Diagnostics for FIRE

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Aspects of Plasma Diagnostics to achieve Burning Plasma Physics Goals in FIRE

• The diagnostic set should provide the same quality of data as in best present-day devices.
• High quality, reliable information on many plasma parameters will be used to provide control signals.
• New information about the alpha-particles.
• The neutron radiation environment must be considered in design of the diagnostic system.

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Outline of Talk

• Specifications of the measurement goals,

• Aspects to be considered in design:
  – Port configurations,
  – Radiation effects,
  – Specific issues for different diagnostic techniques.

• Alpha-particle measurement.
### Examples of Target Plasma Measurement Capability proposed for ITER-FEAT

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>PARAMETER RANGE</th>
<th>SPATIAL RESOLUTION</th>
<th>TIME RESOLUTION</th>
<th>ACCURACY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current</td>
<td>0.1 – 17.5 MA</td>
<td>Not applicable</td>
<td>1 ms</td>
<td>1% (Ip&gt;1 MA)</td>
</tr>
<tr>
<td>Total neutron flux</td>
<td>1x10^{14} - 1x10^{21} n s^{-1}</td>
<td>Integral</td>
<td>1 ms</td>
<td>10%</td>
</tr>
<tr>
<td>Neutron &amp; α-particle source</td>
<td>1x10^{14}-4x10^{18} ns^{-1} m^{-3}</td>
<td>a/10</td>
<td>1 ms</td>
<td>10%</td>
</tr>
<tr>
<td>Divertor surface temperature</td>
<td>200 - 2500°C</td>
<td>-</td>
<td>2 ms</td>
<td>10%</td>
</tr>
<tr>
<td>Core electron temperature profile</td>
<td>0.5 - 30 keV</td>
<td>a/30</td>
<td>10 ms</td>
<td>10%</td>
</tr>
<tr>
<td>Edge electron density profile</td>
<td>(0.05 - 3) x 10^{20} m^{-3}</td>
<td>0.5 cm</td>
<td>10 ms</td>
<td>5%</td>
</tr>
<tr>
<td>Radiation profile in main plasma</td>
<td>0.01 - 1 MWm^{-3}</td>
<td>a/15</td>
<td>10 ms</td>
<td>20%</td>
</tr>
<tr>
<td>Radiation profile in divertor</td>
<td>≤100 MWm^{-3}</td>
<td>5 cm</td>
<td>10 ms</td>
<td>30%</td>
</tr>
</tbody>
</table>
Simplified List of Measurements for Input to Control Systems

- **Fast Plasma Shape and Position Control:**
  - Magnetic diagnostics, IR camera

- **Kinetic Profile Control:**
  - Thomson scattering, Interferometer/Polarimeter, Reflectometer, ECE, CXRS ($T_i$ and He-ash), Neutron Detectors,

- **Current Profile, Rotation Control:**
  - Magnetic diagnostics, MSE, CXRS

- **Optimized divertor operation:**
  - Interferometry, IR camera, Spectroscopy

- **Fueling control:**
  - D,T monitoring (edge good enough?)

- **Disruption prevention (First-wall/ Divertor Protection):**
  - Magnetic diagnostics ($\beta$; MHD), kinetic profile set

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FIRE Port Configuration

- Large radial ports with extended necks,
- Very small vertical ports,
- X-point aligned ports to be shared with in-vessel services, and “blocked sightlines”, but could be used for divertor sightlines.

FIRE vacuum vessel concept

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Use of Access Ports

- Extremely good radial access (with shielding),
- Very limited access top and bottom,
- Use top and bottom outer ports for viewing divertors, bolometers, light arrays,
- Use tangential arrangements for interferometry, TS, etc.
The Impact of the Neutron (Gamma) Environment

• Special design and materials to be used for in-vessel systems
  – Also prevents the use of many present-day diagnostic components.

• Requirement for thick shielding, penetrated by complex labyrinths

• Constraint on the use of optical components, especially lenses and fiberoptics.
How does Radiation Impact Use of Ports for ITER?

