ADAS applications for ITER

Robin Barnsley\(^{(1)}\) and Martin O'Mullane, with ITER and EFDA/JET contributors

\(^{(1)}\) Queen’s University Belfast and EFDA/JET

Visiting researcher at ITER International Team, Garching, Germany

1) Confirming a measurement requirement
   Divertor VUV spectroscopy

2) Input to a diagnostic design
   X-ray crystal spectrometer

3) New measurement opportunities
   Spectroscopic x-ray camera

4) Input to machine design design
   Oxygen radiated power for input to leak spec.
ITER (www.iter.org)
- Superconducting Tokamak
- Single-null divertor
- Elongated, triangular plasma
- Additional heating from RF, and negative-ion neutral-beams and

<table>
<thead>
<tr>
<th>R (m)</th>
<th>6.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (m)</td>
<td>2</td>
</tr>
<tr>
<td>V_p (m³)</td>
<td>850</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>15(17)</td>
</tr>
<tr>
<td>B_t (T)</td>
<td>5.3</td>
</tr>
<tr>
<td>δ,κ</td>
<td>1.85, 0.5</td>
</tr>
<tr>
<td>P_aux (MW)</td>
<td>40-90</td>
</tr>
<tr>
<td>P_α (MW)</td>
<td>80+</td>
</tr>
<tr>
<td>Q (P_fus/P_in)</td>
<td>10</td>
</tr>
<tr>
<td>P_fus(MW)</td>
<td>500</td>
</tr>
</tbody>
</table>
## ITER Construction Schedule

### REGULATORY APPROVAL

<table>
<thead>
<tr>
<th>Months</th>
<th>0</th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
<th>72</th>
<th>84</th>
<th>96</th>
<th>108</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Agreement Initialled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILE Established</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONSTRUCTION LICENSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### CONSTRUCTION

- **EXCAVATE**
  - HVAC ready
  - Purchase Order
- **TOKAMAK BUILDING**
- **SITE FABRICATION BUILDING**
  - PFC site fabrication bldg.
- **OTHER BLDGS.**
  - Place first TF/VV in pit
  - Complete VV torus
  - Complete Blanket/Divertor Installation
- **TOKAMAK ASSEMBLY**
  - Install cryostat bottom lid
  - Place lower PFC
  - Install CS

### STARTUP & COMMISSIONING

- **SYSTEM STARTUP & TESTING**
  - INTEGRATED COMMISSIONING
  - Complete leak & pressure test
  - Magnet excitation
  - 1st PLASMA

### PROCUREMENT

- **MAGNETS**
  - VESSEL, BLANKET & DIVERTOR
  - PFC fab. start
  - Last PFC complete
  - First purchase order
  - TFC fab. start
  - CS fab. start
  - Last TFC complete
  - CS fab. complete
  - First VV sector
  - Last VV sector
  - Last blanket and divertor

---

ADAS workshop, Cosenor's House, 13-14 November 2006. R Barnsley
ITER Operation Schedule

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Construction Phase</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>
</tr>
</thead>
<tbody>
<tr>
<td>First Plasma</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Field, Current &amp; H/CD Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short DT Burn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q = 10, 500 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q = 10, 500 MW, 400 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Non-inductive Current Drive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Installation & Commissioning | Basic Installation |        |        |        |        |        |        |        |        |        |         |
|                              | Commissioning      |        |        |        |        |        |        |        |        |        |         |
|                              | Achieve good vacuum & wall condition |        |        |        |        |        |        |        |        |        |         |
|                              | For activation phase |        |        |        |        |        |        |        |        |        |         |

| Operation                     | H Plasma Phase     |        |        |        |        |        |        |        |        |        |         |
|                              | D Phase            |        |        |        |        |        |        |        |        |        |         |
|                              | Low Duty DT        |        |        |        |        |        |        |        |        |        |         |
|                              | High Duty DT       |        |        |        |        |        |        |        |        |        |         |

| Equivalent Number of Burn Pulses (500 MW x 440 s^*) | Fluence^2 | 1 | 750 | 1000 | 1500 | 2500 | 3000 | 3000 | 0.006 MWm^2 | 0.09 MWm^2 |

| Blanket Test                  | System Checkout and Characterization |        |        |        |        |        |        |        |        | Performance Test |         |
|                              | Electro-magnetic test |        |        |        |        |        |        |        |        | On-line turbine recovery |         |
|                              | Hydraulic test       |        |        |        |        |        |        |        |        | High grade heat generation |         |
|                              | Effect of fertile steel etc. |        |        |        |        |        |        |        |        | Possible electricity generation, etc. |         |

