EFDA E U R O P E A N   F U S I O N   D E V E L O P M E N T   A G R E E M E N T

Progress on common aspects of the EU-supplied ITER diagnostics and prediction of diagnostic performance

LC Ingesson,[1,2] DJ Campbell,[1] M Cecconello,[1,3] E Ciattaglia,[1,4] P Dirken,[4] N Hawkes,[4] M von Hellermann,[2] S Kálvin,[5] P McCarthy,[6] O Neubauer,[7] L Petrizzi,[8] and M Walsh[4]

[1] EFDA Close Support Unit – Garching, Boltzmannstraße 2, D-85748 Garching, Germany
[2] also at FOM-Inst. voor Plasmafysica, Associatie Euratom-FOM, PO Box 1207, 3430 BE Nieuwegein, The Netherlands
[3] also at Div. Fusion Plasma Physics (Association EURATOM-VR), School of Electrical Engineering, Royal Institute of Technology KTH, S-10044 Stockholm, Sweden
[4] EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB Abingdon, Oxon., UK
[5] KFKI-Research Inst. for Particle and Nucl. Physics, Ass. Euratom-HAS, P.O. Box. 49, Budapest-114, H-1525, Hungary
[6] Dep. Physics, University College Cork, Association Euratom-DCU, Cork, Ireland
[7] IPP, Forschungszentrum Jülich GmbH, Association Euratom-FZJ, D- 52425 Jülich, Germany
[8] Associazione ENEA-EURATOM sulla Fusione Frascati, Via E. Fermi, 44 Frascati Rome, Italy

INTRODUCTION

The European Union (EU) will supply a number of **diagnostics for ITER**. **Significant progress** has been made on the **design and integration of** several of these **diagnostics**.

Aim of this presentation:

- Discuss **technical analyses** and **design solutions** that are pursued in **common for several of these diagnostics**:
  - port-plug integration
  - simplification of labyrinths against neutron streaming
  - design measures to be able to protect and replace sensitive optical components
- Discuss **diagnostic performance analysis** in relation to the **ITER measurement requirements**.

EU-SUPPLIED DIAGNOSTICS FOR ITER:

- Plasma-position reflectometer
- Core-plasma charge-exchange recombination spectroscopy (CXRS)
- LIDAR Thomson scattering
- Radial neutron camera
- Visible/ir wide-angle viewing cameras on equatorial ports
- Magnetics diagnostic
- Bolometers
- Pressure gauges
- Thermocouples

The **port plugs** associated with the procurement packages that include these diagnostics will also be supplied.

There is also EU interest in other diagnostics, not yet included in the approved ITER diagnostic set, e.g. a large neutron spectrometer, divertor thermography and collective Thomson scattering.

THE ITER ENVIRONMENT

The ITER environment poses many challenges compared with that encountered on present fusion plasma devices:

Radiation environment

- Typical **neutron flux** in diagnostic-relevant locations: 10^{13}–10^{17} n/m^{2}s (a significant fraction is 14MeV neutrons).
- **Fluence** of between 10^{20}–10^{24} n/m^2 over the lifetime of ITER.
- **Gamma dose rate** between 10^{-2}–10^{2} Gy/s in relevant locations during plasma operation, and up to 1Gy/s **continuously**.
- **Restrictions on materials that can be used**: vacuum and nuclear compatible, structural and physical properties change, re-weldable after activation, transmutation products harmless
- **Volume heating**

Demands on optical diagnostics

Mirror labyrinth needed: reduces neutron streaming and uses reflective optics instead of radiation-sensitive refractive optics. **Particle fluxes**, however, pose a severe challenge to first mirrors.

Access for repair and maintenance

Access will be very restricted → high degree of reliability required

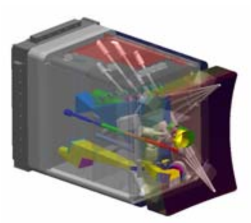
For many reasons, the port based diagnostics are mounted in port plugs.

Challenges

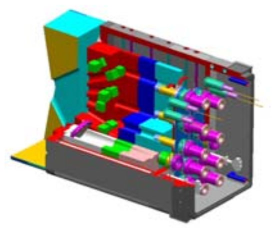
Progress on **R&D on critical components**, such as mirrors and windows, and **radiation-hardness testing/development** of diagnostic components (including cabling, optical fibres and other).

Specific topics, in common for several of the diagnostics, are discussed next: **port-plug integration**, **simplification of labyrinths** against neutron streaming and **design measures to be able to protect and replace sensitive optical components**.

