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# INTRODUCTION TO PLASMA DIAGNOSTICS

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## ABSTRACT

Plasma diagnostics are based on a multitude of different physical processes with wavelengths in the range from sub-nm to tens of cm. Many different techniques are being employed for measuring the spatial profile and evolution of various plasma parameters. Although most of them are already well established, plasma diagnostics is still a very challenging and vivid discipline. On the one hand this is caused by the always-continuing effort to attain a better spatial and temporal resolution, to reach higher accuracies and to measure with more spatial channels. On the other hand diagnostic techniques based on more subtle physical processes (than used in the routine diagnostics) are continuously being developed. This paper will give a brief introduction into the field of plasma diagnostics.

## I. INTRODUCTION

During the last decade the field of magnetic confinement fusion has evolved from a discipline with many small-scaled devices to one in which the main research is done on a limited number of large machines. Equivalent scientific breakeven was achieved in JET and JT-60U,[1,2] whereas more than 16 MW of fusion power was generated in JET.[3] Although present knowledge is sufficient for building the next step machine ITER,[4] it is a given fact that many phenomena, which take place in the plasma, are still not well understood. For instance a basic understanding of the anomalous losses of energy and particles from the plasma is still lacking. Even though it is generally accepted that the anomalous losses are caused by fluctuations in the confining electric and magnetic fields, no theory has been developed giving a satisfactory explanation of the experimental observations.

This lack of understanding has not hindered plasma physicists from finding advanced operational regimes in which the overall confinement is improved. Examples are the reversed or optimized shear discharges[5] and the radiation improved modes[6] that have been established on many devices. For proper operation of the tokamak in these regimes, the active control of many plasma parameters is needed. This implies that new robust and failsafe diagnostic techniques have to be developed, for instance to control the temperature, density and current density profiles. So roughly speaking, progress in plasma diagnostics is dictated by the desire to understand the detailed physical processes underlying transport, as well as by the wish to actively control many important plasma parameters. An additional driver for diagnostic innovation comes from the requirement to have improved machine protection systems.

To obtain a better insight in the processes taking place in the plasma it is a prerequisite that as much as possible plasma parameters are diagnosed simultaneously, preferably with temporal and spatial resolutions smaller than the typical time and length scales of the instabilities. Because many of the instabilities seem to depend on the gradients of one or more plasma parameters, there is a need for multi-channel diagnostics.

Plasma diagnostics can be categorized in various ways. In this paper a sub-division according to the underlying techniques is used. In gross lines the various plasma diagnostics can be categorized in seven subgroups (magnetics, probes, spectroscopy (visible, UV, x-ray), mm- and sub-mm diagnostics, laser-aided diagnostics, particle diagnostics and fusion product diagnostics). The various groups will be discussed in some detail in this paper. The emphasis will be put on those diagnostics that are not presented elsewhere in these proceedings.

## II. GENERAL CONSTRAINTS

The constraints that are imposed upon the diagnostics are quite severe. Temperatures in magnetic confinement devices may range from several eV in the scrape-off layer to tens of keV in the plasma core. Also the density range covers many decades from $10^{17}$ – $10^{21}$ $m^{-3}$. Therefore, the diagnostic systems should preferably have a large dynamic range; even more so because access to the plasma is usually strongly limited by a small number of available ports.

For the measurement of the basic discharge behavior it is sufficient to apply diagnostics with rather coarse spatial and temporal resolution. However, if one is interested in transport processes and the underlying instabilities, the spatial resolution should be as good as possible; preferably in the order of a few mm. For the same reason the temporal resolution should be in the order of a few µs, to be able to follow even the fastest plasma processes. One should be aware though, that an improvement of the spatial and/or temporal resolution is often connected to a deterioration of the measurement accuracy (e.g. lower counting statistics or smaller signal-to-noise ratio).

