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Visible light tomography using an optical imaging system

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A system for tomography in the wavelength range 200–1100 nm has been designed for the Rijnhuizen Tokamak Project (RTP). The plasma is viewed from five directions in one poloidal plane with a total of 80 detectors. An optical imaging system consisting of two spherical mirrors for each viewing direction is used to combine a good spatial resolution (1 cm, the minor radius of RTP being 17 cm) with a sufficiently high signal level for the fast electronics (200 kHz). Because of the complexity of the imaging, implementation of the system into common tomography codes is not straightforward. Ray tracing is used to calculate the contribution of the local emissivities in the plasma to the measured signals of the various detectors.

I. INTRODUCTION

X-ray tomography has been widely applied as a 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 was used to study line-emission profiles¹ and Z_{eff} profiles² in a narrow spectral region, and the total spectral emission in a broad wavelength range.³ For such studies either a very limited set of detectors or a moving detection system was used, resulting in a low spatial or temporal resolution.

The research on the Rijnhuizen Tokamak Project (RTP) is dedicated to the study of anomalous transport and turbulence in tokamaks. The tokamak (minor radius 17 cm) is therefore equipped with a large set of advanced diagnostics,⁴ among them an 80-channel x-ray tomography system for studying x-ray emission from the central part of the plasma. To complement the x-ray tomography setup, a diagnostic for visible light tomography is being prepared for RTP in almost the same poloidal plane. Studies of fluctuations and structures in the edge of the plasma, where most visible light is emitted, can be undertaken. Furthermore, the visible light tomography system will be used to measure H_{α} emission profiles and impurity profiles, and to obtain information for determining Z_{eff} profiles by selecting particular wavelength regions with optical filters. The good spatial and temporal resolution required for these studies explains the large number of detectors as well as the fast electronics applied in this system.

II. OPTICAL SYSTEM

For tomography a large number of line-integrated measurements from many different viewing directions is needed. Reconstructions without strict assumptions about symmetry are possible only if the chords of different viewing directions overlap. In tokamaks it is difficult to fulfill these requirements: the restricted access to the plasma lim-

its the number of viewing directions, whereas the number of viewing chords is limited by the cost of the detectors and the electronics. In the present case the emphasis is put on achieving a high spatial resolution to make it possible to resolve small structures in the plasma. A more than two-fold coverage of the poloidal plasma cross section had to be sacrificed to achieve this with a limited number of detectors.

To collect a sufficient amount of light, an optical imaging system has been designed instead of a much simpler pinhole system. Four of the viewing directions have mirror systems, the fifth viewing direction temporarily having been equipped with a lens system. In Fig. 1 the positions of the mirrors and detectors with respect to a poloidal section of the vacuum vessel of RTP are shown, as well as the viewing "beams" of some detectors. The mirrors are placed inside the vacuum vessel where they can collect more light than would be possible from outside the vessel. Further advantages are the possibility of viewing the plasma from more extreme directions than without mirrors, and that only relatively small vacuum windows are required. Moreover, in contrast to lenses, mirrors have no chromatic aberration by nature, which is important if the detection system is used in the entire wavelength region where the photodiodes are sensitive. The required imaging and mechanical constraints, such as the size of the access ports and the presence of the x-ray tomography system, determine the positions of the mirrors. The imaging systems A and D (see Fig. 1) are in exactly the same plane, while systems B and C are somewhat tilted with respect to the poloidal plane. Since the tilt is small compared to the toroidal correlation length of the fluctuations, it will have a negligible effect on the tomographic reconstruction.

The mirrors are spherical, but cut to rectangles (60 mm in the poloidal direction and 16 mm in the toroidal direction) to fit into the vacuum vessel. To obtain a spatial resolution of 1 cm while the detector elements are 2 mm wide, mirrors have been chosen with "focal lengths" of about 562 mm (M_1) and 155 mm (M_2), with the focus on the opposite side of the plasma. In this way an almost twofold coverage of the plasma (Fig. 1), and a reasonable

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FIG. 1. The regions seen by the detector elements in the poloidal plane of the plasma (shaded) with respect to the vacuum vessel. The detectors for the different viewing directions are numbered D_A through D_E and for four viewing directions the rays that reach every third detector element are shown. M_1 and M_2 are mirrors. For the fifth-viewing direction with a lens L only the total region viewed is shown.

coverage in the (p, ϕ) plane (Fig. 2) are obtained, where p is the distance of the ray to the plasma center and ϕ the angle of the line perpendicular to this ray with the horizontal. The quartz mirrors have a reflective coating of Ag/Al, and a protective coating to withstand the conditions inside the vessel and to facilitate cleaning. Specific wavelength regions can be selected by optical filters, e.g., inter-

FIG. 2. The distribution of the rays of Fig. 1 in the (p, ϕ) plane. Each "cloud" of points corresponds to one detector element and the letters to the designation of viewing directions in Fig. 1.

ference filters, that can be inserted between the vacuum window and the detector. However, very narrow wavelength regions (< 20 nm) cannot be selected because the interference filters have an angular dependence while the angle of incidence of the rays on the filter varies and can be as large as 20° . Therefore only very intense spectral lines can be studied.