- Machine commissioning with plasma.
- Heating & CD Expt.
- Reference resonance with H.
- Development of full DT high Q.
- Development of non-inductive operation aimed Q = 5.
- Short DT burn.
- Development of full DT high Q.
- Development of non-inductive operation.
- Demonstration of high duty operation.
- Blanket test.
## ITER Diagnostic Systems

<table>
<thead>
<tr>
<th><strong>Magnetic Diagnostics</strong></th>
<th><strong>Spectroscopic and NPA Systems</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel Magnetics</td>
<td>CXRS Active Spectr. (based on DNB)</td>
</tr>
<tr>
<td>In-Vessel Magnetics</td>
<td>H Alpha Spectroscopy</td>
</tr>
<tr>
<td>Divertor Coils</td>
<td>VUV Impurity Monitoring (Main Plasma)</td>
</tr>
<tr>
<td>Continuous Rogowski Coils</td>
<td>Visible &amp; UV Impurity Monitoring (Div)</td>
</tr>
<tr>
<td>Diamagnetic Loop</td>
<td>X-Ray Crystal Spectrometers</td>
</tr>
<tr>
<td>Halo Current Sensors</td>
<td>Visible Continuum Array</td>
</tr>
<tr>
<td><strong>Neutron Diagnostics</strong></td>
<td>Soft X-Ray Array</td>
</tr>
<tr>
<td>Radial Neutron Camera</td>
<td>Neutral Particle Analysers</td>
</tr>
<tr>
<td>Vertical Neutron Camera</td>
<td>Laser Induced Fluorescence (N/C)</td>
</tr>
<tr>
<td>Microfission Chambers (In-Vessel) (N/C)</td>
<td>MSE based on heating beam</td>
</tr>
<tr>
<td>Neutron Flux Monitors (Ex-Vessel)</td>
<td></td>
</tr>
<tr>
<td>Gamma-Ray Spectrometers</td>
<td>ECE Diagnostics for Main Plasma</td>
</tr>
<tr>
<td>Neutron Activation System</td>
<td>Reflectometers for Main Plasma</td>
</tr>
<tr>
<td>Lost Alpha Detectors (N/C)</td>
<td>Reflectometers for Plasma Position</td>
</tr>
<tr>
<td>Knock-on Tail Neutron Spectrom. (N/C)</td>
<td>Reflectometers for Divertor Plasma</td>
</tr>
<tr>
<td><strong>Optical/IR Systems</strong></td>
<td></td>
</tr>
<tr>
<td>Thomson Scattering (Core)</td>
<td>Fast Wave Reflectometry (N/C)</td>
</tr>
<tr>
<td>Thomson Scattering (Edge)</td>
<td>IR Cameras, visible/IR TV</td>
</tr>
<tr>
<td>Thomson Scattering (X-Point)</td>
<td>Thermocouples</td>
</tr>
<tr>
<td>Thomson Scattering (Divertor)</td>
<td>Pressure Gauges</td>
</tr>
<tr>
<td>Toroidal Interferom./Polarimetric System</td>
<td>Residual Gas Analyzers</td>
</tr>
<tr>
<td>Polarimetric System (Pol. Field Meas)</td>
<td>IR Thermography Divertor</td>
</tr>
<tr>
<td>Collective Scattering System</td>
<td>Langmuir Probes</td>
</tr>
<tr>
<td><strong>Bolometric System</strong></td>
<td><strong>Diagnostic Neutral Beam</strong></td>
</tr>
<tr>
<td>Bolometric Array For Main Plasma</td>
<td></td>
</tr>
<tr>
<td>Bolometric Array For Divertor</td>
<td></td>
</tr>
</tbody>
</table>

- **Measurements for:**
- Machine protection
- Plasma control
- Physics studies
- ~45 parameters in total
ITER diagnostics are port-based where possible
Each diagnostic port-plug contains an integrated instrumentation package
ITER diagnostic equatorial-port allocations

Each port has a lead diagnostic and lead Party.
ITER diagnostic upper-port allocations

- **01** F03 Position Reflectometry (1 of 2)
  - E04 Diverter Impurity Monitor
  - B08 Activation System (16N, 1 of 2)