Apart from the constraints on the resolution, dynamic range and accuracy, there are other complications that should be taken into account when developing diagnostics. Because of the high temperatures and densities of present-day fusion plasmas, only diagnostic techniques can be employed that have no physical contact with the plasma (except for probes that are usually applied at the very plasma edge). Hence, the plasma must be diagnosed either by analyzing the radiation and particles emitted by the plasma itself (passive diagnostics) or by probing the plasma with electromagnetic waves or particle beams (active diagnostics). Of course none of these techniques should perturb the plasma. Especially in the larger fusion devices it is important that the diagnostics are insensitive to the hostile environment (e.g., high heat loads, neutron and gamma-radiation), which can lead to thermal and mechanical stresses as well as to a large number of radiation-induced effects. Moreover, they must be well screened for the high electromagnetic stray fields around these devices.

## III. OVERVIEW OF THE DIAGNOSTICS

A schematic overview of the diagnostics is shown in Fig. 1. The frequency scale is usually used up to several hundreds of GHz. For frequencies above a few GHz also the wavelength scale is often applied. The practical range of this scale is from a few cm to about 10 nm. For shorter wavelengths it is customary to use the energy scale instead.

In the following sections the various groups of diagnostics will be shortly discussed going from low to high frequency (from top to bottom in Fig. 1). It is certainly not the intention to give an exhaustive overview of all possible diagnostics. For this one is referred to a number of textbooks,[7] review papers,[8] and conference proceedings.[9]

### A. Magnetics

Magnetic diagnostics operate in the frequency range from about 100 Hz up to several MHz. This is the frequency range in which many typical plasma processes are active, like MHD instabilities. Magnetic diagnostics are indispensable for the operation of magnetic confinement devices. They are used for measuring basic plasma parameters as the plasma current, position, shape and pressure, as well as for detecting plasma instabilities. Magnetic diagnostics make use of the electromagnetic waves emitted by the plasma and are therefore passive.

The simplest magnetic diagnostic is the pick-up coil whose integrated voltage output is a measure for the magnetic field strength. Combinations of pick-up coils are generally used to determine the plasma position and shape. If mounted inside the vacuum vessel, coils can be used up to several hundreds of kHz to diagnose fluctuations in the magnetic field. In future fusion devices, which will be operated in a (quasi-) continuous mode, pick-up coils can probably not be employed anymore since they essentially measure changes in the magnetic field. Therefore, alternative techniques, like strain gauges, Hall or NMR (Nuclear Magnetic Resonance) probes, have to be employed.

Another very basic magnetic diagnostic is the Rogowski coil, which is a solenoid wound in such a way around a poloidal cross section of the plasma that its integrated output voltage is proportional to the plasma current enclosed by the coil. Voltage loops are used to measure the loop voltage and, hence, if the plasma current is known from a Rogowski coil, also the ohmic input power. Diamagnetic loops are used to yield a value for the total energy content of the plasma (i.e. plasma pressure).

### B. Microwave diagnostics

Microwave diagnostics (also often indicated by mm and sub-mm diagnostics) are in the frequency range from 1 GHz – 3 THz. Many powerful and widely applied diagnostics like reflectometry, electron cyclotron emission (ECE) and absorption (ECA) and interferometry/polarimetry belong to this group. Apart from ECE all diagnostics in this group are active. Interferometry/polarimetry is often regarded as a laser-aided diagnostic. Most of the diagnostics in this group are extensively presented elsewhere in these proceedings.[10]

In reflectometry, a wave with a frequency below the cutoff frequency is launched into the plasma. As a consequence the wave will be reflected from the so-called critical density layer. One can deduce the position of that layer by measuring the phase shift of the probing wave with respect to a reference wave or by measuring the time-of-flight of a short microwave pulse to the reflecting layer and back. Multiple-fixed or swept frequency systems are employed for measuring the electron density profile. In general reflectometry has problems with diagnosing the central part of the density profile since the density gradient is too small here.

