

The development of diagnostic systems for next step Burning Plasma experiments (BPX) such as ITER requires R&D in some key areas. The International Tokamak Physics Activity (ITPA) Topical Group (TG) on Diagnostics has identified five topics as 'high priority' and these form the focus of the current work of the TG.

## 1] Development of methods of measuring the energy and density distribution of confined and escaping alpha particles

The measurement of the energy and density distribution of confined alpha particles will be important on ITER. The distribution function should be measured as a function of pitch angle in order to separate the physics of passing and trapped ions. This measurement is not at all straightforward. Proposed methods:

### Fast Ion Collective Thomson Scattering

- Study has been completed in Europe [1] on the various collective Thomson scattering options to measure alphas and fast ions in ITER (60 GHz, 170 GHz, 3 THz and 28 THz).
- 60 GHz option is the most attractive: it combines a good s/n ratio with minimum required technological developments, and can provide good resolution in space, velocity and time, and meet the ITER measurement requirements. System is rather robust against density variations and mechanical disturbances.
- A collective Thomson scattering system for measuring confined fast alpha particles on ITER based on the 60 GHz option has been designed. Implementation of the system appears feasible although some key interface details need to be worked through (see Fig.1)
- Detailed calculations have demonstrated that the system can in principle separate the isotropic alpha population from the energetic ions originating from the deuterium beams (see Fig. 2).

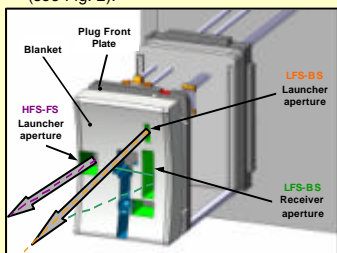


Fig. 1. Design of the 60 GHz collective Thomson scattering system for ITER [1]

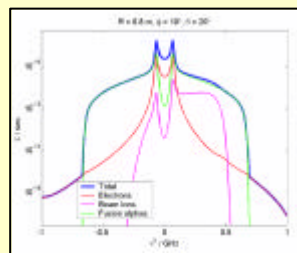


Fig. 2. Calculated collective Thomson scattering system for ITER in the presence of deuterium heating beams [1]

### Alpha knock-on tail measurements

- The high-energy neutron tail (see Fig. 3) can potentially be measured using a neutron spectrometer, such as a Magnetic Proton Recoil (MPR) spectrometer [2], a bubble detector (see Fig. 4) [3,4] or a nuclear emulsion track detector [5].
- The application of large spectrometers, like the MPR, in ITER is not straightforward and therefore much emphasis is devoted to finding smaller spectrometers.
- The discrimination of the alpha knock-on neutrons from beam particle knock-on neutrons is a potential problem that needs to be addressed.
- Another possible approach is to measure knock-on ions neutralised by the 1 MeV D<sup>0</sup> heating beams or by electron capture from intrinsic impurities [6]. In these cases, fast neutrals need to be analysed by a Neutral Particle Analyser (NPA). Calculations for ITER predict NPA count rates up to 10<sup>4</sup>/sec for deuterons of E > 1 MeV [6].

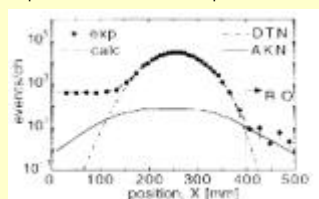


Fig. 3. Alpha knock-on neutron tail measurements at JET with a Magnetic Proton Recoil Spectrometer [2].

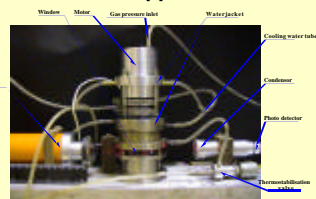


Fig. 4. Threshold bubble detector developed in the Russian Federation for 14 MeV neutron measurements [4].

### Escaping alphas

- Not only to monitor the bombardment location (loss imaging) for machine protection, but also to measure the pitch-angle and energy distribution of the escaping alphas as well as their temporal behaviour during MHD to understand the underlying physics.
- An infrared camera can be used for loss imaging.
- Candidate diagnostics for time-resolved pitch-angle and energy measurement include Faraday-cup and scintillator probes. They need to be installed near the first wall where the radiation conditions are the most severe (see Fig. 5).