- **02** G10 Vis. / IR TV (1 of 6)
  - E02 Hα spectroscopy (divertor outer)
  - E02 Hα spectroscopy (outer edge)

- **03** E01 CXRS core (on the DNB)

- **05** G10 Vis. / IR TV (2 of 6)
  - B08 Activation System (16N, 2 of 2)

- **06** E03 VUV grazing image (x 2)
  - B08 Activation System (foil, 1 of 2)

- **07** E02 Hα spectroscopy (inner edge)
  - E02 Hα spectroscopy (upper edge)

- **08** G10 Vis. / IR TV (3 of 6)
  - F09 Main Reflectometry (1 of 3)
  - B08 Bolometry

- **10** C06 Polarimeter

- **11** G10 Vis. / IR TV (4 of 6)
  - C02 Edge Thomson Scattering
  - B08 Activation System (foil, 2 of 2)

- **12** C07 CTS, (ECH)

- **14** G10 Vis. / IR TV (5 of 6)
  - F03 X-ray Crystal Spectrometry
    - (survey)
  - F03 Position Reflectometry
    - (2 of 2)

- **17** G10 Vis. / IR TV (6 of 6)
  - F02 Main Reflectometry (3 of 3)
  - F03 X-ray Crystal Spectrometry
    - (graphite)
  - E07 Bolometry,
  - E07 Soft X-ray Array
  - N01 Diagnostic Wiring

Note: All port ducts also contain
- Ann + N01 Diagnostic Wiring
## ITER measurement requirements relevant for x-ray VUV spectroscopy

<table>
<thead>
<tr>
<th>10. Plasma Rotation</th>
<th>VTOR</th>
<th>1 – 200 km/s</th>
<th>10 ms</th>
<th>a/30</th>
<th>30 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>VPOL</td>
<td>1 – 50 km/s</td>
<td>10 ms</td>
<td>a/30</td>
<td>30 %</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12. Impurity Species Monitoring</th>
<th>Be, C rel. conc.</th>
<th>1•10^4 – 5•10^2</th>
<th>10 ms</th>
<th>Integral</th>
<th>10 % (rel.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be, C influx</td>
<td>4•10^{16} – 2•10^{19} /s</td>
<td>10 ms</td>
<td>Integral</td>
<td>10 % (rel.)</td>
<td></td>
</tr>
<tr>
<td>Cu rel. conc.</td>
<td>1•10^{3} – 5•10^{3}</td>
<td>10 ms</td>
<td>Integral</td>
<td>10 % (rel.)</td>
<td></td>
</tr>
<tr>
<td>Cu influx</td>
<td>4•10^{15} – 2•10^{18} /s</td>
<td>10 ms</td>
<td>Integral</td>
<td>10 % (rel.)</td>
<td></td>
</tr>
<tr>
<td>W rel. conc.</td>
<td>1•10^{6} – 5•10^{4}</td>
<td>10 ms</td>
<td>Integral</td>
<td>10 % (rel.)</td>
<td></td>
</tr>
<tr>
<td>W influx</td>
<td>4•10^{14} – 2•10^{17} /s</td>
<td>10 ms</td>
<td>Integral</td>
<td>10 % (rel.)</td>
<td></td>
</tr>
<tr>
<td>Extrinsic (Ne, Ar, Kr) rel. conc.</td>
<td>1•10^{4} – 2•10^{2}</td>
<td>10 ms</td>
<td>Integral</td>
<td>10 % (rel.)</td>
<td></td>
</tr>
<tr>
<td>Extrinsic (Ne, Ar, Kr) influx</td>
<td>4•10^{16} – 8•10^{18} /s</td>
<td>10 ms</td>
<td>Integral</td>
<td>10 % (rel.)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>23. Electron Temperature Profile</th>
<th>Core T_e</th>
<th>r/a &lt; 0.9</th>
<th>0.5 – 40 keV</th>
<th>10 ms</th>
<th>a/30</th>
<th>10 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge T_e</td>
<td>r/a &gt; 0.9</td>
<td>0.05 – 10 keV</td>
<td>10 ms</td>
<td>5 mm</td>
<td>10 %</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>28. Ion Temperature Profile</th>
<th>Core T_i</th>
<th>r/a &lt; 0.9</th>
<th>0.5 – 40 keV</th>
<th>100 ms</th>
<th>a/10</th>
<th>10 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge T_i</td>
<td>r/a &gt; 0.9</td>
<td>0.05 – 10 keV</td>
<td>100 ms</td>
<td>TBD</td>
<td>10 %</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>32. Impurity Density Profile</th>
<th>Fractional content, Z&lt;=10</th>
<th>r/a &lt; 0.9</th>
<th>0.5 – 20 %</th>
<th>100 ms</th>
<th>a/10</th>
<th>20 %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r/a &gt; 0.9</td>
<td>0.5 – 20 %</td>
<td>100 ms</td>
<td>50 mm</td>
<td>20 %</td>
<td></td>
</tr>
<tr>
<td>Fractional content, Z&gt;10</td>
<td>r/a &lt; 0.9</td>
<td>0.01 – 0.3 %</td>
<td>100 ms</td>
<td>a/10</td>
<td>20 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r/a &gt; 0.9</td>
<td>0.01 – 0.3 %</td>
<td>100 ms</td>
<td>50 mm</td>
<td>20 %</td>
<td></td>
</tr>
</tbody>
</table>
### Spectral distribution of collection optics on ITER