Interferometry is based on the phase shift that a wave experiences upon passage through the plasma with respect to the vacuum situation. The frequency is above the cutoff frequency and is a trade-off between maximum phase shift and minimum disturbance by vibrations and refraction. By also measuring changes in the plane of polarization of the wave it is possible to extract information about the internal magnetic field and, so, the current density in the plasma.

Electron cyclotron emission (ECE) is based on the cyclotron radiation emitted by the electrons during their gyration around the magnetic field lines. The frequency depends on the strength of the magnetic field and, hence, on the position in the plasma. The intensity of the radiation is for optically thick plasmas proportional to the local electron temperature. For optical thin plasmas, interpretation of ECE measurements becomes a cumbersome task (because of reflections from the vessel and the presence of suprathermal electrons). In this regime it can be more advantageous to use electron cyclotron absorption (ECA). The absorption of the radiation is a function of electron temperature and density. Therefore, an independent measurement of the electron density should be used to disentangle the electron temperature.[10]

A final microwave diagnostic, which should be mentioned, is collective Thomson scattering. This technique can be employed either for measuring fluctuations in the electron density or the velocity distribution of fast ions.[11]

### C. Spectroscopy

In a sense spectroscopic diagnostics are employed from very long to very short wavelengths. The full range runs from approximately 10 m (ion cyclotron emission spectroscopy) down to 10 pm (hard x-ray spectroscopy).

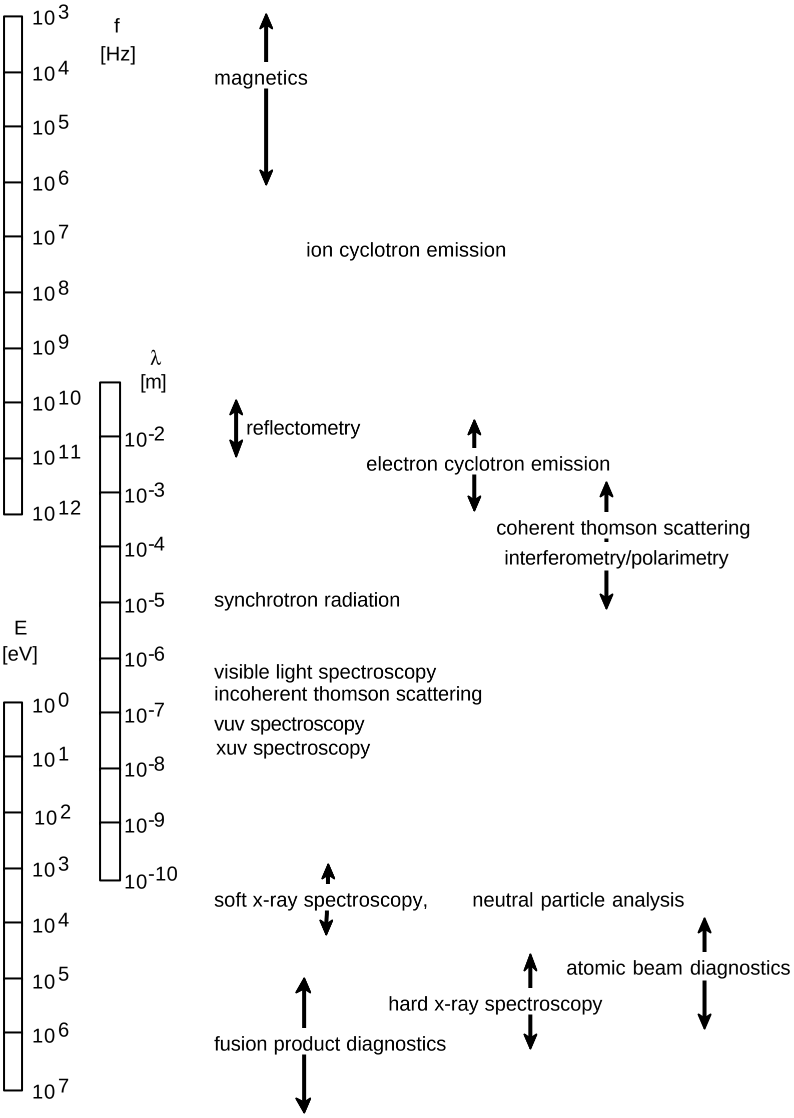

*Fig. 1. Overview of the various diagnostics on a frequency, wavelength and energy scale. 1 eV »1.24 mm »242 THz.*