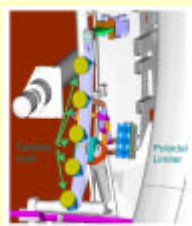


Fig. 5. Proposed installation of Faraday-cups in JET

## 2] Review requirements for measurements of the neutron/a source profile and assessment of possible methods of measurement

A key question here is whether the neutron/a source profile can be expected to be a flux function?

- If so, then the source profile can be derived from measurements with the Radial Neutron Camera, combined with knowledge on flux surfaces from magnetics. The need for the Vertical Neutron Camera would be much reduced (see Fig. 6)

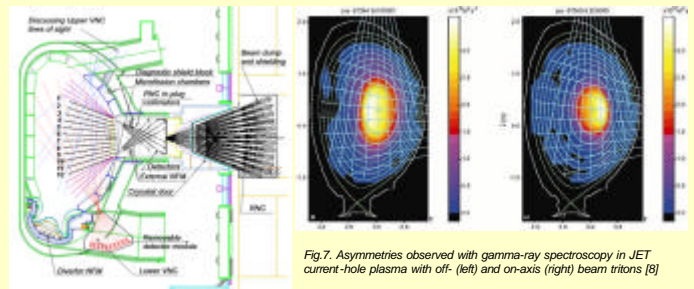


Fig. 7. Asymmetries observed with gamma-ray spectroscopy in JET current-hole plasmas with off- (left) and on-axis (right) beam tritons [8]

Fig. 6. Layout of the Neutron Cameras in ITER. The Radial Neutron Camera (RNC) features an ex-vessel system combined with in-plug detectors for a complete coverage. A recent design for a Vertical Neutron Camera (VNC) looking up from a divertor port is also shown [7].

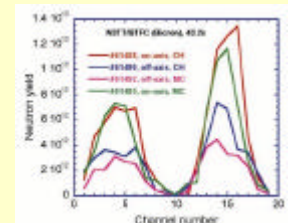


Fig. 8. Asymmetries in the neutron yield in JET current-hole plasmas go unnoticed by the RNC (channels 1-10), but are clearly observed by the VNC (channels 11-19) [9]

### The answer is basically 'Maybe'

- Good arguments were made that under conditions where non-isotropic fast ions are present (ICRH), that the neutron source profile cannot be relied on to be a constant on a flux contour. Under these conditions both cameras (RNC and VNC) are needed to reliably measure the neutron source profile. Such conditions have been seen in JET (see Fig. 7, 8).

### Can this also be the case in ITER?

- Modeling calculations are underway in Europe to judge whether similar asymmetries can be expected in ITER.

### Radial neutron camera consists of two parts:

- 'Traditional' type of ex-vessel neutron camera (see Fig. 6), and
- Additional inport detector/collimator units (see Fig. 6).

### Vertical neutron camera

- Design for Vertical Neutron Camera viewing up from divertor (see Fig. 6) is in preparation.

This is necessary to have a full coverage of the plasma and improve the accuracy for flat neutron emission profiles and also to be able to see sharp gradients in the profiles (e.g. due to Internal Transport Barriers – see Fig. 9).

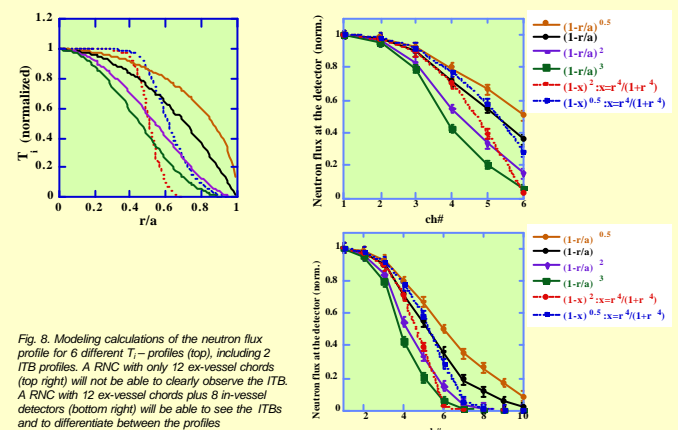


Fig. 9. Modeling calculations of the neutron flux profile for 6 different T<sub>1</sub> - profiles (top), including 2 ITB profiles. A RNC with only 12 ex-vessel chords (top right) will not be able to clearly observe the ITB. A RNC with 12 ex-vessel chords plus 6 in-vessel detectors (bottom right) will be able to see the ITBs and to differentiate between the profiles

