From present Fusion devices to DEMO:
A changing role between diagnostics and modeling

A.J.H. Donné
Is understanding needed for building a reactor?

Even though the detailed physical processes (esp. turbulence) taking place in a tokamak plasma are not fully understood we can design a fusion reactor.

A better understanding leads to improvements in reactor performance.

Richard T. Whitcomb
Invention of winglets
Scaling laws

World Wide Data Base (13 Devices)

Measured Confinement Time vs. Predicted Confinement Time

My hobby: extrapolating

As you can see, by late next month you'll have over four dozen husbands. Better get a bulk rate on wedding cake.

A.J.H. Donné; LAPD 16, 2013
A diagnostic dilemma

Diagnosticians need – at the same time – to:

– Design state-of-the-art diagnostics for present day devices (high accuracy, high spatial and temporal resolution, many channels) falsifying/verifying models

– Consider how to diagnose and control DEMO with as low a number of crude (but robust and reliable) diagnostics as possible heavily utilizing models

Although seeming to be a dilemma, both developments are highly challenging
Many measurements needed

DEMO

JET
This lecture

Introduction

New physics insight by diagnostic advances
- Present tokamak devices

Diagnostics for ITER
- Extreme engineering, environmental effects

Diagnostics for DEMO
- Strong limitations for diagnostics

Epilogue
New physics by diagnostic advances – the sawtooth*

*Warning: this part goes fast to just catch the flavour
Sawtooth instability – discovery (1974)

Discovery of the sawtooth led to the development of the full reconnection model

Island formation starts as soon as $q < 1$.

New experimental insight (1986)

Polarimetry at TEXTOR

Very precise and accurate measurements of the Faraday rotation angle (related to current density) led to the conclusion the in ohmic discharge $q_0$ stays well below 1 during sawtooth activity

In contrast with full reconnection model

More new (but confusing) insight

Two-dimensional X-ray tomography results from JET gave new input to the studies

A new sawtooth model (1986)

X-ray tomography measurements at JET have motivated the development of the quasi-interchange model


Work at TdeV falsified the earlier conclusions from the JET x-ray tomography work:
X-ray tomography with limited number of cameras cannot distinguish between full reconnection and quasi-interchange model

ECE ‘rotational tomography’ (1996)

ECE ‘tomography’ at TFTR
Assuming rigid rotation of the m=1 mode


Localized temperature bulge at low field side was interpreted as finite pressure effect $\Rightarrow$ pressure driven ballooning mode model

ECE Imaging sawtooth observations (2007)

Comparison with models

New observation: Dual flux tubes in KSTAR

Control of sawteeth is possible without fancy diagnostics

Sawtooth pacing in TCV:

Within a certain interval it is possible to force the sawtooth oscillation period to predetermined values.

No fancy diagnostics are needed!

Very simple, very robust.

M. Lauret et al., Nucl. Fusion 52 (2012) 062002
Physics still not fully understood

New and better diagnostics introduced over the years have improved our insight
⇒ New diagnostic observations drive theory

Continuous innovation is needed to ultimately lead to more optimized reactors

Much to be expected from simultaneous imaging of several plasma parameters

E.g. combined ECE Imaging with Imaging Reflectometry and Beam Emission Imaging
Diagnostics for ITER
## ITER parameters

<table>
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<tr>
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<td><strong>Fusion power</strong></td>
<td>$P_{\text{fus}}$ (MW)</td>
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<td>16 (JET)</td>
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<td><strong>Power multiplication</strong></td>
<td>$Q = P_{\text{fus}}/P_{\text{in}}$</td>
<td>10</td>
<td>0.8 (JET)</td>
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<tr>
<td><strong>Total # of neutrons</strong></td>
<td>(n/s)</td>
<td>$1.4 \times 10^{21}$</td>
<td>1.2 $\times 10^{19}$</td>
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<td><strong>Neutron flux on PFC</strong></td>
<td>(n/m$^2$s)</td>
<td>$3 \times 10^{18}$</td>
<td>3 $\times 10^{17}$ (JET)</td>
</tr>
<tr>
<td><strong>Neutron power density at plasma wall</strong></td>
<td>(MW/m$^2$)</td>
<td>$\sim 0.5$</td>
<td>$\sim 0.05$ (max) (JET)</td>
</tr>
<tr>
<td><strong>Neutron fluence</strong></td>
<td>$M$ year/m$^2$</td>
<td>0.3</td>
<td>0 (JET)</td>
</tr>
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<td><strong>Neutron fluence</strong></td>
<td>(n/m$^2$)</td>
<td>$\sim 3 \times 10^{25}$</td>
<td>$\sim 3 \times 10^{21}$ (JET)</td>
</tr>
<tr>
<td><strong>Displacements per atom in PFC (plasma facing components)</strong></td>
<td>(dpa)</td>
<td>$\sim 3$</td>
<td>0 (JET)</td>
</tr>
</tbody>
</table>