However, in practice the working range of a spectroscopist is from about 10 nm to 10 µm (i.e. the range in which optical techniques can be employed). Apart from charge exchange recombination and beam emission spectroscopy (CXRS and BES) all spectroscopic diagnostics are passive.

Around 10 µm one can observe synchrotron radiation, which is a fingerprint of the runaway electrons in a tokamak. Synchrotron radiation spectroscopy is only being applied at a small number of fusion devices. However, it might become a standard technique in the future when x-ray diagnostics cannot be employed anymore because of the high background levels.

Spectroscopy in the visible, VUV, XUV and soft x-ray spectral regions can give a wealth of information on the atomic (ionic) processes in the plasma. The plasma emission in these spectral regions consists of continuum radiation (Bremsstrahlung and recombination radiation) and line radiation. The intensity of the continuum radiation is a complicated function of the electron temperature and density and the impurity content. When knowledge is obtained about the electron temperature and density from other diagnostics, the impurity enhancement factor (related to $Z_{eff}$) may be obtained from measurements in line-free spectral regions. Measurements of line intensities, broadening and shifts can yield valuable information on ion densities (albeit after considerable modeling), temperatures and plasma rotation. For many of these measurements a good spectral resolution is of prime importance.

The field of optical spectroscopy is reviewed elsewhere in these proceedings.[12]

### D. Laser-aided diagnostics

Very similar to spectroscopy, laser-aided diagnostics are applied in a very wide wavelength range.[13] However, for wavelengths exceeding 100 µm we categorize the diagnostic under microwave diagnostics. The short wavelength limit is approximately 100 – 150 nm and is continuously shifting towards smaller values because of progress made in laser technology.

Incoherent Thomson scattering is being applied at nearly every confinement device. It is a very powerful method to measure very localized values (or profiles) of the electron temperature and density. The drawback of this technique is that it only yields snapshots, since its repetition rate is limited to at maximum a few hundred Hz. Ruby and Nd:YAG lasers are most often applied for this purpose. Coherent Thomson scattering for measuring either the velocity distributions of fast ions or electron density fluctuations in the far-forward direction are often employing a $CO_2$-laser system.

With laser-induced fluorescence (LIF) transitions are induced between excited states of certain ion species. Often dye lasers are employed to tune to the specific wavelength of the transition. The induced radiation yields information on the impurity ion densities in the plasma.

An overview of laser-aided diagnostics is to be found elsewhere in these proceedings.[14]

### E. Probes

Probes are active diagnostics in direct contact with the plasma. Therefore, they can only be applied at the very plasma edge. The most well known is the Langmuir probe. The simplest probe consists of an isolated metallic pin inserted into the plasma. Only the tip is not isolated. By applying a voltage to the tip, a current is drawn from the plasma. From the exponential part of the I-V characteristic, the electron temperature at the edge can be deduced.[15]

Other plasma parameters like the electron density and the plasma potential can also be determined from probe measurements. Sophisticated analyzers with electron repeller grids often measure parameters of the ion population. The logarithmic slope of the ion collection current is proportional to the ion temperature at the plasma edge.

Bolometers are used to measure the radiation losses from the plasma in a wide wavelength range. Bolometers are also sensitive to particle losses. Wide-angle bolometers yield a value for the total radiation losses from the plasma.

