Visible light tomography on RTP

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Introduction

X-ray tomography has been widely applied as a tokamak plasma diagnostic. Emission tomography in the near-IR, visible and near-UV on the other hand is not very usual. In a few cases it has been used to study line-emission profiles[1-3] and Z_{eff}-profiles[4-6] in a narrow spectral region, and the total spectral emission in a broad wavelength range.[7] For these studies either a moving detector, a moving mirror or a very limited set of detectors looking at the plasma in only one or two directions have been used. Hence, the resulting spatial resolution is quite low as well as the temporal resolution in the cases of moving parts. Moreover, often assumptions about the symmetry have to be made.

Besides the study of line-emission and Z_{eff}-profiles, it would be very useful to have a diagnostic to study fluctuations and substructures in the plasma, which requires a good spatial and temporal resolution. Therefore, a large number of detectors with fast electronics is needed.

A diagnostic for visible light tomography is being prepared for the Rijnhuizen Tokamak Project (RTP). Light emitted in the range of 200 to 1100 nm will be detected by five cameras positioned around the plasma in one poloidal plane. Each camera has 16 detector elements. The 80 channels are provided with parallel electronics with a bandwidth of

200 kHz. Imaging systems are used to collect the light on the detector elements. The resolution of this system is of the order of 1 cm. Optical filters in front of the detectors can select interesting wavelength ranges, such as spectral lines or a line-free part of continuum radiation. As far as we know, this is the first time that a tomography system for a tokamak is built for this wavelength region with so many detectors and such a large bandwidth for the electronics.

Plasma-physics aspects

Z_{eff}-profiles can be reconstructed from measurements of the continuum radiation (Bremsstrahlung) in a line free part of the spectrum with absolutely calibrated detectors. The relation between the emitted continuum radiation and Z_{eff} is:[5]

$$\frac{dE}{d\lambda} \propto \frac{n_e^2 Z_{eff}}{\lambda\, T_e^{1/2}} e^{-hc/\lambda T_e},$$

where E is the local emissivity (units W m^{-3}), λ the wavelength, n_e and T_e the electron density and temperature, respectively. The factor of proportionality can be derived from theory and is relatively well known. Values for n_e and T_e are obtained from the multichannel interferometer[8] (19 channels) and the electron cyclotron emission radiometer[9] (20 channels) on RTP. However, these diagnostics only give profiles when certain assumptions about symmetry in the plasma are made, so the requirements on the reconstruction of the continuum radiation are limited to about the same resolution.

Line emission of hydrogen (H_α, H_β) and impurity ions, and charge-exchange emission can be measured by using narrow optical filters. The impurity line radiation is proportional to $n_e n_i$ with a small dependence on T_e, where n_i is the impurity ion density. The emissivity of H_α is proportional to $n_e n_H$. Hence, when the n_e-profile is known, H_α and impurity ion profiles can be calculated. The same limitations as in the case of continuum radiation apply.

The study of filamentation and other substructures sets completely different requirements than above. Recent measurements with the Thomson-scattering diagnostic on RTP give strong evidence for the existence of filaments in the plasma.[10] These seem to have a diameter of the order of 3 mm in the centre of the plasma, i.e. in agreement with the theoretical expected dimension of the ion Larmor radius. On other tokamaks much evidence has been found that filaments exist in the edge of the plasma. The light in the visible region is mainly from the plasma edges, and therefore a visible light tomography diagnostic should be suitable to visualize these structures. With only 80 detectors and a plasma radius of 0.16 m, the tomographic reconstruction cannot be expected to have a high enough resolution to observe such small structures in a direct way. However, it seems possible to obtain information about the structures indirectly by using algorithms that take into account the poloidal rotation of the plasma (plasma velocity 10^3-10^4 m/s at the edge) and the use of measurements at succeeding sampling times. Therefore a high sampling frequency is necessary. The bandwidth of the electronics is about 200 kHz, making a sampling frequency of 500 kHz—1 MHz possible, yielding a temporal resolution of 2—5 μs.

The visible light tomography system is positioned at the same cross section as the 80-channel X-ray tomography system for RTP.[11] Since X-rays originate primarily from the centre of the plasma, and visible light from the edge, these diagnostics are complementary.

Tomography

Several algorithms for reconstructing emissivity profiles from the measured line-integrated emissivities exist. The most widely applied method for X-ray tomography on tokamaks is Cormack's method.[12] However, this method cannot be used because it is only applicable to pinhole camera systems. Furthermore, it uses certain assumptions on symmetry, and it is not suited to reconstruct a "hollow" emissivity profile as is the case in the visible region.