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>System</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Mirr. or slots</th>
<th>Party</th>
<th>ADAS input</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>Thermography</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR-Vis-UV</td>
<td>Vis IR upper</td>
<td>6</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vis-IR, equatorial</td>
<td>4</td>
<td>EU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H-alpha</td>
<td>6</td>
<td>RF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Visible cont. array</td>
<td>1</td>
<td>CN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Divertor visible</td>
<td>3</td>
<td>JA</td>
<td>EU study</td>
</tr>
<tr>
<td></td>
<td>Edge CXRS</td>
<td>2</td>
<td>RF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Core CXRS</td>
<td>1</td>
<td>EU</td>
<td>EU M.Von Hellerman</td>
</tr>
<tr>
<td></td>
<td>MSE edge + core</td>
<td>2</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TS (LIDAR, edgeTS, etc)</td>
<td>3</td>
<td>EU JA RF</td>
<td>Background light</td>
</tr>
<tr>
<td>VUV</td>
<td>Main plasma VUV</td>
<td>2</td>
<td>KO</td>
<td>EU STRAHL, W.Biel</td>
</tr>
<tr>
<td></td>
<td>Divertor VUV</td>
<td>2</td>
<td>EU study</td>
<td></td>
</tr>
<tr>
<td>X-ray</td>
<td>X-ray survey spectrometer</td>
<td>1</td>
<td>IN?</td>
<td>O’Mullane 1997 Varenna</td>
</tr>
<tr>
<td></td>
<td>High resolution x-ray</td>
<td>3</td>
<td>US?</td>
<td>EU studies 20034-6</td>
</tr>
<tr>
<td></td>
<td>X-ray camera</td>
<td>1</td>
<td></td>
<td>ADAS/SANCO M.O’Mullane 2006</td>
</tr>
<tr>
<td>y-ray</td>
<td>y-ray spectrometer/camera</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Modelled Tungsten spectrum in ITER divertor

Left Modelled divertor sight-line

Right Spectra of individual W ionization stages

Left W ionization balance along divertor sight-line

Right Composite W spectrum
ArXVII spectrum from NSTX - Manfred Bitter

Te = 0.58 keV from all diel. satellites & line w; Ti = 0.45 keV

Credo in high-resolution x-ray spectroscopy
Extensively, but not exclusively, He-like ions.

\( \sim \frac{Te}{Z} \): 250eV: Ne, 500eV: Ar, 2keV: Fe-Ni, 10keV: Kr

Requires \( \frac{\lambda}{\delta\lambda} \) \( \sim 5000 \), hence \( \lambda < 1.3 \) nm for crystals

Ti: Doppler broadening
Vtor/pol: Doppler shift
Te: Dielectronic satellite ratio
ne: Forbidden line ratio \( z/(x+y) \) (sometimes)
Zeff: Continuum \( \tau_{\text{imp}} \) Impurity injection
nimp: Absolute calibration

Simple and reliable - bent crystal & pos. sens. detector.

Crystals are cheap dispersive elements, eg Si < 1kEur

Energy resolving detector makes it doubly dispersive, with excellent signal-to-noise ratio.

All crystal-window-detector processes are volume effects, leading to calculable and stable calibration. (1 mm Carbon \sim transparent at 10 keV).