PORT-PLUG INTEGRATION



Port Plug of equatorial port 1



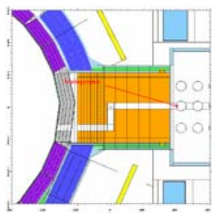
Port Plug of equatorial port 10

Design issues of upper and equatorial port plugs and integration issues in the divertor port are being addressed in a cross-party activity. The EU has addressed and is addressing:

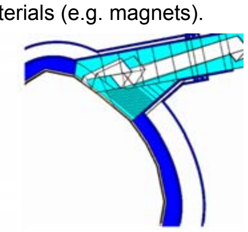
- **Manufacturing options** for the port-plug structure. Forging of the components and gun-drilling cooling channels appear to be suitable manufacturing methods.
- **Thermohydraulic analysis and hydraulic design** (e.g. draining and drying analysis) in order to optimize the cooling channels. Design of a remote-handling orbital welded water connection.
- **Neutronics analysis**: use as a design tool, and effects of diagnostic components integration → **next section**
- **Studies** of: far forward extending diagnostic modules, attachment of the blanket shield module, and a common approach with other port-based ITER systems (e.g. upper ECH launcher).

NEUTRON EFFECTS

The **allowable neutron streaming** through ITER ports is limited by the activation at the port flange (to allow manned intervention) and by the acceptable damage levels to materials (e.g. magnets).



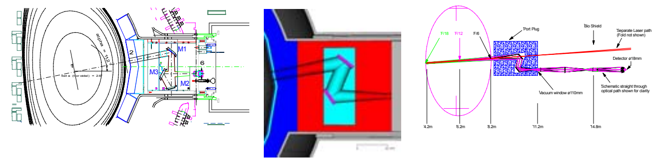
Parametric study (aperture size and dog-leg offset) of neutron streaming through diagnostic labyrinths. A complicated non-linear dependence on the two parameters is found, related to a threshold in neutron streaming when offset is small compared with the aperture size.



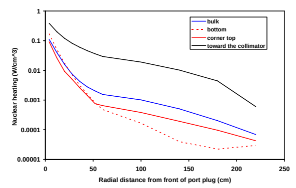
MCNP model of the CXRS diagnostic in the upper port, with two mirrors in the reference far-forward position and overlaid two recessed mirrors (0.3 m). The recessed mirror model → heating rates, neutron and gamma fluxes are 70-80% lower than the reference far forward mirror.

A straightforward rule-of-thumb of the labyrinth parameters for diagnostic design could not be derived. Reduction of two dog-legs to one is being considered for CXRS.

For remote-handling, a **gap** is needed between the port and port plug. Even with measures to **minimize neutron streaming through the gap**, for most port plugs the gap is the dominant source of streaming. This **provides a guide to the extent efforts are needed to limit streaming through diagnostic apertures and labyrinths**.



Various options considered for the labyrinth for the LIDAR system: reference 3-mirror solution (left), 2-mirrors for combined laser and scattered light (middle), 2-mirror option with direct laser beam (right).

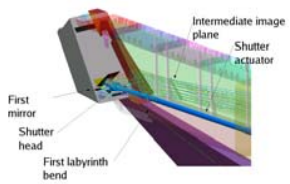


Calculated nuclear heating in the port plug as a function of distance from the front of the port plug.

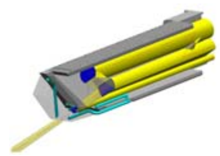
PROTECTION AND REPLACEMENT OF SENSITIVE OPTICAL COMPONENTS

Extraction of a port plug for maintenance or replacement of components is a major undertaking (only possible a few times over the ITER operating life for each individual port plug). **Sensitive optical components**, such as mirrors, may need to be replaced more often. Two alternative measures are being developed:

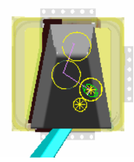
- **Diagnostic shutters**
- Optical components mounted on **extractable tubes**



Raytrace of first mirror and first labyrinth bend super-imposed on CAD model of port plug and shutter (acticated by rotating the blue rod).



One concept studied: the mirrors mounted on several extractable tubes (yellow).



End-on view of mirror and shutter tubes

Future work:

- Various options for **shutters** are being assessed.
- **Engineering feasibility study of the tube concept**: flange attachment, steps in diameter to reduce neutron streaming, free-hanging or supported front, insertion and handling mechanisms, rotation of the tube for optics alignment purposes.

PERFORMANCE ANALYSIS

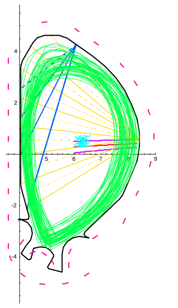
The ITER diagnostics will mainly be procured on the basis of **functional specifications**. **Performance analysis** to predict the likely capability of the diagnostics to meet the ITER measurement requirements is therefore **an important aspect of the design process**. Examples of performance analyses are given related to the derivation by an **inverse process** of physical plasma parameters from the measurements.