### F. Particle diagnostics

Particle diagnostics are in the 10 eV – 1 MeV working range.[16] Neutral particle analysis (NPA) is in essence a passive diagnostic. In the very low energy range (up to 0.5 keV) time-of-flight analyzers are often applied to measure the energy spectrum of neutral particles escaping from the plasma. This type of instrument is especially sensitive to atomic processes in the edge of the plasma. NPA at higher energies (1 – 10 keV) is used to diagnose the temperature of hydrogenic ion species in the plasma core. Since the measurements are essentially line-averaged, extensive modeling is needed to obtain central values for the ion temperature. NPA at higher energies is employed for studying fast ion populations. In large confinement devices the number of neutral atoms emitted by the plasma core is dominated by particles emitted in copious amounts from the edge. This can be partly overcome by seeding the plasma core with neutral atoms from a beam (i.e. active NPA).

Charge exchange recombination spectroscopy (CXRS) is a hybrid of a particle and a spectroscopy diagnostic. This very powerful diagnostic can yield information on the impurity ion temperature, -density and –rotation but also on the electron density fluctuations and internal magnetic field. For the latter two parameters one observes basically the radiation of excited beam atoms.

Heavy-ion probing beams are used to study the magnetic field and electric potential of the plasma. The particles injected into the plasma are usually singly charged ions of heavy isotopes like thallium, cesium or gold. The injection energy is usually in the range of a few –hundreds of keV to several MeV to be able to penetrate the core of the plasma. The magnetic field is determined by observing the deflection of the primary beam and in addition that of a secondary beam, which is caused by further ionization of the injected ions. The plasma potential can be deduced from the energy change in the secondary beam.

Beams of energetic neutral lithium atoms may be injected into the plasma for measuring the magnetic field strength from the Zeeman splitting of its emission lines. The shift of the $\sigma$-component with respect to the unshifted $\pi$-component is proportional to the magnetic field strength. Injecting the beam of a dye laser collinear with the lithium beam and making use of the LIF effect may further increase the emission.

### G. Fusion product diagnostics

The field of particle diagnostics smoothly goes over into that of fusion product diagnostics, which operate in the energy range from 500 keV – 14 MeV. Most fusion product diagnostics are based on the passive energy analysis of particles that are resulting from fusion reactions (e.g. tritium, protons, $^3$He, neutrons and gammas).

The neutron production rate strongly depends on the ion temperature. A measurement of the neutron fluence therefore gives a first order estimate of the ion temperature. When the neutron fluence is measured along a number of well-collimated chords, the neutron birth profile and, hence, the ion temperature profile may be obtained. A problem in the interpretation of the neutron measurements is the large background of neutrons, which are generated by other processes. To partly overcome this one has to analyze the neutron energy spectrum. Time-of-flight analyzers with good energy resolution can be applied to measure the width of the neutron peaks around 2.45 and 14.1 MeV arising from d-d and d-t reactions, hence giving information on the ion temperature.

Charged fusion products like protons, tritium and $\alpha$-particles may escape from the plasma because of their high energy. When detected at the plasma edge it is possible to make a back-calculation along the trajectory of the particle to determine the point of birth of the particle.

## IV. RESOLUTION

To be able to understand the detailed plasma processes it is required to measure the various parameters with as good a spatial and temporal resolution as is possible. The temporal resolution is on the one hand often dictated by the statistical properties of the process under consideration (e.g. the minimum amount of time needed to collect enough particles in a spectrum, etc.), and on the other hand by instrumental properties (e.g. the fastest read-out time of a CCD-camera or the repetition rate of a probing laser). Especially passive diagnostics are hampered by limitations on counting statistics, whereas the limitations of active diagnostics are often determined by the state-of-the-art in technology.