Donné, LAPD 16, 2013
Challenges: particle fluxes

- 50 times higher ion fluxes
- 5000 times higher ion fluence
- > $10^4$ times higher neutron fluence
ITER Diagnostics: many challenges

Relatively harsh environmental conditions
  – Phenomena new to diagnostic design have to be handled

Nuclear environment
  – Stringent demands on the engineering, robustness

Long plasma pulse length
  – Requires high stability

Control role of the measurements
  – Requires high accuracy and reliability

Integration of multiple diagnostics in single ports
  – Requires well organized project teams, good communication, QA

Setting up the measurement requirements
ITER will require:

An extensive set of diagnostics to provide measurements for

Machine protection
- Separatrix/wall gap, first wall temperature, etc.

Plasma control
- Plasma shape and position, plasma current, divertor diagnostics, etc.

Physics studies
- Confined alpha particles, alpha-driven modes, etc.

> 50 individual measurements
Parameters to be measured/controlled in ITER

Number of Measurements

<table>
<thead>
<tr>
<th>ITER operational phase</th>
<th>Control</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-phase</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>D-phase</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>High power DT-phase</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>High DT phase</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Hybrid operation</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Steady State operation</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>
Environmental effects: new phenomena for fusion diagnostics

**Magnetic coils**
- Radiation Induced Conductivity (RIC)
- Radiation Induced Electric Degradation (RIED)
- Radiation Induced Electromotive Force (RIEMF)

**Bolometers**
- RIC
- Nuclear Heating
- Sputtering
- Contact degradation
- Differential swelling and distortion

**Pressure gauges**
- RIC
- RIED
- Filament aging

**Neutron cameras**
- Noise due to $\gamma$-ray, proton, $\alpha$
- Radiation damage on solid state detectors

**Optical diagnostics**
- Mirror
  - Deposition, erosion
  - Swelling, distortion
- Window
  - Permanent transient absorption
  - Radioluminescence
  - Swelling, distortion

**Impurity monitoring**
- Mirror and windows
  - same as above
- Fibers
  - Permanent transient absorption
  - Radioluminescence
Radiation induced absorption and emission

HfO₂ / SiO₂ layers on Sapphire

<table>
<thead>
<tr>
<th>Irradiated</th>
<th>Irradiated + Annealed 1.5 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilted</td>
<td>Flat</td>
</tr>
<tr>
<td>300°C</td>
<td>400°C</td>
</tr>
</tbody>
</table>

Controls

1x10¹⁸ n/cm²

1x10¹⁹ n/cm²

1x10²⁰ n/cm²

Radiation Induced Emission (RL or RIE) of two types of quartz fibers exposed to gamma irradiation of 700 Gy/s

Refraactive components can be used from the end of the port plug onwards.

Radiation Induced Absorption (RIA) due to neutron irradiation

Courtesy E.R. Hodgson

A. J. H. Donné, LAPD 16, 2013
Erosion/redeposition


M. Rubel, 18th ITPA Diagnostics meeting

Set 2: mirrors at room temperature
Set 3: mirrors at temperature 140°C → 85°C. Doubled exposure time; doubled plasma parallel fluence.

Courtesy: A. Litnovsky
Transmutation was an issue for bolometers with Au resistors (transmuting into Hg)

Good results have been achieved with Pt resistors
Local absorption contours for X-mode propagation at perpendicular incidence for a low density, high temperature regime ($T_e$ on axis is 45 keV and the line average density is $0.6 \times 10^{20}$ m$^{-3}$) and represents an extreme case of what might occur in an ITER steady-state scenario.