Another method that has also been applied in plasma physics is the maximum entropy method.[7] In this case the profile is reconstructed such that its entropy in the sense of information theory is maximal with some constraints regarding the total emitted power, the measured intensities and a certain amount of noise. The advantages of this method are that no assumptions about the symmetry are needed, that smoothing takes place automatically to the resolution limit of the system and that a useful reconstruction can be obtained with relatively few detector channels. The method can be further improved when an approximate profile is known (e.g. from other diagnostics) and the reconstruction is made to have minimum cross-entropy with respect to the approximate profile,[13,14] making it easier to visualize deviations such as fluctuations.

Presently the maximum entropy algorithm of Holland and Navratil[7] is being implemented for the case of our optical system. This algorithm will suffice for the studies of spectral line emission and Z_{eff}-distributions. For the fluctuation measurements, however, a more advanced reconstruction will be needed, for example a three-dimensional one (two spatial dimensions and time) in which the poloidal rotation of the plasma is taken into account.

Optical system

The optical imaging system has been designed to obtain as much light as possible. This is essential to have a signal-to-noise ratio that is sufficiently high to resolve structure when impurity lines are observed, and to be able to see fluctuations. Therefore, an imaging system is used instead of pinholes. In four cameras sets of mirrors are used, in the fifth camera a lens system. In Fig. 1 the positions of the mirrors and lenses with respect to the vacuum vessel of RTP are shown. The mirrors are mounted in a Z-configuration, which reduces coma. They are placed inside the vessel where the viewing angle can be larger than when placed outside the vessel; furthermore, smaller vacuum windows are possible. With mirrors it is possible to view the plasma from directions that would not have been possible with lenses. Another advantage of mirrors is that they do not suffer from chromatic aberration, which would distort the image when a large spectral region is studied.

The mirrors are spherical, but cut to rectangles to fit into the vacuum vessel. They have a reflective coating of silver and a protective coating of YO_3 to withstand the conditions inside the vessel. The focal length of M_1 is about 560 mm (i.e. the distance to the back side of the plasma as seen from the mirror), and that of M_2 is about 155 mm (the detector is in the focal plane of this mirror). The side-camera has a lens system instead of mirrors to be more flexible; presently an ordinary camera objective is being used. A disadvantage of optical imaging by mirrors and lenses is that it is complicated to find an analytical expression for the amount of light emitted by the plasma and received by each detector, contrary to the case of a pinhole camera. Therefore, ray-tracing calculations are used for this.

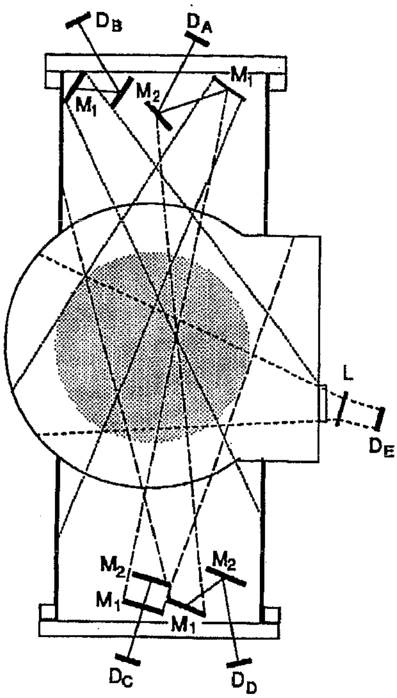

Figure 1. The configuration of the optical components with respect to a poloidal plane of the tokamak (the plasma is shaded). The Ds are the detectors, M_1 and M_2 are mirrors and L is a lens system.

Care must be taken to have a good coverage of the plasma. When no assumptions about symmetry are made, each part of the plasma cross-section should at least be covered twice. Except for some minor regions this is the case, as can be seen in Fig. 1. The configuration is the result of a compromise between the magnification (the quotient of the focal lengths of the two mirrors) needed for two-fold coverage and the required resolution (about one centimetre). In Fig. 2 the coverage is presented in another way. A three- to four-fold coverage in the impact parameter p with a reasonable distribution over the impact angle ϕ can be observed. The side-camera E can be moved so that at $\phi \approx 90°$ and low p-values the coverage is improved at the expense of some larger uncovered areas at $\phi \approx 270°$ and large p. The impact angles in Fig. 2 were largely constrained by the limited openings of the access ports and the cameras for X-ray tomography that are mounted in the same ports. The result of these constraints is that two of the cameras view a plane that is slightly tilted with respect to the poloidal plane. This, however, has a negligible effect because the plasma moves much further between two sampling times than the plane is tilted.