Possible methodologies of performance analysis:

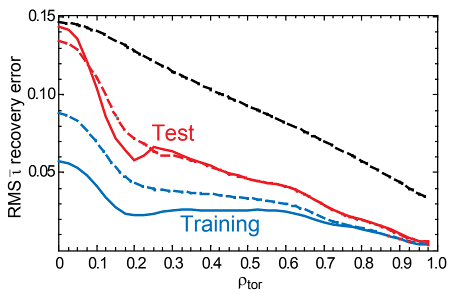
- **Statistical methodology**: covering a **large range** of the relevant plasma parameters
  - Typical question: "Are the results within the required accuracy for the required percentage of cases (e.g. 'ok in 95% of cases')"?
  - Two approaches:
    - Solving inverse problem (e.g. equilibrium solver)
    - Fitting to a database generated by forward equations (Function Parametrization, neural networks, fuzzy logic)
      → Example *q*-profile determination
- **Direct comparison methodology**: covering a **small range** of the relevant plasma parameters specifically related to the standard ITER scenarios **→ Example bolometry**
  - Typical question: "do we reconstruct sufficiently well within the requirement for typical cases?"

Performance analysis example: q-profile determination

Assessment of ***q*-profile reconstruction capability from simulated magnetics, poloidal polarimeter and MSE measurements in ITER**. Iota-bar $\bar{\iota}=1/q$ is used instead of *q* because the error propagation is more well-behaved (homoscedastic). Method used: Function Parametrization (FP) on a database of a wide class of ITER equilibria and simulated diagnostic measurements.



Range of equilibria used (green), selected mainly from what is possible in ITER rather than being variations of the ITER standard scenarios. Diagnostics are indicated.



*The best RMS recovery errors of $\bar{\iota}=1/q$ as a function of radius (ρ_{tor}) from FP regression using magnetics data (22 principal components (PCs)), 16 polarimeter PCs and 12 MSE PCs (solid curves), and magnetics&MSE data only (dashed curves). The **black curve** indicates the 10% target accuracy of the RMS $\bar{\iota}$ in the database (for each radius separately). The **blue curves** show the training dataset results. The **red curves** show the recovery errors for the test dataset which was not included in the training stage.*

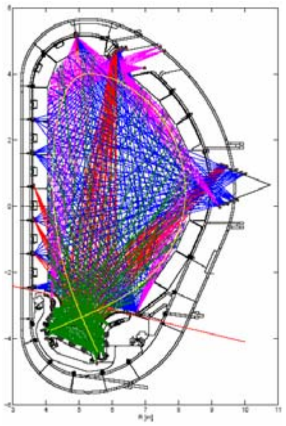
Conclusion on q-profile determination

- The target accuracy is met everywhere.
- The apparent lack of improvement when polarimetric data is added to MSE (solid versus dashed **red curves**) may be due to shortcomings in the analysis method (FP model size).

ACKNOWLEDGEMENTS

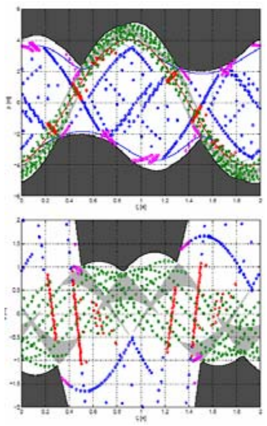
This work, supported by the European Communities under various contract of Association between EURATOM and EU Fusion Laboratories., was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Performance analysis example: bolometry

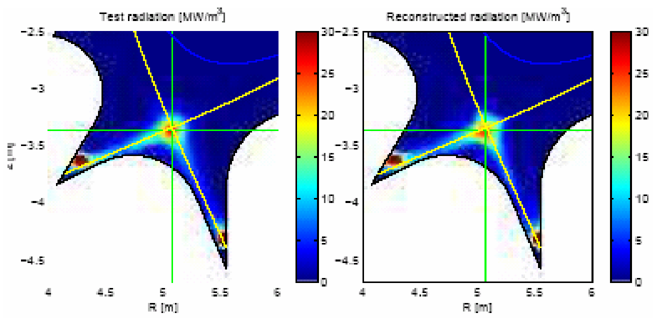


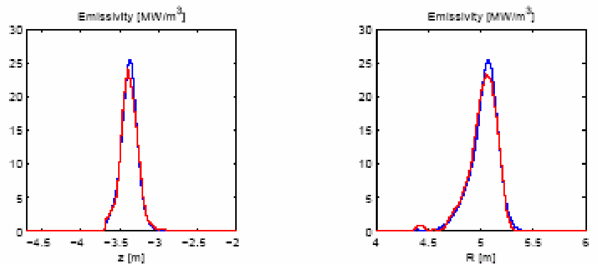
***Optimized bolometer lines of sight** (LOS) taken into account technical constraints and regions of interest.*