ITER port for LIDAR Thomson scattering

ITER Physics Basis, Chapter 7

Tangential arrangement proposed for interferometer/polarimeter in ITER

Breakdown of shielding sections for ITER neutron camera

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# Radiation Effects

(Ceramics (1), Optical components (2), Mirrors (3))

<table>
<thead>
<tr>
<th>Components</th>
<th>1st Wall (Gy/s)</th>
<th>Interspace Structure/Shielding</th>
<th>Outside Vac. Vess. Port (Gy/s)</th>
<th>Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER- FEAT</td>
<td>$4 \times 10^3$</td>
<td>$\rightarrow$</td>
<td>$\rightarrow$</td>
<td>Issue at 1st wall (long-term damage) Few x 0.1 dpa</td>
</tr>
<tr>
<td>(700 MW, 0.8 MW/m²)</td>
<td>+ neutrals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIRE</td>
<td>$2 \times 10^4$</td>
<td>$\rightarrow$</td>
<td>$\rightarrow$</td>
<td>Non-issue</td>
</tr>
<tr>
<td>(220 MW, 3.6 MW/m²)</td>
<td>+ neutrals</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Components**

- Magnetics (1)
- Mirrors (3)
- MI-cable (1)
- Lost-Alpha
- Retroreflectors (3)
- Thermocouples (1)
- Gauges (1)
- Fiberoptics (2)
- Optical components ? (2)
- Vacuum-diag.
- Detectors? (1)

Numbers are approximate and average

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## Radiation Effects on Diagnostic Components

<table>
<thead>
<tr>
<th>Diagnostic Component</th>
<th>Worst Radiation Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics (and Detectors)</td>
<td>Electrical (RIC, RIED, RIEMF)</td>
</tr>
<tr>
<td></td>
<td>- Studies of RIEMF in progress for MI-cable used in coils.</td>
</tr>
<tr>
<td>Fiberoptics (and Windows)</td>
<td>Absorption, Luminescence, Numerical aperture</td>
</tr>
<tr>
<td></td>
<td>- Developments of new doped fibers in progress for reducing absorption,</td>
</tr>
<tr>
<td></td>
<td>- Luminescence problem for low-light level signals.</td>
</tr>
<tr>
<td>Mirrors</td>
<td>Mechanical + Neutrals in Surface Modification (near first wall)</td>
</tr>
<tr>
<td></td>
<td>- Studies of surface damage impact and of surface preparations in progress.</td>
</tr>
</tbody>
</table>

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Magnetic Diagnostics: Issues

- Loops, coils, MI-cable must be inside vacuum vessel,
- Maximally unfriendly environment; RIC and RIEMF, temperature, neutral particles,
- No in-built protection,
- Renew R&D program on radiation impact on ceramics/MI cable.

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Radiation Effects on Optical Systems

- Radiation discolors/blackens optical components,
- Hence must use reflective optics in high-radiation areas.
- Optical fibers suffer from:
  - Prompt luminescence,
  - Prompt absorption,
  - Long-term absorption damage,
  - Effective change in numerical aperture.
- Running fibers hot only affects the long-term absorption.
- Great disparity in radiation effects on nominally identical fibers.

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Luminescence (and Absorption) Impact on Measurement in an $\alpha$-diagnostic

Lost-$\alpha$ diagnostic on TFTR with fiberoptic outside vacuum vessel. TFTR shot at 5MW ($5 \times 10^{-2}$ MW/m$^2$) at first wall. Dose at front end of fiber $\sim$ 30 Gy/s

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Issues for other Individual Systems

• Good spatial resolution diagnostics like x-ray diodes, bolometers, CCD cameras susceptible to failure in radiation background,

• Low-light level spectroscopic measurements susceptible to radiation noise, absorption (calibration!)

• Magnetic field, density range affect choice of microwave diagnostics,

• Auxiliary heating technique affects diagnostics.

