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Introduction

A system for tomography in the wavelength range 300 - 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 *pin*-diode detectors. To obtain a sufficiently large number of photons on the detectors and to have a good spatial resolution, an optical imaging system relatively close to the emitting plasma is used to collect the light. This is in contrast with pin-hole cameras or lenses on a large distance from the plasma that are normally used in tomography. The regions of the plasma viewed by different detectors are effectively 1 cm wide (the plasma radius in RTP is 17 cm). The electrical system has a large bandwidth (200 kHz) so that fluctuations can be monitored on a microsecond timescale. Different wavelength regions can be selected by optical filtering, e.g. to study H_α- and Z_{eff}-profiles. For four of the viewing directions the imaging system consists of two spherical mirrors inside the vacuum vessel; one viewing direction has a lens system outside the vacuum instead (see Fig. 1). The system for visible light tomography has been described in more detail in Ref. 1.

Preprocessing data for tomography

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 g in the plasma to the power f measured by the various detectors[1]. This can be expressed in a so-called weighting matrix W:

$$f_j = \sum_{i=1}^{N} W_{ji} g_i \quad , \tag{1}$$

where i is the indicator of the N cells in which the poloidal cross-section is divided, and j indicates one of the M detectors. Inversion of this problem by tomographic techniques gives an approximate emission profile.

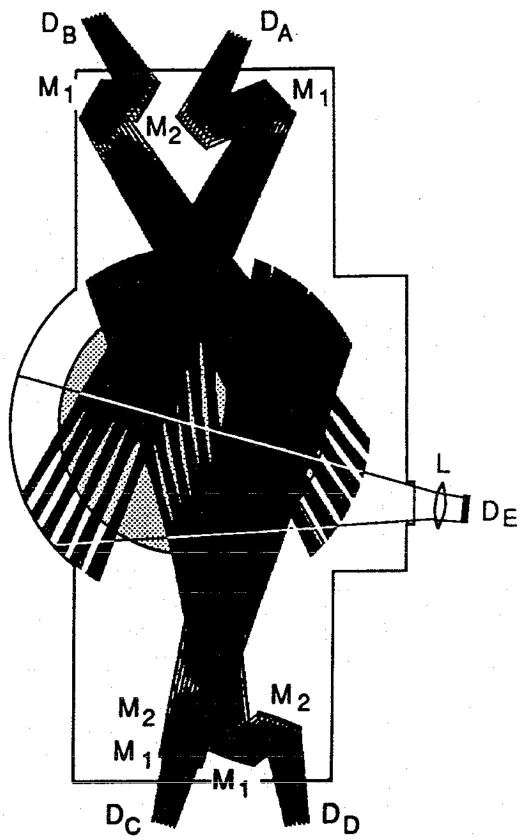

Fig. 1. The regions seen by the detector elements in the poloidal plane of the plasma (shaded) with respect to the vacuum vessel. The detectors for the different viewing directions are numbered D_A through D_E and for four viewing directions the rays that reach every third detector element are shown.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

Because of the limited number of views of the plasma, as a first approach the weighting matrix will not be used directly to obtain a reconstruction from the measurements [as for example in the Algebraic Reconstruction Technique (ART)[2]], but the number of views and the number of detectors will be "increased" by interpolation and smoothing of the measurements. The new viewing directions can best be chosen to be part of a detection system with parallel beams. The transformation from the real system to a set of parallel beams can be depicted in the so-called (p,ϕ)-plane (Fig. 2), where p is the distance of the viewing beam to the plasma centre and ϕ the angle of the line perpendicular to this beam with the horizontal. In Fig. 2 the points corresponding to the detectors of the real system and an arbitrary set of parallel beams are depicted. Interpolation and smoothing is done by fitting a surface to the measured data when the detectors are ordered in the (p,ϕ)-plane. Such an interpolation scheme for fan-beams has been developed, for the case of the current system (Fig. 2) it is under development. Two interpolation schemes have been tested: bi-linear and bi-quadratic. Computer experiments show that the bi-quadratic interpolation scheme provides a more exact reconstruction of the tomogram, albeit more time consuming.