The spatial resolution is in most cases dictated by the geometry of the diagnostic set-up and not so much by the physical processes under study. Many passive diagnostics like spectroscopy and passive neutral particle analysis are essentially line-averaged (see Fig. 2a). The spatial resolution in a direction perpendicular to the viewing direction depends on the detector etendue. It is tempting to conclude that the spatial resolution along the viewing line is essentially equal to the plasma diameter. However, often the signal is strongly weighted towards a certain plasma region. For instance visible light spectroscopy (in hotter plasmas) is strongly weighted towards the relatively cool plasma edge, where many line transitions take place. Other diagnostics like x-ray spectroscopy are more dominated by processes taking place in the plasma core.

Also some active diagnostics, like single-chord interferometry/polarimetry are line-averaged. Under special assumptions (i.e. cylindrical symmetry) the line-integrated measurements may be inverted to local values of the plasma parameter. The multi-chord diagnostic is essentially an extension of the single-chord setup (see Fig. 2b). Also here inversion procedures should be applied to convert the line-integrated data to local values within the plasma, albeit with less severe assumptions than used for the single-chord measurements. Very often the inversions are done numerically.

By observing the same plasma volume simultaneously from different directions the localization of line-integrated diagnostics can be drastically improved. Especially when tomographic reconstruction codes are applied to analyze the data (see Fig. 2c). With specialized mathematical reconstruction routines it is possible to make multi-dimensional maps of one or more plasma parameters. The number of and distance between viewing chords in essence determine the spatial resolution. The number of independent viewing directions, the number of detectors for each viewing direction and the geometrical distributions of views around the plasma, determines the number of poloidal and radial harmonics that still can be resolved. Tomographic techniques are nowadays widely employed in plasma diagnosis.

The spatial resolution in scattering experiments is to first order determined by the geometrical overlap between the probing beam and the viewing chord (see Fig. 2d). A very good localization can be obtained in 90° scattering experiments (e.g. incoherent Thomson scattering). Contrarily, in small-angle scattering experiments (e.g. coherent Thomson scattering) the scattering volume is stretched in one direction, leading to a less well-defined localization.

ECE is a passive diagnostic that features basically a good spatial resolution (see Fig. 2e). This is because the frequency of this diagnostic is proportional to the magnetic field strength and, hence, is a function of location in the plasma. The spatial resolution of ECE is determined by the width of the antenna pattern, the bandwidth of the detector, and by a number of line-broadening mechanisms. It can be as good as 1 cm in all directions.

