General information

The exercise sessions will be held as blackboard sessions, where the participants will present their solutions to the group. As such, the problems should be set up and solved before the session. The focus of the exercises lies on analyzing and discussing the task at hand together with the group: thus, a perfect solution is not required to be awarded points. A point will be awarded for each question, and a person will be chosen to present their solution from the pool.

Exercise 1.
Plasma diagnostics

(a) What is the primary purpose of plasma diagnostics in magnetic confinement fusion?

(b) List the basic groups of diagnostics used in magnetic confinement fusion.

(c) List the basic diagnostic methods in these groups.

(d) What are the main plasma parameters measured with these diagnostics?

(e) Explain qualitatively the underlying physics principles in these diagnostics.

(f) The diagnostics span the entire range of electromagnetic radiation. Can you identify the physics processes responsible for the different ranges of electromagnetic radiation?

Solution 1.

(a) The plasma diagnostics must enable [ITER Physics Expert Group on Diagnostics and ITER Physics Basis Editors 1999 Nucl. Fusion 39 2541]:

(1) Machine protection (**basic control**) – Cannot operate the machine without!

(2) Plasma control (**advanced control**) – Needed for satisfying operation!

(3) Physics evaluation (**understanding the physics**) – Not necessarily needed in DEMO, but crucial for ITER!

What measurements are required to ensure **machine protection**?

- Gap between the plasma and first wall → avoid melting
- First wall surface temperature → avoid melting
- Divertor plate temperature, fusion power → avoid melting
- Line-averaged density → prevent NBI shine through
- Locked modes → prevent disruptions (by increasing NBI torque)
- ELM types → prevent type I (giant) ELMs and divertor ablation

What additional measurements are required for **plasma control**?

- Plasma shape and position
- Plasma current, toroidal field and loop voltage
- Vertical speed
- Line-averaged density
- Plasma rotation speed
- Impurity content and influxes
- Divertor ionization front location
- Density and temperature profiles
- Radiated power
- D-T density ratio and helium densities
- Safety factor profiles
- MHD instabilities
- ELM types
- Runaway electrons

What additional measurements are required for **physics evaluation**?

- plasma control measurements but with higher time and space resolution
- edge plasma turbulence
- toroidal currents in the vessel
- neutral gas partial pressures in the divertor
- particle and energy fluxes in the divertor
- α-particle escape and confinement
- ignition domain boundaries
- radial electric fields

(b) One possible way to categorize different diagnostics methods is to group them into magnetic, passive radiation, active radiation or particle diagnostics. Other categorization schemes exist: for a discussion, see Hutchinson, Principles of Plasma Diagnostics, 2002, section 1.3.

(c)
- Magnetic diagnostics include coils and loops situated around and inside the vessel.
- Passive radiation diagnostics include bolometry, thermography, electron cyclotron emission radiometry and spectroscopic measurements from infrared to soft X-rays.
- Active radiation diagnostics include Thomson scattering, interferometry, reflectometry, polarimetry and charge-exchange diagnostics.

- Particle diagnostics include Langmuir probes and neutron diagnostics include fission chambers, proton recoil spectrometers and scintillators.

(d)
- Magnetic diagnostics are used measure magnetic fields, plasma current, loop voltage, diamagnetic energy and plasma position.
- Bolometers (foil or semiconductor) are used measure plasma radiated power whereas IR thermography measures the surface temperature of wall materials. Electron cyclotron emission is used to measure the radial profile of plasma electron temperature. Passive spectroscopic methods are used to infer e.g. the effective charge state, impurity influx and impurity concentrations.
- Thomson scattering measures electron temperature and density, interferometry measures electron density and polarimetry measures the line-averaged magnetic field. Charge-exchange spectroscopy is used to measure temperature, flow velocity and impurity concentrations.
- Langmuir probes are used to measure ion flux, electron temperature and electron density at the probe surface. Fission chambers measure neutron flux, proton recoil spectrometers resolve the neutron energy spectrum and arrays of scintillators can be used to reconstruct the neutron production distribution two-dimensionally.