# ITER/BPX Diagnostic Development



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## 3] Life-time of plasma facing mirrors used in optical systems

Refractive optics cannot be used as front-end optics because of Radiation Induced Absorption (RIA) and Emission (RIE or Radioluminescence)

First mirrors will be subject to:

- intense neutron, gamma and ultra violet radiation,
- neutron heating,
- particle fluxes arising from charge exchange (CX) atoms (typically  $2 \cdot 10^{19}$  atoms·m<sup>-2</sup>·s<sup>-1</sup> with energies up to several keV),
- deposition of material eroded from the divertor, first wall and shield structure,
- laser damage (in laser-aided diagnostics).

Systematic measurements of the effect on reflectivity and on mirror lifetime of potentially damaging effects are being conducted:

- Single crystal mirrors (made of Mo, W and stainless steel SS) are very resistant to erosion caused by sputtering (see Fig. 10). They can be made in large sizes (up to 12 cm). Good results are also reported for mirrors made with metallic coatings such as Mo and Rh. First mirrors of these types will survive if sputtering is the dominant effect.

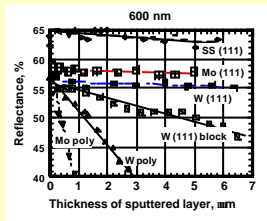
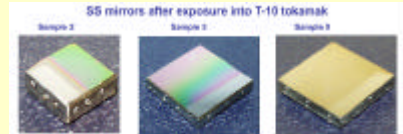
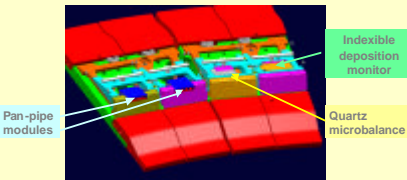


FIG. 10 (Left). Reflectance of Stainless Steel (SS) single crystal, W and Mo mirrors of different structure (polycrystal, block single crystal and single crystals with (111) planes of orientation) at 600 nm depending on the thickness of the layer eroded due to bombardment by ions of deuterium plasma. (Adapted from [10]).  
 Fig. 11 (bottom). Deposition of CH films after exposure to plasma in the T-10 tokamak



- the role of deposition on windows and mirrors for the core plasma is less clear and dedicated studies are needed at present day large-scale fusion devices. Tests are ongoing amongst other at (LHD, NSTX, TEXTOR, Tore Supra, T-10 (Fig.11))
- Special diagnostics will be implemented in the divertor of JET (see Fig. 12) to study the effects of deposition

Fig. 12. Pan-pipe modules in the divertor of JET each contain four mirror samples of different material and at different depth in a small duct. The indexable monitor measures the deposition history over a long time. The quartz microbalances will yield information during the shot



## 4] Develop new methods to measure steady state magnetic fields accurately in a nuclear environment and assessment of thermal EMF on irradiated coils used for s.s. magnetic field measurements

Irradiation and thermal effects on Mineral Insulated Cables

- The understanding of the three principal radiation effects - Radiation Induced Conductivity (RIC), Radiation-Induced Electro-Motive Force (RIEMF) and Radiation-Induced Thermo-Electric Sensitivity (RITES) - and their relative importance is improving.
- For RIC, the insulator materials and thickness have to be chosen so that the corresponding loading error is negligible.
- New irradiation tests in the JMTR reactor confirm the earlier result that probably RITES dominates over RIEMF (Fig. 13, 14).
- These effects can readily generate parasitic voltages in the 100 nV – 10 mV range. An ITER/BPX will therefore need some supplementary measurements of key equilibrium parameters that do not rely on passive inductive sensors alone.

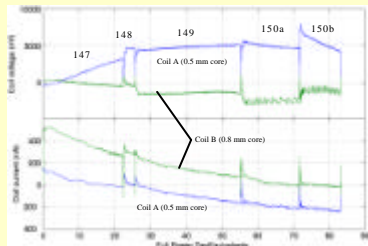
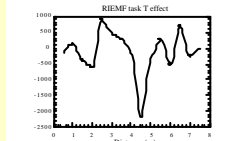


Fig. 13. (Left) RIEMF core-to-sheath voltage and current are not related [11].  
 Fig. 14. (Bottom) Voltage across terminals of coil wound Mineral Insulated cable locally heated in the tail region by 55 degrees C at intervals of 0.5 m [12].