Courtesy J. Sanchez, V. Tribaldos
Traditional methods to measure steady-state magnetic fields have problems with drifts in the integrator, etc. (apart from radiation-induced effects)

Challenge to find alternative solutions

Better integrators

Alternative magnetic field probes (e.g. Hall probes, micromechanical sensors)

Alternative measurements (position reflectometer)

Micromechanical sensors (force-balance)

Two layout types: torsional (top) and double-ended turning fork (bottom)

Blue: electrodes.
Red: Multi-turn excitation coils

A. Kärkkäinen et al., VTT, TEKES
<table>
<thead>
<tr>
<th>Eq#01</th>
<th>DIAGNOSTICS</th>
<th>package</th>
</tr>
</thead>
<tbody>
<tr>
<td>E01</td>
<td>Port Cell</td>
<td>P11</td>
</tr>
<tr>
<td>G01</td>
<td>G01-Visible-IR TV</td>
<td>P11</td>
</tr>
<tr>
<td>B01</td>
<td>B01-Radial Neutron Camera</td>
<td>P11</td>
</tr>
<tr>
<td>B07</td>
<td>B07-Gamma Ray Spectrometers</td>
<td>P11</td>
</tr>
<tr>
<td>B10</td>
<td>B10-Bubble Chambers</td>
<td>P11</td>
</tr>
<tr>
<td>B10</td>
<td>B10-High Resolution Neutron Spectrometer</td>
<td>P11</td>
</tr>
<tr>
<td>D01</td>
<td>D01-Bolometry</td>
<td>P21</td>
</tr>
<tr>
<td>E04</td>
<td>E04-Divertor Impurity Monitor</td>
<td>P17</td>
</tr>
<tr>
<td>E11</td>
<td>E11-MSE-Core on heating Neutral Beam (HB)4</td>
<td>P12</td>
</tr>
<tr>
<td>N01</td>
<td>N01-In-Vessel Diagnostic Services</td>
<td>P10</td>
</tr>
<tr>
<td>N02</td>
<td>Equatorial BSM</td>
<td>BI-xxx</td>
</tr>
<tr>
<td>N04</td>
<td>N04-Interspace Blocks and Second Enclosures</td>
<td>P10</td>
</tr>
<tr>
<td>N06</td>
<td>N06-Ex-Bioshield Electrical Equipment</td>
<td>P10</td>
</tr>
<tr>
<td>N07</td>
<td>N07-Window assemblies</td>
<td>P31</td>
</tr>
</tbody>
</table>

Many diagnostics in a single port plug
Table 7. Assessed measurement capability relative to requirements.