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Thomson Scattering: Issues

- Imaging system required for spatial resolution (cannot use LIDAR),
- Optical systems need shielding,
- Difficult sightline arrangement; will have to use tangential laser beam, view from nearby port, with close front-end mirror.

KSTAR Concept for TS

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Good Profile Diagnostics currently Require a Neutral Beam

- $T_i(r)$, $v_f(r)$, $v_q(r)$, $q(r)$, $n_{HE-ash}(r)$, $(E_r(r))$,
- Good poloidal rotation needs opposing views; not possible,
- Diagnostic beam near-radial; penetration at $\sim$100keV/amu problematic,
- Diode beam, $5 \times 10^9$W for <1ms for CXRS?
- MSE prefers > 300 keV/amu.

MSE q-profiles in the target phase of two JET Optimized Shear discharges. The q-profile for shot 49651 is typical for JET OS plasmas. Shot 49382 had LHCD and ICRF in the pre-heat as well as the beams and it shows a strongly reversed q-profile (Stratton, Hawkes, et al.)

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Divertor Diagnostics

• Divertor diagnostics must relate to the physics goals of the device
  – Needs strong modeling interaction,
  – Important for impurity, fueling and ash measurements, tritium accountability,
  – Need validated control schemes.

• Detachment monitoring.

• Survivability of position and shape measurements.
Diagnostics for Alpha-Particle Physics

- Lost fast-ion detectors and IR camera,
- $\alpha$-CHERS,
- Collective scattering ($\text{CO}_2$, ?),
- Li-pellet, fast neutral particle analyzer,
- Knock-on neutron,
- New confined-$\alpha$ detector???
- High-frequency Mirnov coils, reflectometry.

Fast-ion spectra from Collective Scattering in TEXTOR (Bindslev, Woskov et al.)

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Alpha-Chers can Provide Absolute Measurement of some Confined Alphas

Charge Exchange between fast beam ions and slowing-down Alphas

No data taken in TFTR during neutron pulse.
Improved optical design should provide time-resolved measurements of alpha distribution

Stratton, Fonck et al.

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## FIRE: Diagnostics Schedule

### FIRE DIAGNOSTICS SCHEDULE: REVISION 0  1 SEPTEMBER 1999

### SYSTEMS PHYSICS & ENGINEERING
- Concept Designs, R&D and Integration
- Facilty hardware integration, mock, use & installation

### START UP DIAGNOSTICS
- Magnetic Diagnostics
  - Design
  - Mechanical Fabrication
- Thermocouples
  - Design
- Fixed probes
  - Design
- Ion gauges
  - Design
- Fast pressure gauges
  - Design
- Glow discharge
  - Design
- Hard x-ray
  - Design
- Residual gas analysis
  - Design
- Plasma/IR TV
  - Design
- Bolometer array
  - Design
- Visible/UV survey spectorscopy
  - Design
- H-alpha monitors
  - Design
- Visible filterscopes
  - Design

### 2ND SET
- Survey Plasma/IR TV
  - Fabrication
- Divertor IR TV
  - Fabrication
- Moveable probes
  - Fabrication
- Bolometer arrays
  - Fabrication
- Visible survey spectorscopy
  - Fabrication
- H-alpha monitors
  - Fabrication
- Visible filterscopes
  - Fabrication

### 3RD SET
- Reciprocating edge probes
  - Fabrication
- Vacuum vessel illumination
  - Fabrication
- Soft x-ray arrays
  - Fabrication
- Soft x-ray spectrometer
  - Fabrication
- Edge Thomson scatt.
  - Fabrication

### 4TH SET
- Impurity pellet injector
  - Design
- Multichannel neutron camera
  - Design
- Escaping fast ion/Alpha-particle detectors
  - Design
- Confined alpha-particle diagnostics
  - Design