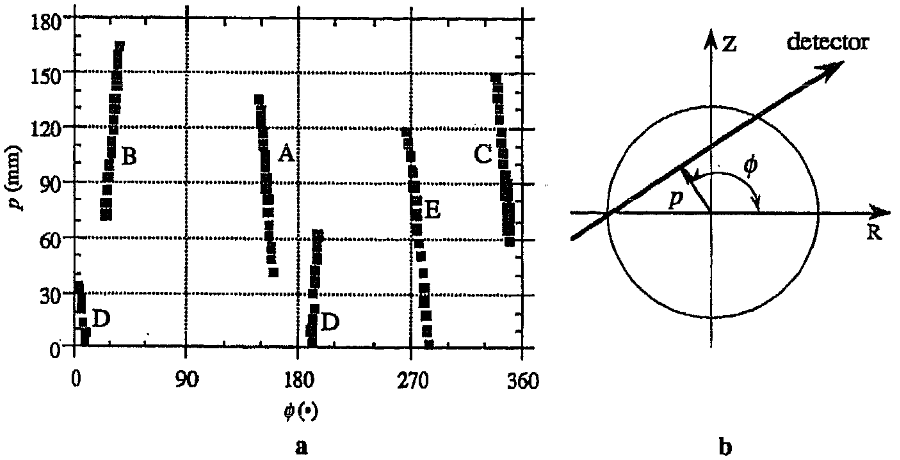

Figure 2. (a) The distribution of the observation chords in the (p,ϕ)-plane and (b) the definition of the impact parameter p and impact angle ϕ. The letters in (a) correspond to the designation of the cameras in Fig. 1.

Electrical system

For the detectors a photodiode array is used (Hamamatsu S2313-Q35). The photocurrent is amplified by a trans-impedance amplifier with an effective bandwidth of 200 kHz and a line driver for the 30 m long coaxial cable to the data-acquisition system. There the signals are amplified, filtered and digitized by a 12 bit, 1 MHz ADC which has a local microprocessor and an internal memory of 0.5 Mbyte per channel.[15] All processing is done in parallel. The local processor will do digital filtering and data reduction, but at a later stage it may execute tomography routines as part of a network of microprocessors.

The response of the cameras is about 0.4 V/μW for red light, yielding typical signals of the order of 1 V when the entire spectrum is observed, at a noise level of less than 1 mV (peak-to-peak).

The camera is positioned in a copper box, which is connected to the Faraday cage for electric shielding. Because the cameras are close to the coils for the plasma position correcting fields, magnetic shielding is also very important. μ-Metal has little effect because it saturates in the high magnetic field, so ordinary tin-plate is used around the camera. Because the feedback system for plasma position control on RTP is chopper-controlled, large changes in the magnetic field occur when the field is turned on or off, causing induction voltages in the electronics. This problem has not been entirely solved yet.

Measurements with three cameras

Three of the five cameras have been installed on RTP. Raw signals from one detector are shown in Fig. 3. Plasma phenomena such as raised emission during ECR heating, sawteeth and m=2 activity can be observed. The latter two phenomena have been confirmed by other diagnostics. Rotation of the m=2 mode can be determined from the time lag between

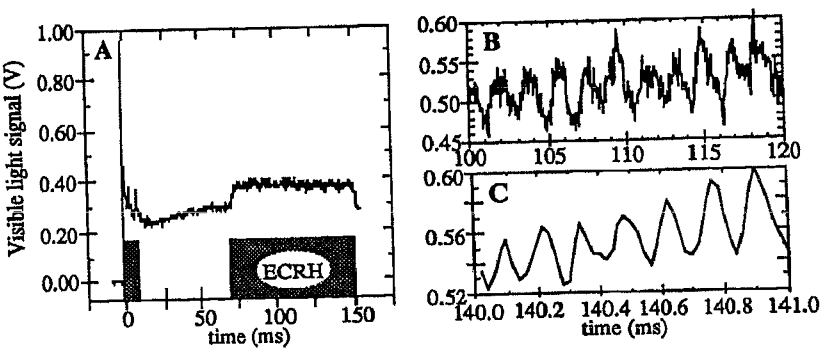

Figure 3. Raw signal from one of the detectors. A: the signal during one shot where the effect of ECR heating can be observed. On a smaller timescale sawteeth (B) and m=2 activity (C) can be distinguished.

signals from different detectors. Reconstructions of emission profiles will be made with data from these three cameras and some assumptions about symmetry when the reconstruction routines become operational.

Conclusions

A system for visible light tomography has been constructed and has already been partly installed on RTP. The optical configuration is being implemented in the maximum entropy reconstruction routines. Several plasma phenomena can be observed from the raw signals of the cameras that are operational. Fluctuation measurements will be possible when some interference problems caused by plasma control systems have been overcome.

Acknowledgements

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