91 cameras with 5 LOS each



Projection-space coverage of ITER bolometry. LOS parameters: p *distance from origin (top: magnetic axis; bottom: X-point),* ξ *angle with horizontal.*





*Many situations (e.g. noise levels, number of LOS) **simulated** for bulk, attached and detached plasmas.*

***Conclusions can be drawn on the typical reconstruction-quality dependence** on e.g. noise level (strong dependence) and number of LOS (weak dependence).*

Conclusions on performance analysis in general:

- The choice of **input assumptions** (e.g. range of plasma parameters included) may have a large influence on the results:
  - It may be **impossible to compare results with earlier analysis** if the assumptions are significantly different.
  - Discrepancies also because of **differences between analysis codes or the specifics of the method** → verification of results from other analysis and **benchmarking** of codes using standardized input is important.
  - A careful consideration of the **input assumptions** in line with the aim of the performance analysis is very important.
  - To obtain the most relevant information, it seems preferable to **focus** performance analysis on **a narrow range of plasma parameters around the ITER standard scenarios**. However, it is also relevant to **verify** the performance predictions for the much **wider range of plasma parameters** possible in ITER (e.g. as in *q*-profile example).
- The **choice of statistical methods** (e.g. *q*-profile example) or **testing the performance on a few specific cases** (e.g. bolometry example) depends largely on what analysis is practical for a particular diagnostic.
- **Interpretation of simulation results is far from trivial**: it may depend on details of analysis method used and it may be difficult to extract general conclusions from a large number of test cases.
- The "**spatial resolution**" specified in the ITER measurement requirements has an **ambiguous interpretation for non-local measurements** from which the profiles are reconstructed by solving an inverse problem **→ next section**.
- Quantification of reconstruction quality is ambiguous and difficult to show graphically for **2D data**. **Derived quantities in 1D** (e.g. flux-surface averaged emissivity and cross-sections) **and 0D** (e.g. total radiated power, radiated power within the separatrix, radiated power in the divertor), however, can be shown graphically with error bars (from sensitivity analysis or statistical methods) and are a convenient and physically meaningful way to quantify the performance.

SPATIAL RESOLUTION

The definition of **spatial resolution for profiles derived from non-local measurements**, as is the case in many diagnostics, **is not trivial:**

The above example of *q*-profile reconstruction shows that for reconstructed profiles the accuracy can be sufficient requirement. The notion of **spatial resolution**, however, is useful to quantify spatial profile correlation lengths and gradients that should be resolvable.

Possible definitions of spatial resolution can include information from:

- Statistical methods (e.g. number of meaningful nodes in spline fitting).
- Maximum grid size that does not affect the reconstructed profile.
- Smallest feature/gradient in the profile that can be resolved, e.g. the smallest distance between two features that can be resolved.

These suggestions do not, or only partially, take into account **measurement errors** and the resulting effect on the reconstructed profiles. An **alternative measure of spatial resolution** (e.g. 1D in the radial direction) could be: $\Delta\rho = \varepsilon(b)/(db/d\rho)_{RMS}$, where $b(\rho)$ is the radial profile quantity and $\varepsilon(b)$ the uncertainty in reconstructed profile. The RMS gradient over a database is taken to avoid mathematical problems with zero gradients in individual profiles.

Examples of diagnostics for which the question of spatial resolution arises in ongoing performance analysis in the EU, other than bolometers and the *q*-profile, are: X-ray crystal spectroscopy imaging system, reconstruction of equilibria from magnetics data, radial neutron camera, SXR tomography, and deconvolution of laser pulse shape from LIDAR measurement.

CONCLUSIONS

- Technical solutions are successfully being developed to overcome the significant challenges posed by diagnostic integration in ITER.
- Predicting the likely performance of diagnostics in the ITER environment is not trivial. Even if all technical details of the diagnostic and environment are known, the analysis method and input assumptions chosen may have a significant impact on the results and should be carefully considered to obtain meaningful predictions.
- The definition of a spatial-resolution target in the ITER measurement requirements in inadequate. Suggestions are given for alternatives. An adequate choice will, however, depend on the analysis method (e.g. whether statistical information is available).