Detector developments have been the key to progress:

1st gen. Photographic film
2nd gen. Multiwire prop. counter, \( \sim 3 - 25 \) m radius
3rd gen. Solid state eg CCD, 0.5 - 2 m radius
4th gen. Imaging with fast 2-d detector
Doubly curved crystal optics

Fig.14a. Spherical crystal optics

Fig.14b. Toroidal crystal optics

+ Spherical or toroidal crystal allows plasma imaging
+ Improves S/N ratio with smaller entrance aperture and smaller detector

\[
\frac{f_s}{f_m} = -\frac{1}{\cos(2\theta_B)}
\]

- No real focus for \( \theta_B < 45^\circ \)

\( f_s \): Sagittal focus  \( f_m \): Meridional focus  \( \theta_B \): Bragg angle
Vignetting due to the input flange on TEXTOR.
The observation range is about 20% of the plasma, i.e. 9cm from a minor plasma radius of 45 cm.
The electron temperature shows a clear dependence on the plasma radius. No clear variation is detected for the ion temperature, within the errors of the measurement.

This is due to two reasons:

1) In ohmic discharges, the ion temperature is broader than the electron temperature and therefore less variation over the limited observation range is expected.

2) The ion temperature is proportional to the square of the line width, whereas the electron temperature depends on the square root of the line ratio between the resonance line and the dielectronic satellite and therefore the errors are larger for the ion temperature.

The indicated variation of the plasma rotation over the radius is unrealistically large. In plasmas with ohmic heating, the total plasma rotation in the center is in the order of 25 km/s and decreases to the plasma edge.

The deviations are probably due to errors in the correction for the curved spectral lines, or non-linearities in the detector. For TEXTOR, these deviations can be measured and corrected by reversing the toroidal field and the plasma current.
High resolution imaging crystal spectrometer for ITER

Plasma coverage by radial views

- Yellow represents view tunnel within the port plug and its virtual extension into the plasma
- Aim is to view the tangent to all plasma flux surfaces
- Spatial coverage drives detector height

Plasma coverage by toroidal views

View from top of plug

Necessary to reduce the crystal-detector distance for the furthest-forward toroidal view spectrometer
ITER radial profiles used for ADAS-SANCO and signal simulations.

The most challenging Doppler measurement is the poloidal rotation.

Toroidal rotation derived from centroid shifts of core Cl XVI lines in COMPASS-D. $V_{tor}$ of 2 km/s was measurable in ~10 ms.
**Table 5.** Concentrations of Ar, Fe and Kr, for \( \Delta P_{\text{rad}} = 500 \text{ kW} \) in H-mode. The right-hand column gives a guide to efficiency of the impurity as a diagnostic tracer, in terms of count-rate per MW of \( \Delta P_{\text{rad}} \).

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength (nm)</th>
<th>( n_{\text{imp}} / n_e ) for ( \Delta P_{\text{rad}} = 500 \text{ kW} )</th>
<th>Count-rate for ( \Delta P_{\text{rad}} = 500 \text{ kW} ) (MHz)</th>
<th>Count/( \Delta P_{\text{rad}} ) (MHz/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar(^{16+})</td>
<td>0.3948</td>
<td>36</td>
<td>288</td>
<td></td>
</tr>
<tr>
<td>Ar(^{17+})</td>
<td>0.3731</td>
<td>2.10(^{-5})</td>
<td>33</td>
<td>264</td>
</tr>
<tr>
<td>Fe(^{24+})</td>
<td>0.1850</td>
<td>17</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Fe(^{25+})</td>
<td>0.1778</td>
<td>6.10(^{-5})</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>Kr(^{34+})</td>
<td>0.0946</td>
<td>3.6.10(^{-5})</td>
<td>1.2</td>
<td>1.72</td>
</tr>
<tr>
<td>Kr(^{35+})</td>
<td>0.0918</td>
<td>0.28</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>
The main constraint on the allowable added impurity concentration is not the increase in $Z_{\text{eff}}$, which is very small, but the additional radiated power, $\Delta P_{\text{rad}}$.

The H-mode incremental radiated powers for added impurity concentrations of $10^{-5}.n_e$ are:

- Ar $0.25 \text{ MW}$
- Fe $0.8 \text{ MW}$
- Kr $1.4 \text{ MW}$

ITB values are about 30% lower.

All signal estimates are normalized to $\Delta P_{\text{rad}} = 500 \text{ kW}$.
Modelled emissivity and line/continuum ratios for ITB with $n_{\text{imp}}/n_e = 10^{-5}$.