(e)
- Magnetic diagnostics typically measure the voltage around a loop induced by the change in the magnetic flux passing through the loop. This change can be (electronically) integrated to give the magnetic field.
- Foil bolometers measure radiation through the change in conductivity of a gold foil as its temperature increases. IR thermography is based on an array of detectors sensitive to photons with an energy in the IR part of the EM spectrum, which generate e.g a change in voltage or resistivity that can be ”read out” electronically from the array. The intensity of electron cyclotron emission (more precisely the second harmonic e-mode) along a line of sight traveling from low-field side of a tokamak through its magnetic axis is linearly proportional to the electron temperature. The broadening of the electron cyclotron emission can be used to calculate the temperature profile along the line of sight. Bremsstrahlung emission from free electrons is proportional to the effective charge state and the square root of the plasma temperature. Passive impurity spectroscopy is based on radiation emission from electronic transitions between bound states of neutral or partially ionized impurities.
- Thomson scattering measures the intensity and Doppler broadening of photons scattered by the plasma electrons. Interferometers relate the phase-shift accumulated by a light wave traveling through the plasma to its density. Together with interferometry, polarimetry relates the rotation of polarization axis of a light wave to the magnetic field. In charge-exchange recombination spectroscopy, energetic neutral beams are used to transfer electrons to impurity ions, which radiate at a characteristic frequency (intensity, Doppler broadening and Doppler shift can give concentration, temperature and flow velocity, respectively).

- Langmuir probes are electrodes whose bias voltage is swept to determine the I-V characteristic, which can be related to the temperature and density of the plasma. Fission chambers measure the ionization produced by the fission fragments in the chamber filled with argon gas. Proton recoil spectrometers transfer the momentum of the neutron to a proton whose velocity is measured using the principle of a mass spectrometer. Scintillators measure the light produced in a transparent substance through excitation by neutron impact.

(f)
- Most of the line radiation emitted by the plasma is in the vacuum UV and soft x-ray regions, but also visible line is emitted (hydrogenic Balmer lines and low-Z impurity lines).
- Visible continuum (Bremsstrahlung) is used for deriving Z_{eff}. Typically a narrow spectral range at around 523 nm is used (happens to be free from spectroscopic line emission). However, molecular emission does happen.
- Bremsstrahlung and impurity line emission in the soft X-ray region (high temperatures)
- Hard X-rays are produced by relativistic runaway electrons hitting the wall surfaces
- Gamma rays from high energy ions (nuclear reactions in the plasma). When fast ions (fusion products, ICRH, NBI) interact with the fuel or impurity ions. Nuclear reaction gamma ray diagnosis is one of the leading methods in JET for fast ion studies.

.

Exercise 2.
Power balance of the fusion plasma

How can the following quantities be measured:

(a) the confined energy in the plasma?

(b) the total radiated power?

(c) the spatial distribution of the radiated power?

(d) the wall power deposition distribution?

Solution 2.

(a) The magnetic measurement systems can be used to track the time evolution of the plasma stored energy.

(b) The total radiated power can be estimated by utilizing an array of foil (or semiconductor) bolometers. By reconstructing the radiation profile and integrating the reconstruction, one can obtain the total radiated power. In practice, this is done with an empirical formula on the fly between the shots.

(c) Similarly as in the previous task, measuring the line-averaged radiated power using arrays of bolometers would allow a reconstructions of the spatial distribution of radiated power.

(d) Possible diagnostics for estimating the heat loads include

- IR cameras
- Thermocouples
- Langmuir probes

Exercise 3.
Characterizing plasma conditions

Imagine that your task is to characterize a plasma discharge by measuring the electron, ion and impurity densities and temperatures, and particle and power fluxes, in as many spatial locations as possible. How would you do this? Which methods would you use and why?

Solution 3.

- **Electron cyclotron emission:** Electron temperature, (the emitted frequency is localized in space (B-field dependence), and intensity is proportional to T_e

- **Spectroscopy:** Impurity and fuel fluxes from the walls. Impurity concentrations. Electron density and temperature from line broadening and line ratios of hydrogenic lines. Doppler spectroscopy using NBI CX-reactions can be used to interpret T_i and plasma flow velocities.

