from multiple measurements without tomography (ex.3.3)

3b) Line radiation diagnostics
   3.3 What are the mechanisms for line broadening? Which effects are used for what diagnostics and how? What hardware is used in the visible, XUV and X-ray domains?
   3.4 Relate the number of photons collected by a charge exchange spectroscopy system to the beam parameters, impurity concentration and the characteristics of the optical system (ex. 3.4 CXS feasibility study). Detailed calculations are not required, but principles must be well explained.

4) Diagnostics based on plasma refractivity
   4.1 Explain the principle of the heterodyne interferometry as applied in fusion plasmas. Explain its limitations and guide the choice of an appropriate wavelength (exercise 4.1)
   4.2 Present the principles of phase contrast imaging. What is the sensitivity of a phase contrast device with 1mW of effective local oscillator power (exercise 4.2).

5) Electron cyclotron emission
   5.1 Explain the concept of optical thickness. Which waves are optically thick in current tokamaks? What are the operational limitations of ECE? How can reflective walls help to alleviate some of these limitations (ex. 5.2)?
   5.2 Explain the detection schemes are available for ECE. Derive the noise-to-signal ratio ΔTe/Te for a heterodyne receiver (ex. 5.1).

6) Particle diagnostics
   6.1 Explain the principle of the HiBP and of its potential use for the measurement of poloidal flux in a tokamak.
   6.2 List and explain the techniques that are available for neutron detection and spectroscopy.
   6.3 How can the ion temperature be measured from a neutron spectrometer (exercise 6.1)?

8) ITER diagnostics
   8.1 What are the specific difficulties expected for ITER diagnostics? Brief presentation of the most important systems.
   (8.2 What are the challenges for ITER magnetic diagnostics? Brief presentation of planned ITER magnets)
Regular attendants to course AND exercises may choose small project or literature compilation, to be agreed with one of the lecturers. Prepare a 20 minute presentation on this for science meeting. Not within your PhD subject. Duration: equivalent to exam preparation, 1-2 weeks full time equivalent Deadline: tbd, mid-september Examples:
- Present and discuss

**Literature:**
- Fusion product diagnostics options in more detail than in course (AZ)
- Options for steady state magnetic diagnostics
- …any topic within the course you wish to explore in more detail
- … any topic of diagnostic interest not addressed in the course
  
  *You may consider diagnostics from the technical point of view (what can we measure with a particular class of diagnostics, how were they developed and improved etc) or from the physics point of view (what are/were the required diagnostics for making advances on a particular subject).*

**Applied:**
- Selected method(s) for signal processing
- Feasability study for application of some method to TCV, TORPEX or other
- A small spectroscopic survey of TCV using available diagnostics, such as visible spectrometer
- X-ray detection using photoelectric effect in Be (RRC detector prototype, at CRPP)

encourage exchange TCV-TORPEX-IND.PLASMAS-THEORY