**Left:** Local photon emissivity

**Right:** Line/continuum ratios

ADAS-SANCO modelling for $n_{\text{imp}}/n_e = 10^{-5}$. 

ADAS workshop, Cosenor's House, 13-14 November 2006. R Barnsley
Fig.9. Coronal fractional abundance of W ions (below), with (above) a guide to the shells with greatest ionization potential ranges ΔIP/IP.
a. Fractional abundance for W ions.

b. $W^{63+}$ emissivity.

**Fig.10.** SANCO-modelled ITB plasma with Tungsten, for $n_W=10^{-5} n_e$
Modelled signals and detector requirements

Outline detector specification

- Number of detectors: \(~6\)
- Radiation hard
- Photon counting with at least one energy window

<table>
<thead>
<tr>
<th>Species</th>
<th>Count-rate per chord</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar 16(^+)</td>
<td>(~10^7)</td>
</tr>
<tr>
<td>Ar 17(^+)</td>
<td>(~10^8)</td>
</tr>
<tr>
<td>Fe 24(^+)</td>
<td>(~10^6)</td>
</tr>
<tr>
<td>Fe 25(^+)</td>
<td>(~10^5)</td>
</tr>
<tr>
<td>Kr 34(^+)</td>
<td>(~10^5)</td>
</tr>
<tr>
<td>Kr 35(^+)</td>
<td>(~10^4)</td>
</tr>
</tbody>
</table>

Simulated count-rates per chord for x-ray crystal spectrometer with 35 effective chords

These are line-of-sight integrals, because plasma is optically thin

- Height (spatial): \(~100\) mm
- Width (wavelength): \(~25\) mm
- Height resolution: \(~1\) mm
- Width resolution: \(~100\) \(\mu\)m
- QDE: \(> 0.7\)
- Energy range: \(3 – 13\) keV
- Average count rate density: \(~10^6\) count/cm\(^2\).s
- Peak count rate density: \(~10^7\) count/cm\(^2\).s
- Read out time: \(~10\) ms
Simulation results for ITER ITB  
C Ingesson et al HTPD 2004

- Fe concentration of $10^{-5}$
- H-like line at 1.784 Å
- Integration time of 0.3 s

Two views of the top half of the plasma were assumed measuring at toroidal angles $h = 0°$ and $18.5°$.

Left-hand column: moments calculated from the simulated measurements (solid circles) and backcalculating moments from the reconstruction (curves).

Right-hand column: input profiles of the simulation (solid curves) and reconstructed profiles (dotted lines).

Rows, from top to bottom: emissivity, toroidal rotation, poloidal rotation and $T_i$. 

ADAS workshop, Cosenor's House, 13-14 November 2006. R Barnsley
MEDIPIX2 Hybrid Pixel Detector

Detector and electronics readout are optimized separately.

Charge sensitive preamplifier with individual leakage current compensation
2 discriminators with globally adjustable threshold
3-bit local fine tuning of the threshold per discriminator
1 test and 1 mask bit
External shutter activates the counter
13-bit pseudo-random counter
1 Overflow bit

Medipix2 Cell Schematic

Medipix2 Cell Layout

Medipix2 Chip Architecture

256 x 256 pixels
3 ms readout time

ADAS workshop, Cosenor's House, 13-14 November 2006.
The revolution in x-ray/particle detectors

CERN Medipix II active pixel detector

Applications:
- X-ray imaging PHA
- Imaging X-ray crystal spectrometer
- Counting heavy ion beam probe
- Compact (imaging?) NPA

Medipix II in 2 x 2 array
Photon-counting ~ 5% energy-window at ~20 keV

Medipix II with USB interface
The JET D-T compatible soft x-ray cameras

Demonstration of plasma vertical stabilisation from 20 - 21 s, using the soft x-ray control signal.
Update of x-ray camera on Eq 09

Reference design
Based on JET D-T x-ray camera “KJ5”
Discrete chords

Continuous poloidal resolution
Outer plasma viewed by in-port detectors in removeable cassettes
SANCO/ADAS modelled x-ray emission for ITER Te, Ne profiles
Martin O’Mullane, Strathclyde University & EFDA/JET
Estimates of x-ray and neutron emission

Approximate analytical expression for x-ray continuum
\[
\varepsilon_{ph}(E,r) = \frac{10^{-7}}{h \cdot E} \cdot 6.4 \cdot 10^{-40} \cdot \frac{\zeta \cdot N_e(r)^2}{T_e(r)^{0.5} \cdot Z \cdot \text{eff}} \cdot \frac{g}{f(r)}
\]