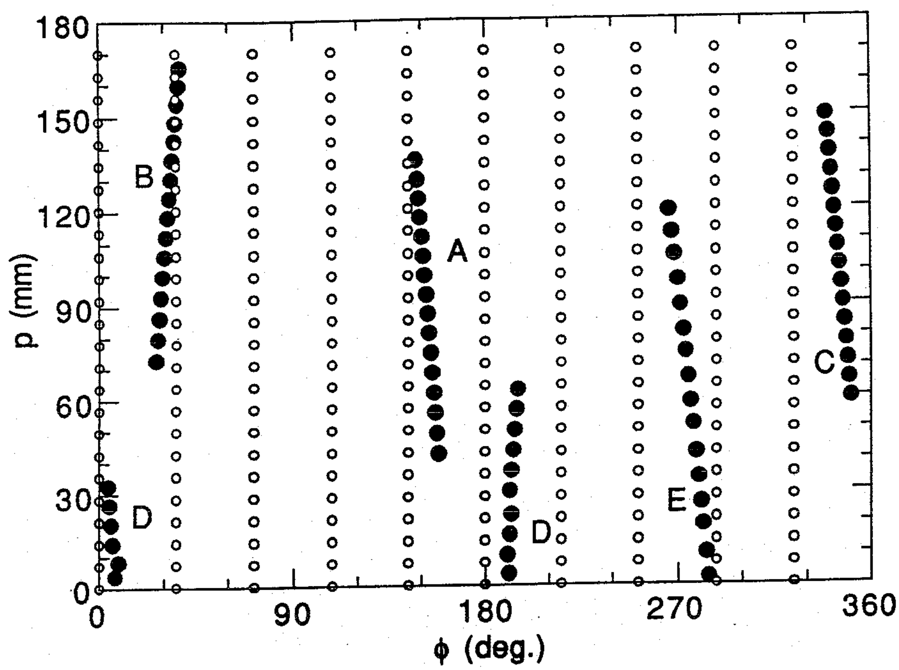

Fig. 2. The distribution of viewing beams in the real detection system (•) and a set of parallel beams (∘) in the (p,ϕ)-plane (each point corresponds to one detector and the letters correspond to the viewing directions in Fig. 1).

The transformation to a set of parallel beams is not entirely straightforward because owing to the imaging system a uniformly emitting object does not result in the same measured value by the different detectors (this can be compared with the $\cos^4\theta$ dependence of the angle of incidence θ in the case of a pin-hole system), as is the case for parallel beams. The "scaling factor" to obtain signals for this system corresponding to parallel beams is more complicated than the simple factor in the case of lenses or pin-holes, since the contribution of the emissivity to the measured power varies along the viewing direction and perpendicular to this direction in a complicated manner.[1] An approximate scaling factor for each detector is the inverse of the line average of the weighting-matrix elements of the detector. Figure 3 shows the simulated power measured by each detector, ordered by its p-value, for three cylinder-symmetric emission phantoms before and after scaling. After the scaling the points lie on a smooth curve, while without scaling there is a large scatter of the points. The line integrals for real parallel beams of the same profiles give a slightly lower result (some per cent) for non-constant profiles, which is probably due to the fact that the approximation of the weighting matrix by a line average is not perfect (the scaling factor depends on the emission profile).