To determine which part of the plasma is observed by each detector and other important parameters for tomography, ray-tracing codes have been developed and used. This is necessary because it is difficult to obtain an accurate analytic description of the complex imaging system and because accurate measurements on the system are difficult to perform. The ray-tracing calculation does not have these shortcomings, since the positions and shapes of the mirrors can be measured accurately. Figures 1 and 2 have been obtained by such a two-dimensional ray-tracing calculation (because the systems B and C are out of the poloidal plane these have been projected onto this plane). In tomography, in particular in the algebraic reconstruction technique (ART) and the maximum entropy method, a so-called weighting matrix^{3,5,6} is used. The matrix describes the relation between the locally emitted power in the plasma and the power measured by each detector, thus containing all the information about the imaging system, detectors, and the grid that is applied to the poloidal plane. If this reconstruction plane is divided in N cells, the emissivity of the n th cell is g_n (units W m^{-3}), there are M detectors and the power measured by the m th detector is P_m (units W), the relation between g_n and P_m can be written as

$$P_m = \sum_{n=1}^N W_{mn} g_n,$$

where W is the weighting matrix. The elements of the weighting matrix contain geometrical information (the area of the detector and the imaging), and information about the volume of the emitting "grid point" and the sensitivity of the detector. The geometrical contribution to the weighting matrix is in fact the fraction of the solid angle which the detector takes up, seen from the emitting point through the imaging system, with respect to the total solid angle. This can be calculated quite easily by tracing rays equally divided over 4π sr and determining how many of these reach a specific detector element. For the examples discussed in this paper this has only been done in two dimensions (the poloidal plane), while the contribution of the third dimension (the toroidal direction) has been approximated. This is possible because the imaging in the toroidal direction is quite simple due to the limited size of M_1 with respect to the focal length. However, for the calculation of the matrix that will be used in the tomography routines, three-dimensional ray tracing is necessary. It is interesting to note that the angular dependence of the transmission of an interference filter can be incorporated in the matrix because the angle of incidence of each ray can be calculated.

In Fig. 3(a) the matrix elements for one detector are shown. Each "square" in the figure corresponds to a cell in the reconstruction plane, the "height" to the value of the

FIG. 3. (a) Three-dimensional graph of the elements of the weighting matrix belonging to one detector element of the visible light tomography system. (b) Contour plot of the matrix elements of the same detector element, but for a larger part of the reconstruction plane [the part of (a) is indicated]. (c) Contour graph of the weighting matrix of a pinhole imaging system with the same properties as the mirror imaging system.

matrix element (only a small part of the entire plasma is shown). In Fig. 3(b) a larger part of the same “beam” is shown as a contour plot. The matrix elements are neither constant over the different cells along the viewing direction [Fig. 3(b)], nor in the perpendicular direction [Fig. 3(a)]. In Fig. 2 this nonuniformity is reflected in the shape of the area in (p, ϕ) space corresponding to one detector element. In Fig. 3(a) the width of the peaked part of the beam is about 1 cm (the “resolution”). The peaked part of the adjacent beam will overlap the low region, so that the peaked parts are very close, but well separated. A contour plot of the matrix of a pinhole camera with a comparable resolution and meeting the same mechanical constraints as the mirror systems is shown in Fig. 3(c) for comparison. The beam of the pinhole system is more symmetric and the height of the beam decreases with the distance by the same factor as the width increases. In our case the mirror system is preferable since the calculations showed that the detec-

tors receive more than one order of magnitude more power than in the pinhole case.

In the present configuration it is possible that light reaches some detectors directly without imaging of the mirrors. This undesirable effect will be reduced by placing shields close to the plasma with openings only for the beams as seen in Fig. 1. Such shields could also help to reduce undesirable reflections of light on the walls of the vessel.

III. ELECTRICAL SYSTEM

As detectors an array⁷ with 35 silicon *pin* photodiodes is used. 32 of the diodes are connected in pairs to form 16 detector elements. These detectors are sensitive in the wavelength range 200–1100 nm with a maximum quantum efficiency of 88% at 720 nm. The photocurrent of each element is amplified by a transimpedance amplifier which has a field-effect transistor input. The response of the detection system is about 0.4 V/ μ W 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 effective bandwidth is about 200 kHz. After the amplifier there is a line driver for the 30-m-long coaxial cable to the data-acquisition system. The amplifier and line driver were designed in the laboratory. After filtering and additional amplification, the signals are digitized by a 12-bit, 1-MHz ADC which has a local microprocessor and an internal memory of 0.5 Mbyte per channel. All processing is done in parallel. The local processor will do digital filtering and data reduction.

The detector array, preamplifiers, and line-drivers are placed in copper boxes that are connected to the screened data-acquisition room for electric shielding. The boxes are close to the coils for the plasma current and the plasma position correcting fields. Because the feedback system for plasma position control on RTP is chopper controlled, large changes in the magnetic field occur when the voltage for the coils is turned on or off, causing induction voltages in the electronics. Therefore magnetic shielding is essential. μ -metal has little effect because it saturates in the high magnetic field, so ordinary tin plate is used around the box. This approach has reduced pick-up problems largely, but not completely. When interpreting small signals the effects of the chopper spikes should be considered.

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