### Additional systems and measurements for plasma position and shape

- Install coils outside the vacuum vessel in a lower radiation environment. It appears that suitable Hall effect sensors can also be installed if R&D to extend their temperature range to ~ 140 degrees C is successful [13].
- Use a plasma position reflectometer to measure the gaps between wall and separatrix.

## 5] Develop requirements for measurements of dust, and assessment of techniques for measurement of dust and erosion

The measurement of dust and erosion and the related tritium retention are considered to be very important for ITER but progress in defining the measurement requirements and developing the required techniques is slow.

Some work is presently underway, but this field needs much more attention from the international community.

### A new type of dust detector has been developed and is in use on NSTX [14]

- A fine grid of interlocking traces is biased with 30-50 v DC (see Fig. 15).
- Grid spacing range 25 μm - 762 μm (vacuum standoff > 200 v)
- Impinging dust produces a short circuit and current pulse that vaporises the dust.
- A signal is generated by the return current and recorded with standard nuclear counting electronics

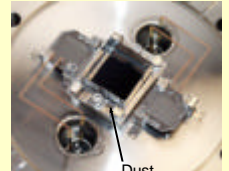


Fig. 15. Dust detection grid used in NSTX

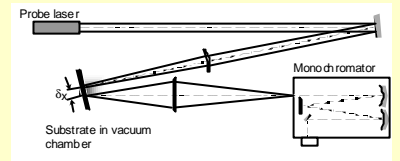
### Capacitive diaphragm microbalance to measure dust

Work on these devices that are radiation hard is ongoing at UKAEA in Europe

### Laser ablation

Laser ablation to measure dust is presently being tested at the Ioffe Institute in Russia (Fig. 16)

Fig. 16. Setup for the measurement of dust via laser ablation.



### Erosion measurements

Erosion from different materials has been studied by putting small samples at close vicinity to the Tore Supra plasma (see Fig. 17)



Fig. 17. Erosion of three different materials after long time exposure to the Tore Supra plasma. The effects on the reflectivity were only small.

## Concluding Remarks

Many of the above issues are of a rather urgent nature. Although ITER, including its diagnostic systems, is not expected to come into operation for about 10 years, many aspects of the system will be 'frozen' in an early phase of the design. This is especially the case for interfaces with other tokamak components and for components installed in the vacuum vessel. **This calls for an intense research programme on several issues including first mirror issues and radiation effects, and for an early definition of the diagnostics to be implemented and the establishment of their feasibility under ITER conditions.**

Apart from the five High Priority issues, discussed here, there are twelve issues with Intermediate or Long Term Priority that also need to be resolved in the years to come [15].

## References

1. Bindsev, H., et al. Rev. Sci. Instrum. **75** (2004) 3598.
2. Käline, J., et al. Phys. Rev. Lett. **85** (2000) 1246.
3. Fisher, R.K., et al., Rev. Sci. Instrum. **72**(2001) 796.
4. Trusillo, S., Agureev, V., from Progress Meeting on ITER Diagnostics, St. Petersburg, Russia, Nov. 2001.
5. Fisher, R.K., et al., Rev. Sci. Instrum. **75** (2004) 3556.
6. Alanastev, V.I., et al., Proc. 30th Conference on Contr. Fusion and Plasma Phys., St. Petersburg (2003) Paper O-4-40.
7. Sasao M. et al., This conference, paper PC/P3-23.
8. VYavorskij, et al. Proc. 31st Conference on Contr. Fusion and Plasma Phys., London (2004) Paper P1.157.
9. L. Bertalot, Presented at JET Neutron Diagnostics Workshop, April 2004.
10. Voitsenya V. et al. Rev. Sci. Instrum. **72** (2001) 475.
11. Vayakis G. et al., Rev. Sci. Instrum. **75** (2004) 4324.
12. Vila R. and Hodgson E. (in preparation).
13. Duran I. Et al., presented at the High-Temperature Plasma Diagnostics Conference, San Diego (2004).
14. Skinner Ch. Et al., Rev. Sci. Instrum. **75** (2004) 4213.
15. Donne A.J.H. and Costley A.E., IEEE Transact. on Plasma Sci. **32** (2004) 177