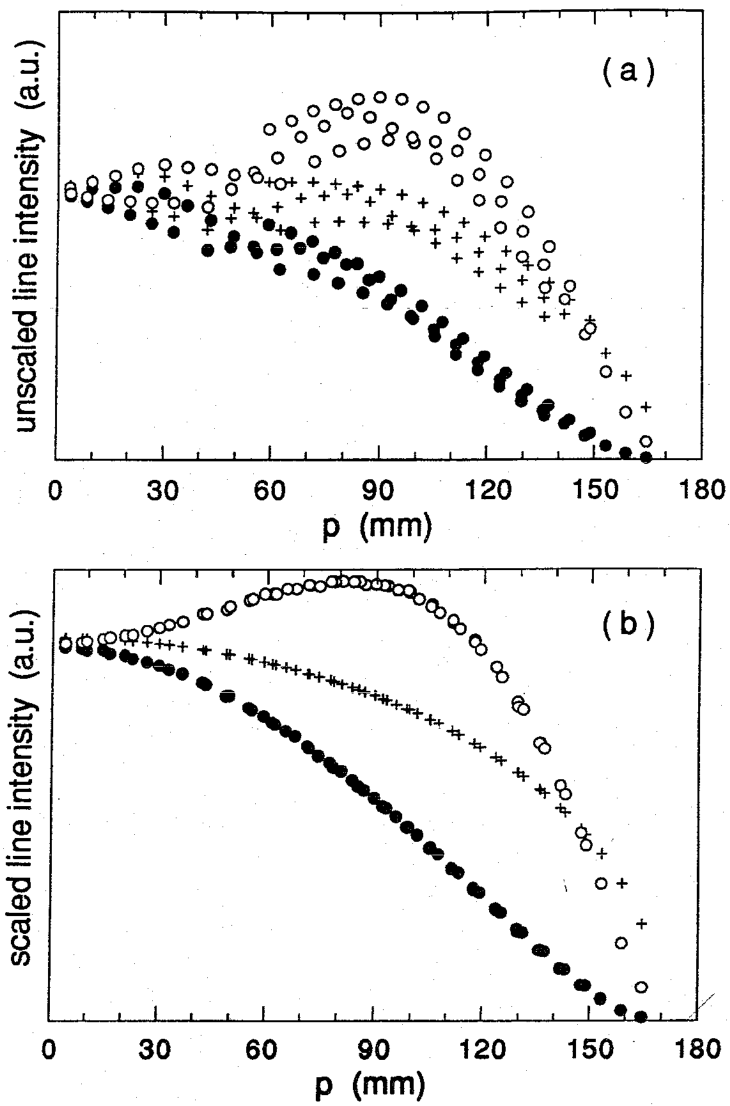

Fig. 3. Simulation of various cylinder-symmetric emission profiles with the detectors ordered according to p-value before (a) and after (b) scaling. The profiles, which are normalized so that the total emissivity is the same for all, are: + = constant, • = peaked [$h(r)$] and ∘ = hollow [$h^{1/2}(r)$ - 0.9 $h^2(r)$, and the maximum emissivity is at $r \approx 129$ mm]. Here $h(r) = 1 - (r/a)^2$, r is the radial coordinate and $a = 170$ mm (minor radius of tokamak).

Tomography methods

Some two-dimensional tomography algorithms have been modified for this detection system. These algorithms are: regularized schemes of the Filtration and Back Projection (FBP)[2] algorithm and the Algebraic Reconstruction Technique (ART).[2] The former algorithm has the form:

$$g(x,y) = \int_0^{\pi} \mathrm{d}\phi \int_{-\infty}^{\infty} f(p,\phi) h(p + x \sin\phi - y \cos\phi) \mathrm{d}p \ , \qquad (2)$$

where h is the filter function and $f(p,\phi)$ are the parallel beam projection data restored from measured signals by an interpolation scheme. Because of the finite width of the parallel beams and other properties of the imaging system that the FBP algorithm does not take into account, the resulting tomogram is convoluted by some "apparatus" or "point spread" function. It is possible to reconstruct such functions, thus obtaining an estimate of the half-width of the apparatus functions and the spatial resolution.

For the ART algorithm the following simple form was investigated:

$$g_i^{l+1} = g_i^l + \frac{f_{j(l)} - \sum_{k=1}^{N} W_{j(l)k} g_k^l}{\| W \|_{j(l)}} W_{j(l)i}, \tag{3}$$

where l indicates the iteration step, $j(l) = l \bmod M$, $\| W \|_j$ is the norm of the weighting-matrix elements for detector j, and the other symbols have the same meaning as in Eq. (1). Some parts of the plasma are poorly viewed by the current system (see Fig. 1). For the ART algorithm the solution of Eq. (1) is therefore ill-conditioned. An improvement can be made by "adding signals" by interpolation, thus using *a priori* information about smoothness of the tomogram. It is also possible to take into account other *a priori* information, for example by using a smoothed tomogram obtained with the FBP algorithm.

Preliminary results

Figures 4(a) and (b) show a mathematical phantom of plasma emission (on a grid of 59 x 59). A reconstruction has been made from projections, where 5% gaussian random noise is added, by the FBP algorithm with the Erokhin-Shneiderov filter function[3]. Figure 4(c) shows the result of this reconstruction for five fan-beams with 17 detectors each (similar to the current system, but with a simpler distribution in the (p,ϕ)-plane) after interpolation to 25 sets of parallel beams with 35 detectors each. The mean error for this reconstruction is 13%, compared to 29% without interpolation. The two islands can be distinguished clearly. To examine the information content for different viewing directions of the imaging system, a scheme for calculating Kazantsev's information parameters[4] is under development.