### START UP
- Facility hardware integration, mock, use & installation

### 1ST PLASMA
- Physics of ICRF/divertor
- Full DD Physics
- Full DT/Alpha Physics

### FIRST PLASMA
- RF Physics
- DD Physics
- DT/Alpha Physics

### BUILDING COMPLETION
- Divertor & 1st Wall

### VAC. VESSEL DELIVERY
- Start Tests

### YEAR

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
</table>
| Vac. Vessel Delivery | Building Completion | Divertor & 1st Wall | Start Tests | First Plasma | DD Physics | DT/Alpha Physics | RF Physics | 1 SEPTEMBER 1999 | K.M. Young 1/17/01

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Development Concerns

- What are impacts of high-field, highly shaped, high-\(n_e\), high radiation, RF-only on diagnostics selection and development?
  - Radiation “hardness” of diagnostic components?
  - Lifetime of plasma-facing mirrors, other optical elements?
  - Reliability of magnetic diagnostics?
  - ECE/reflectometry functionality?
  - Interferometry refraction/wavelength?
  - Use of bolometry, x-ray techniques?
  - CXRS and MSE techniques; capability for diagnostic neutral beam(s)?
  - Confined alpha-particles?
Physics Input Needed prior to detailed Diagnostic Design

• Will the new physics need the same high resolutions as now in U.S.?
• What input will be needed for control systems?
• What is needed for fluctuation (turbulence) measurement?
• What level of detail is needed about the $\alpha$-particles?
Provisional List of Diagnostics (1)

• Magnetic Measurements
  – Rogowski Coils, Flux/voltage loops, Discrete Br, Bz coils, Saddle coils, Diamagnetic loops, Halo current sensors, Hall effect sensors

• Current Density Profiles
  – Motional Stark effect with DNB, Infrared polarimetry

• Electron Density and Temperature
  – Thomson Scattering, ECE Heterodyne Radiometer, FIR interferometer, Multichannel Interferometer, ECE Michelson interferometer, ECE Grating Polychromator, Millimeter-wave Reflectometer

• Ion Temperature
  – Charge Exchange Spectroscopy with DNB, X-Ray Crystal Spectrometer, Charge Exchange Neutral Analyzer (edge)

• Visible and Total Radiation
  – Visible Survey Spectrometer, Visible Filterscopes, Visible Bremsstrahlung Array, Bolometer Arrays, Plasma TV and Infrared TV

• Ultra Violet and X-Ray Radiation
  – UV Survey Spectrometer, Hard X-ray detectors, Soft x-ray Spectrometer, X-ray pulse height analysis

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Provisional List of Diagnostics (2)

- **MHD and Fluctuations**
  - Mirnov Coils, Locked-mode coils, Soft x-ray array, Beam emission spectroscopy, Millimeter wave reflectometer, Collective scattering

- **Particle Measurements and Diagnostic Neutral Beam**
  - Epithermal Neutron detectors, Multichannel Neutron Collimator, Neutron Fluctuation detectors, Diagnostic Neutral Beam

- **Charged Fusion Products**
  - Escaping Alpha Particle detectors, IR TV (shared with total radiation), Collective Scattering (CO2?), α-CXRS, Knock-on neutron detectors

- **Divertor Diagnostics**
  - Divertor IR TV, Visible Hα TV, UV Spectrometer, Divertor Bolometer Arrays, Multichord visible spectrometer, Divertor Hα monitors, ASDEX-type Neutral Pressure Gauges, Divertor Thomson Scattering, Penning Spectroscopy, Divertor reflectometer

- **Plasma Edge and Vacuum Diagnostics**
  - Thermocouples, Fixed Edge Probes, Fast Movable Edge Probes, Torus Ion Gauges, Residual Gas Analyzers, Glow Discharge Probes, Vacuum Vessel Illumination

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Conclusions

• A compact advanced copper-coil tokamak, like FIRE, can make major contributions to fusion science studies leading ultimately to fusion energy,

• but significant challenges for diagnostics
  – radiation and other environmental impacts on components,
  – demand for fine spatial resolution profile data for control,
  – alpha-physics diagnostics: alpha-particles and their impact,
  – limited funding.