<table>
<thead>
<tr>
<th>GROUP 1a</th>
<th>GROUP 1b</th>
<th>GROUP 1c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measures for machine protection and basic control</td>
<td>Additional measurements for control in specific scenarios</td>
<td>Additional measurements for performance evaluating and physics</td>
</tr>
<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>
</tr>
<tr>
<td>Plasma current, $q(a)$, $q(15%)$</td>
<td>Helium density profile (core)</td>
<td>TAE modes, fishbones</td>
</tr>
<tr>
<td>Loop voltage</td>
<td>Plasma rotation (toroidal and poloidal)</td>
<td>$T_e$ profile (edge)</td>
</tr>
<tr>
<td>Fusion power</td>
<td>Current density profile ($q$-profile)</td>
<td>$n_{e2}$, $T_e$ profiles (X-point)</td>
</tr>
<tr>
<td>$\beta_N = \beta_{tot} (a B/I)$</td>
<td>Electron temperature profile (core)</td>
<td>$T_i$ in divertor</td>
</tr>
<tr>
<td>Line-average electron density</td>
<td>Electron density profile (core and edge)</td>
<td>Plasma flow (divertor)</td>
</tr>
<tr>
<td>Impurity and D,T influx (divertor and main plasma)</td>
<td>Ion temperature profile (core)</td>
<td>$n_T/n_D/n_H$ (edge)</td>
</tr>
<tr>
<td>Surface temp. (divertor and upper plates)</td>
<td>Radiation power profile (core, X-point and divertor)</td>
<td>$n_T/n_D/n_H$ (divertor)</td>
</tr>
<tr>
<td>Surface temperature (first wall)</td>
<td>$Z_{eff}$ profile</td>
<td>$T_e$ fluctuations</td>
</tr>
<tr>
<td>Runaway electrons</td>
<td>Helium density (divertor)</td>
<td>$n_e$ fluctuations</td>
</tr>
<tr>
<td>‘Halo’ currents</td>
<td>Heat deposition profile (divertor)</td>
<td>Radial electric field and field fluctuations</td>
</tr>
<tr>
<td>Radiated power (main plasma, X-point and divertor)</td>
<td>Ionization front position in divertor</td>
<td>Edge turbulence</td>
</tr>
<tr>
<td>Divertor detachment indicator ($J_{sat}$, $n_e$, $T_e$ at divertor plate)</td>
<td>Impurity density profiles</td>
<td>MHD activity in plasma core</td>
</tr>
<tr>
<td>Disruption precursors (locked modes, $m = 2$)</td>
<td>Neutral density between plasma and first wall</td>
<td></td>
</tr>
<tr>
<td>H/L mode indicator</td>
<td>$n_e$ of divertor plasma</td>
<td></td>
</tr>
<tr>
<td>$Z_{eff}$ (line-averaged)</td>
<td>$T_e$ of divertor plasma</td>
<td></td>
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<tr>
<td>$n_T/n_D$ in plasma core</td>
<td>Alpha-particle loss</td>
<td></td>
</tr>
<tr>
<td>ELMs</td>
<td>Low $m/n$ MHD activity</td>
<td></td>
</tr>
<tr>
<td>Gas pressure (divertor and duct)</td>
<td>Sawteeth</td>
<td></td>
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<tr>
<td>Gas composition (divertor and duct)</td>
<td>Net erosion (divertor plate)</td>
<td></td>
</tr>
<tr>
<td>Dust</td>
<td>Neutron fluence</td>
<td></td>
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</table>

Note: Expect to meet measurement requirements; performance not yet known; expect not to meet measurement requirements.
Diagnostics for ITER - Conclusion

Large emphasis on control of plasma parameters

Hostile environment (neutrons, gammas, ions, tritium)

Long pulses

Many of the present diagnostic techniques still work (but some marginally)

Some new techniques (alpha-particles)

Many diagnostics integrated into a port
Diagnostics for DEMO
Towards (multiple) DEMO(s)

KO-DEMO

JA-DEMO

EU-DEMO

H. Donné, LAPD 16, 2013
## ITER & DEMO parameters

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<td><strong>Magnetic field</strong></td>
<td>B/B&lt;sub&gt;max&lt;/sub&gt; (T)</td>
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<td>6,8/14,6</td>
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<td><strong>Minor radius</strong></td>
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<td>2</td>
<td>2,1</td>
<td>1,05 (JT-60U)</td>
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<td><strong>Central ion temperature</strong></td>
<td>T&lt;sub&gt;i&lt;/sub&gt;(o) (keV)</td>
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<td><strong>Fusion power</strong></td>
<td>P&lt;sub&gt;fus&lt;/sub&gt; (MW)</td>
<td>400</td>
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<td><strong>Power multiplication</strong></td>
<td>Q = P&lt;sub&gt;fus&lt;/sub&gt;/P&lt;sub&gt;in&lt;/sub&gt;</td>
<td>10</td>
<td>35</td>
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<tr>
<td><strong>Total # of neutrons</strong></td>
<td>(n/s)</td>
<td>1,4 x 10&lt;sup&gt;21&lt;/sup&gt;</td>
<td>1,4-7 x 10&lt;sup&gt;21&lt;/sup&gt;</td>
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<td><strong>Neutron flux on PFC</strong></td>
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<td><strong>Neutron fluence</strong></td>
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<td>0,3</td>
<td>5·15</td>
<td>0 (JET)</td>
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<td><strong>Displacements per atom in PFC (plasma facing components)</strong></td>
<td>(n/m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>~3 x 10&lt;sup&gt;25&lt;/sup&gt;</td>
<td>50·150 x 10&lt;sup&gt;25&lt;/sup&gt;</td>
<td>~3 x 10&lt;sup&gt;21&lt;/sup&gt; (JET)</td>
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<td>(dpa)</td>
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Challenges: particle fluxes

- 50 times higher ion fluxes
- 5000 times higher ion fluence
- up to 5 times higher ion fluence
- $10^4$ times higher neutron fluence
- 100 times higher neutron fluence
Environmental conditions more extreme than in ITER (>100 times higher neutron fluence):

No electrical and refractive components close to the plasma
Limited application for first mirrors

Very limited access possibilities

Large emphasis on

Reliability, Maintainability, Robustness

Needs:

Development programme for new materials
Testing under DEMO conditions
Application of diagnostics using mirrors and in-vessel sensors might be very difficult to impossible on DEMO.