Acknowledgement

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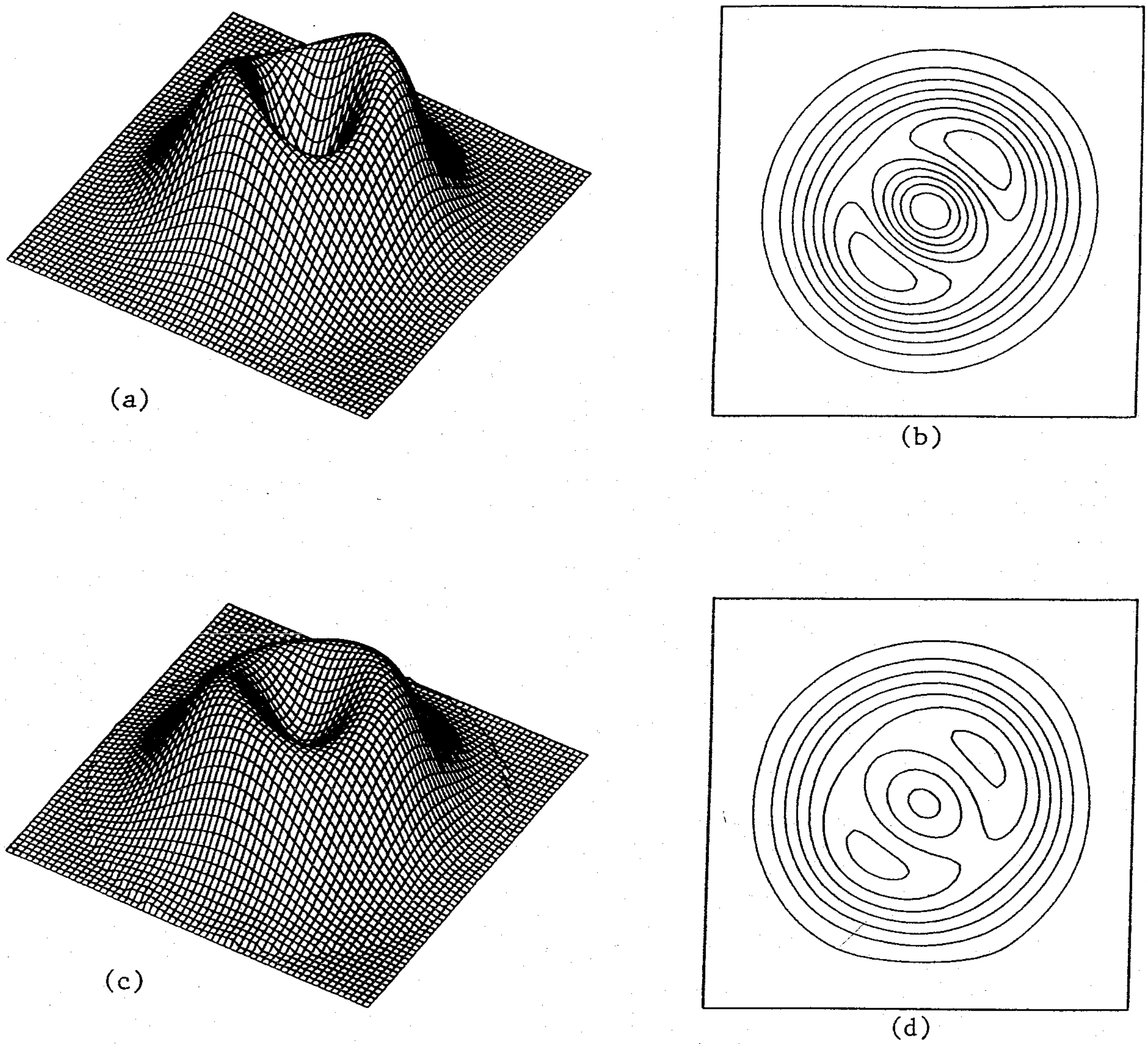

Fig. 4. Three-dimensional plot (a) and contour plot (b) of a phantom of the visible light emission with m=2 islands.The reconstruction of the phantom, 'measured' with five fan-beams and transformed to parallel beams, is also shown as a three-dimensional plot (c) and a contour plot (d).

References

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