X-ray emission profile, 20% bandwidth

Neutron emission profile
Outline parameters of ex-vessel x-ray camera module

- Narrow angle of view to maximize neutron shielding
- Window can be substantial eg 1-5 mm Be or **1-2 mm diamond**
- Detector: Fast, radiation-hard, photon-counting, energy-resolving position-sensitive detector
  - eg CERN-Medipix, PSI-Pilatus, ENEA-Pacella

Outline dimensions
- Entrance slit to detector: ~ 1 m
- Entrance slit to plasma: ~ 5 m
- Slit width x height: 1 x 5 mm^2
- Angle of view: 5 deg.
- Poloidal resolution for 1mm slit: 5 mm
- Blanket slot width: < ~20 mm

Detector performance
- 1d spatial resolution: <~ 250 um
- Energy range: 1 – 100 keV
- Multi-channel energy resolution: 5 -15%
- Peak count-rate: 1.5 . 10^9 /cm^2.s
- Max direct neutron flux: 6 . 10^6 /cm^2.s
- Time for n-fluence of 10^14 /cm^2: ~ 10^7 s
Ex-vessel x-ray camera in Eq 09

In-port detectors in removeable cassette
Signals, and emission reconstruction

- Instrument geometry
- 1 mm Be window
- Detector QDE
  (x-ray 0.5, and neutron 1.0)
- Poisson counting noise
- Neutron background
  (only direct so far)

Analytic Abel inversion

Fit 1/e gradient for local Te at each chord

Artefact due to fixed energy range for fit at each chord. Can be improved
ADAS/SANCO modelled ITER broadband x-ray spectra
Line and continuum in 5% energy bands, radially resolved

< 10 keV: mainly impurity information

> 10 keV: mainly Te information

Modern detectors will be able measure this…
Summary

- ADAS contributes to ITER on several levels:
  - Clarification of VUV measurement requirements
  - Input to x-ray spectrometer design
  - Prospects for a spectroscopic x-ray camera
  - Impurity radiated power (M O’Mullane, this meeting)
  - Beam-aided spectroscopy (M Von Hellerman, this meeting)

- Future:
  - All impurity radiated power components for power balance
    - Start-up, operating scenarios etc.
  - Prediction of Tungsten spectrum
    - Visible: contamination etc
    - VUV: diagnostic potential, especially divertor
    - X-ray: diagnostic potential for Ti profiles
SLHC and tracking

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Energy</td>
<td>7 TeV</td>
<td>12.5 TeV</td>
</tr>
<tr>
<td>Collision rate</td>
<td>40 MHz</td>
<td>80 MHz</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$10^{35}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Int. luminosity</td>
<td>500 fb$^{-1}$</td>
<td>2500 fb$^{-1}$</td>
</tr>
</tbody>
</table>

~ 100 pile-up events per bunch crossing for 12.5 ns bunch spacing compared to ~20 at $10^{34}$ cm$^{-2}$ s$^{-1}$ and 25 ns

- If same granularity and integration time as now, the tracker occupancy and radiation dose increases by a factor of 10 ⇒ implication for radiation damage and physics

M. Hutinen: "Radiation issues for Super-LHC", SLHC Electronics Workshop, 26/2/04, CERN

Daniela Bortoletto Vertex 2005 Nikko Japan
SLHC and tracking

- $dn^{cha}/d\eta/crossing \approx 600$ and $\approx 3000$ tracks in tracker $\Rightarrow$ more granularity if we aim at same performance we expect from the LHC trackers

$H \rightarrow ZZ \rightarrow e\mu\mu \ m(\text{higgs})=300 \text{ GeV}$ all tracks with $p_T<1 \text{ GeV}$ removed

- Integrated Luminosity (radiation damage) dictates the detector technology
- Instantaneous rate (particle flux) dictates the detector granularity

<table>
<thead>
<tr>
<th>R (cm)</th>
<th>$\Phi$ (p/cm$^2$)</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;50</td>
<td>$10^{14}$</td>
<td>Present p-in-n (or n-in-p)</td>
</tr>
<tr>
<td>20-50</td>
<td>$10^{15}$</td>
<td>Present n-in-n (or n-in-p)</td>
</tr>
<tr>
<td>&lt;20</td>
<td>$10^{16}$</td>
<td>RD needed</td>
</tr>
</tbody>
</table>