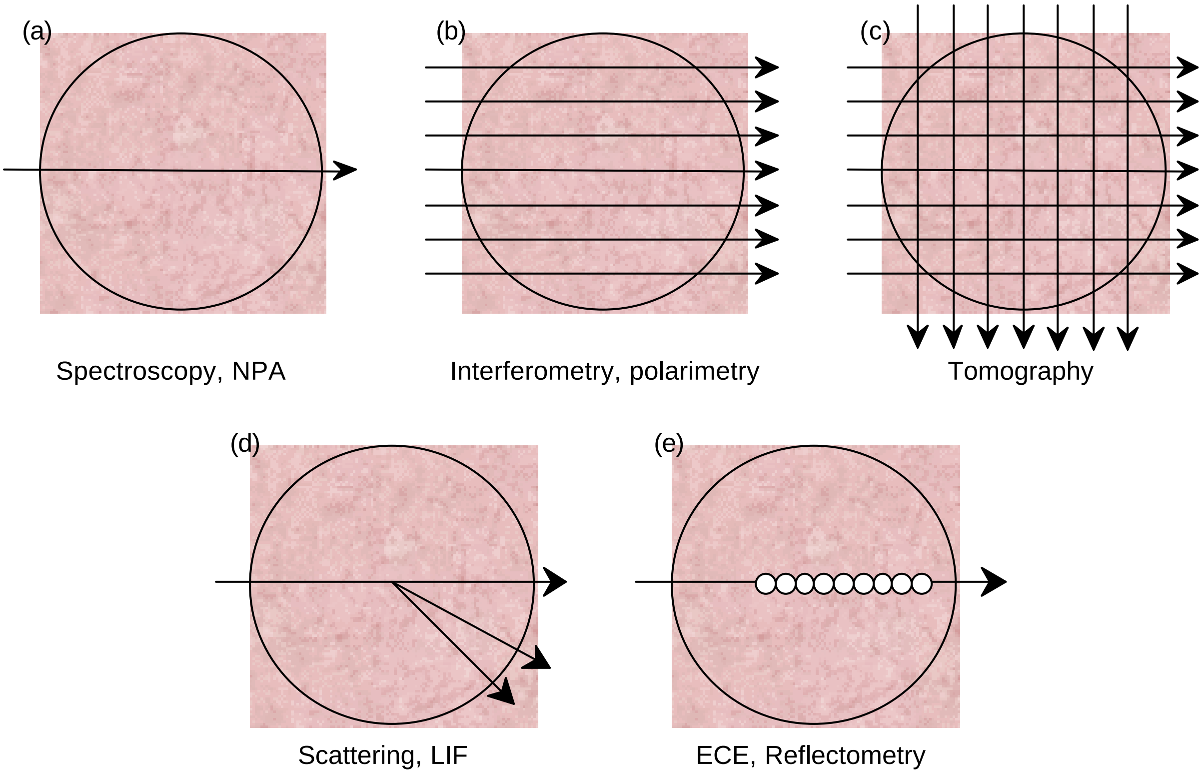

*Fig. 2. Schematic overview of various experimental arrangements: (a) single-chord line-averaged measurement, (b) multi-chord line-averaged measurement, (c) tomographic set-up, (d) scattering experiment, (e) localization along a chord.*

## V. REDUNDANCY

Very often it is not possible for a single diagnostic to cover the complete operational range of a confinement device and to measure a plasma parameter accurately at many locations with good spatial and temporal resolution.

An example is the measurement of the electron temperature profile. Incoherent Thomson scattering can measure the temperature profile at many positions with ultra-high spatial resolution (down to a few mm) and with high accuracy. Unfortunately, the repetition rates of the laser systems are not sufficient to follow the dynamic behavior of the electron temperature with a good time resolution. Therefore, it is better to employ ECE spectroscopy, giving the temperature values with a time resolution in the µs range. The problem with ECE is, firstly, that it has to be absolutely calibrated (e.g. against Thomson scattering) and, secondly, that it is only applicable for relatively high densities where the plasma is optically thick. For lower densities, the time evolution of the electron temperature can in principle be retrieved from combined analysis of ECA and interferometry measurements. When large amounts of supra-thermal electrons are present, it might be worthwhile to have a closer look at the soft x-ray spectrum, to conclude whether it makes any sense at all to speak of an electron temperature (defined in terms of a maxwellian electron velocity distribution).

Also for the electron density profile several diagnostics are available. Multi-chord interferometry yields line-integrated data that should be inverted to obtain local density values. However, these inversion procedures are not applicable in cases where the plasma is far from cylindrical symmetry. Reflectometry could still be applied in these cases, but this method cannot be used to diagnose the profile in areas where the density gradient is small. Incoherent Thomson scattering can give very localized density values for any profile shape. However, the repetition rate of this diagnostic is in the best case only moderate, as was discussed above. Moreover, absolute calibration of Thomson scattering as far as the density measurements are concerned is rather cumbersome.

Similar examples can be given for diagnostics measuring other plasma parameters, leading to the conclusion that a complementary set of diagnostics is often needed to measure a single parameter

## VI. DATA ACQUISITION AND ANALYSIS

The amount of data collected during a typical discharge is in general huge because of the necessity of a good temporal resolution and multiple channels on the one hand, and the long discharge duration on the other hand. In some experiments the emphasis is put on simultaneous operation of several multi-channel diagnostics with high time resolution. In this way the number of data channels can amount to numbers between a several hundred to over one thousand (especially including tomography systems). Due to this the total amount of data collected during a single discharge ranges typically from tens of Mbytes in smaller devices up to several Gbytes in large devices.