Techniques that seem feasible are:
- Microwave techniques
- Direct line-of-sight techniques (neutrons, x-rays)
- Laser-aided diagnostics

Further technology development needed
- (e.g. transient probes, fibre-Bragg, metal photon sieve lenses, holey fibre, etc)
New technologies

- Photon sieve lense
  (Courtesy Mitre)

- Freestanding metallic transmission gratings
  (Courtesy CNRS-LPN)

- Hollow or holey fibre
  (Courtesy Optics.org)

- Photonic crystal hollow fibres
  (Courtesy Crystal Fibre)
Optimized control system for neoclassical tearing mode:
Observation and actuation via a single line-of-sight

Optimizing access

System for colinear ECE/ECRH at ASDEX
Courtesy W. Bongers
DEMO: fewer diagnostics needed

DEMO is not a flexible research machine but will have only 1-2 operating scenarios

- Smaller number of measurements/diagnostics
- Advanced predictive/analysis codes to combine data from various diagnostics in an intelligent way needed to reduce the number of required diagnostics.

Experience on ITER may guide the selection of diagnostics that can best cope with the harsh environment
Identify possible approaches to measurement needs

“fuzzy” measurements with “sharpening” based on forward modelling of various types, or consistency checks between multiple independent fuzzy data types

use of unconventional approaches (calorimetry maps for example, to get the neutron source function)

“dipstick” methods – inserting probe-based systems at intervals

sparse very constrained views where conventional windows can survive (or be replaced during operation, via identical views at different locations, used/maintained cyclically)
Dynamic state observers

Real-time control

Controller

Plasma controller

Actuator commands

Tokamak

Tokamak simulation time step

Diagnostic model

Measurement update

predicted state

updated state

z^{-1}

predicted measurements

measurement residual

Model-based, dynamic state estimator ("observer")
Unscented Kalman Filter to track TM in TEXTOR

(a) data section 1

(b) data section 2

(c) spectrogram

J. Borgers, submitted to Fusion Eng. Design
Selection of diagnostics for DEMO

Set of ITER diagnostics can be only validated to a limited extend on present day devices.

So the ultimate test of the techniques will be on ITER

The same will be true for DEMO

Going from ITER to DEMO is a smaller step for plasma physicists than that from JET to ITER, but it is a much larger step for plasma diagnosticians

Experience on ITER will be beneficial for DEMO

Note: fluence in DEMO is still ~50 times higher than that in ITER. This could imply that issues that are marginally acceptable in ITER might be impossible/unacceptable in DEMO
New physics in burning plasmas

Actuators (NBI, ICRH, ECRH, LHH) can’t be used as we are accustomed to use them.

We have to find new ways to control and to use the actuators.

Localized current drive could be an option for MHD control
Diagnostic design process

- Design of DEMO reactor
- Determination of measurement requirements & justifications
- Selection of diagnostic techniques
- System conceptual design
- Integration of diagnostics onto DEMO
- Performance Assessment Relative to Requirements
  - No
  - Design meets requirements?
    - Yes
    - Detailed design
    - No, and loop A not converging

A.J.H. Donné et al., Nucl. Fusion 52 (2012) 074015
Developing diagnostics for DEMO will be extremely challenging

Some important conventional diagnostics may not be usable

New hardware/software techniques are required

Needs innovative integral approaches and a fully new mindset/paradigm on how to use diagnostics

The limited possibilities (or impossibilities) for diagnostics at DEMO might well affect the design of the tokamak and the choice of plasma scenarios and the possibilities to control.

The diagnostics should be incorporated in the DEMO design right from the start.
The field of diagnostics is extremely challenging. All corners of the brain are needed to:

- Develop state-of-the-art techniques for present machines
- Develop the strategy (and techniques) for diagnosing DEMO with a limited number of systems