- **Interferometer:** Line average electron densities. Simple and robust -> Good for real time control. (Measure the phase shift of a laser beam penetrating through the plasma).

- **Photon scattering of electrons (Thomson scattering):** Very high spatial and time resolution. Repetition rate limits the minimum time interval between the data points. The system measured scattered light from the plasma electrons. The density is proportional to the intensity of the scattered light, whereas the local electron temperature is proportional to the Doppler broadening of the scattered light.

- **LIDAR (light detection and ranging):** An incoherent Thomson Scattering method.

  - Short laser pulse: sub-nanosecond
  - High speed detection system
  - Record backscattered light

  The time resolution is given by the transit time of the laser pulse through the plasma. The system is a Thomson scattering system basically, so electron densities and temperatures are the outcome.

- **Lithium beam diagnostics:** Electron density profiles, especially in the scrape-off layer.
- **Charge exchange recombination spectroscopy:** NBI ions to produce CX reactions with fuel ions and lead to line-emission. Doppler spreading for temperatures, Doppler shift for flow velocities (and/or rotation), and intensities for impurity densities.
- **Interferometry/Reflectometry** – Electron densities (line average + profiles)
  - Interferometry: *Phase shift of a laser beam crossing the plasma proportional to the plasma density.*
  - Reflectometry: *Reflection of a wave at cutoff. The position of the cutoff layer is given by the change of the phase or by the time delay of the wave. By varying the frequency, different depth layers can be investigated. The cutoff is proportional to the square root of the electron density.*
- **Langmuir Probes:** Standard divertor diagnostic. Measure the I-V –curve of the plasma. Can be used to interpret electron densities and temperatures, floating potentials. Electric field and Mach numbers can also be measured (especially with RCP systems in the main scrape-off layer outside the divertor). Can be used to interpret the **electron heat** flux to the divertor surface.
- **Infrared cameras:** Total heat flux to the divertor surface.
- **Bolometry:** Total radiated power and distribution.

Exercise 4.
Diagnostics in fusion plasmas

Assume the plasma has reached fusion temperatures.

(a) How can the fusion power density be measured?

(b) Explain the physics principles of a magnetic proton recoil spectrometer.

(c) What other neutron diagnostics exist?

(d) What are the impacts of neutrons and fast particles on the diagnostic performance and properties of materials?

Solution 4.

(a)
- The most direct method is to measure the neutrons exhausted out of the plasma.
- Also escaping charged fusion products can be measured. Technical difficulties due to detectors being very close to the plasma.
- Gamma rays emitted as a result of nuclear reactions between the fast ions and plasma particles can also be measured.

(b)

(c) Fission chambers and scintillators

(d) Mechanical properties

- Radiative swelling – Irradiation causes the sample to expand
- Irradiation hardening and embrittlement – Material becomes stronger and more brittle after irradiation
- Relaxation and creep – Bolted connections loosen up and the elasticity of springs decline
- Amorphization – Crystalline materials may turn amorphous
- Transmutation – Transmutation of the target material can lead to significant changes in the properties of the material
- Radiation-induced diffusion – Diffusion welding of contacting part.
- Sputtering – Dust production and material life time issues.

Electrical properties

- Radiation induced electromagnetic force – Irradiation of electric cables. The EMF can be comparable to the amplitude of the signal!
- Radiation induced electrical degradation – The resistance of conductors typically increase under irradiation.
- Radiation induced conductivity – The conductivity of insulators increase upon irradiation. Sometimes several orders of magnitude!

Optical properties

- Radioluminescence - Transparent materials luminesce over different wavelength ranges.
- Radiation induced absorption – Transparent materials acquire colour under irradiation. May become opaque with high dosages! Big problems for optical cables and optical elements.
- Radiation effects on polymers – conductivity of polymeric materials increase by 3 – 4 orders of magnitude. Polymers can be broken up through radiolysis. No polymer insulator cables in reactors!