Data reduction methods are becoming more and more common to compress the amount of data that has to be stored. In this way the diagnostic capabilities can be exploited more fully. Especially for confinement devices with (quasi-) continuous discharges, real-time data analysis is a requirement to have the plasma information already available during the plasma discharge. On-line data reduction and analysis can profit considerably from recent developments in the field of neural networks, making it possible to convert the raw data from several simultaneously operated diagnostics into time traces of the relevant plasma parameters.

Neural networks can also be excellently applied in the off-line analysis of diagnostics data. For instance inversion of reflectometer data by means of a neural network is about three orders of magnitude faster than the classical inversion procedure. Moreover, the influence of the non-diagnosed part of the electron density profile can be accounted for in an unambiguous way.

## VII. DIAGNOSTICS FOR FUTURE DEVICES

The next step of fusion devices, that will be operated close to ignited conditions, like ITER, will have a large influence on the field of plasma diagnostics.[17] Diagnosticians will be facing many new problems. Firstly, the diagnostic access will be strongly limited because a large number of ports are needed to facilitate machine systems (like heating devices, articulated robot arms for remote handling). In other words many different diagnostics have to be integrated into only a limited number of diagnostic ports. Secondly, diagnostic components that are close to the plasma are exposed to high heat fluxes as well as to high background of neutron and gamma radiation. Extensive R&D is needed to find proper solutions for the various radiation-induced effects.[18] Thirdly, because of the high central densities and temperatures in combination with low densities at the edge and divertor ($5\ \text{eV} < T_e < 30\ \text{keV}$; $10^{17}\ \text{m}^{-3} < n_e < 10^{21}\ \text{m}^{-3}$), combinations of diagnostics with wide dynamic range are required. Fourthly, the diagnostics should be tritium compatible implying that devices must be build up in as modular way such that parts of it can be removed by remote control. Finally, the diagnostics should be reliable, also during the (quasi-) continuous operation of ITER when discharges with duration of up to 1000 s will be made.

A large emphasis in diagnostics R&D is presently placed on the development of optical components (mirrors, windows, fibers) and waveguides that can withstand high heat loads and large fluxes of gamma and neutron background radiation.[18] Most of the present diagnostic systems can be applied also at future fusion devices, albeit that many changes and improvements should be made. However, it is clear that several diagnostics that are routinely used on many present confinement devices (magnetics, broadband-swept reflectometers) may have problems with the long discharges. Others like x-ray diagnostics cannot be applied in a simple way because of the high background of neutron radiation. Particle diagnostics are not easy to apply for diagnosing the core of the plasma, because of the high attenuation of neutral particles on their way out. New techniques like strain gauges for diagnosing the magnetic field, synchrotron radiation for the runaway electrons, fast wave reflectometry for measuring the D/T ratio have to be further developed.

It should be mentioned that the diagnostic design process for next step of fusion devices is different from that of most present day machines. Hitherto, the machine was often first built, and after that the diagnostics were designed and implemented. Given the complexity and costs of diagnostics for future devices, along with the limited access to the machine, diagnostics should be included into the machine design right from the beginning. In this way the diagnostic access ports can be optimised. An important first step in this process is to develop the *minimum* requirements that support the measurements for machine protection, basic and advanced control as well as those for physics evaluation in the various operational scenarios. All requirements should be justified, such that it is clear in one glance which operational scenarios (and more particularly physics experiments) are not anymore supported in case the requirements are not met. In case of a mismatch one can either put more effort into the diagnostic design (e.g. more channels, other techniques) or one can decide to relax the requirements even though this could mean that some physics scenarios are not anymore supported. The requirements along with the justifications are also fundamental in making a prioritisation of diagnostic techniques,

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