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Plasma Boundary Reconstruction using Fast Camera on the COMPASS Tokamak

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Abstract. Determination of the plasma boundary is an important task for safe operation of the tokamak and diagnostic systems as well as for correct interpretation of the measured data. Magnetic reconstruction codes routinely used to determine the shape of the plasma have a number of limitations which can make the reconstruction problematic. Recently, it has been demonstrated on several devices that it is possible to provide independent measurement of the plasma boundary by observation of the visible-light emission using fast framing cameras. In the presented work, a single fast camera on the COMPASS tokamak was used for reconstruction of the optical plasma boundary, assuming a toroidally symmetric visible-light emission profile located in the edge of plasma. As a first result, application of the method on D-shaped COMPASS shot #7145 and its comparison with magnetic reconstruction from the EFIT code is given. Both methods show good agreement with average difference 0.5 cm.

Introduction

The detailed knowledge of the plasma position and boundary during a tokamak discharge is important both from the operation point of view and for post-shot data analysis. There are several widely used techniques using magnetic diagnostics (i.e., EFIT [*Luo*, 2002]) for reconstruction of the magnetic topology of the plasma, determining central plasma position, magnetic plasma boundary (last closed flux surface — LCFS), X-points and strike points. However, these techniques suffer from a number of drawbacks (i.e., discharge phases far from the equilibrium, coil misalignments, passive conducting structures etc.). The reconstruction can therefore be problematic or result in a substantial error.

Fast visible-light cameras are frequently used as a plasma diagnostic on tokamaks and their importance grows with the rapid development of camera technology [*Shibaev et al.,* 2008]. The cameras are used for basic monitoring of plasma as well as for more detailed analysis of the plasma edge, observation of instabilities and turbulence [*Nguyen et al.*, 2012; *Maqueda et al.*, 2001]). Recently, it has been shown on several devices [*Hommen et al.*, 2010; *Nam et al.* 2010] that fast framing cameras can provide reliable independent measurement of the plasma boundary and thus complement the standard magnetic reconstruction methods.

Plasma emits visible radiation mostly from a relatively thin emissive layer located in the edge region, where the temperature is low and where interaction of neutral particles with plasma takes place. The main sources of the radiation are recombination and deexcitation events of plasma ions/neutrals and impurities. The central plasma column is hidden to the visible light detectors as it emits more energetic radiation (SXR, HXR), mostly bremsstrahlung from decelerated electrons. The width of the edge emissive layer is determined mainly by the local plasma temperature profile and experimental observations on the COMPASS tokamak show that its width varies from several mm to several cm. The fact that visible light comes from the edge plasma allows us to reconstruct the optical plasma boundary. The reconstruction is not a simple task as each pixel of the two-dimensional camera image contains integrated signal from its particular line of sight (LoS). This problem can be solved by assuming a toroidal symmetry of the plasma emissive layer. Generally, the assumption is valid if the exposure time of the camera is long enough to smooth out fast edge plasma fluctuations and considering the toroidal magnetic field ripple effect to be sufficiently low. On COMPASS, the characteristic timescales of edge plasma fluctuations are in the order of tens of microseconds, therefore operating the camera with millisecond integration time is sufficient to fulfil the first condition and still be able to follow the bulk plasma behavior.

It must be noted, however, that the exact relation between magnetic (LCFS) and optical plasma boundary is unclear and so we may not consider one method a reference to the other.

Fast camera diagnostics on COMPASS

The COMPASS tokamak currently features an event detection intelligent fast camera (EDICAM) developed by Hungarian Academy of Sciences [*Szappanos et al.*, 2010]. The camera is located on an angular upper port and it has a tangential view of almost the whole poloidal cross section of the tokamak vessel. It is mounted on a mechanical holder outside the toroidal field coils due to the sensitivity to magnetic field. The optical system comprises of a commercial 24 mmf/1.2 Nikon objective behind the port window, relay optics guiding the image to a mirror, second objective with 105 mm focal length and a CMOS sensor. The CMOS sensor is sensitive to light with in wavelength range of 400–1000 nm and it has peak quantum efficiency 15 % (for 500–700 nm). The camera readout speed is 450 fps in full resolution (1280×1024 pixels) and it is capable to increase the frame rate up to 11600 fps at reduced resolution (16×16 pixels).

Description of the reconstruction method

For an optical plasma boundary reconstruction from a fast camera image we use a method described by *Hommen et al.* [2010]. We assume that there is a thin, toroidally symmetric emissive surface located at the plasma boundary. Every pixel on the camera image corresponds to a line-integrated measurement of the light coming from the plasma (from the emissive surface). Pixels which correspond to a line of sight that is tangent to the emissive surface will have a maximum in intensity, as the line of sight crosses the longest path through the surface. Those intensive pixels can be usually clearly observed on the camera images on COMPASS (see Figure 1.). The reconstruction problem is defined in two coordinate systems, a Cartesian system (u,v,w) and the cylindrical tokamak coordinate system (R,Z,φ). The origin and the v and Z axes of both coordinate systems are the same. The projection plane of the camera is chosen as the vertical $(u,v,0)$ plane. If we know the camera location (u_c,v_c,w_c) and the projection properties of the optics (from camera calibration), then trajectories of all lines of sight are known and each has a projection on the projection plane. The tangent line of sight l_e corresponding to an intensive edge pixel $p_e = (u_e,v_e)$ lies on a tangent plane determined by two vectors — toroidal unit vector V_t and the direction V_e of the plasma edge on the projection plane at point p_e. This allows us to find the tokamak coordinates of the point of tangency (R_e, Z_e, φ_e) of the sightline l_e [*Hommen et al.*, 2010]. Therefore after we have determined the edge pixels on the camera image, we can reconstruct the optical plasma boundary using the coordinate transform $(u_e, v_e) \rightarrow (R_e, Z_e, \varphi_e)$.

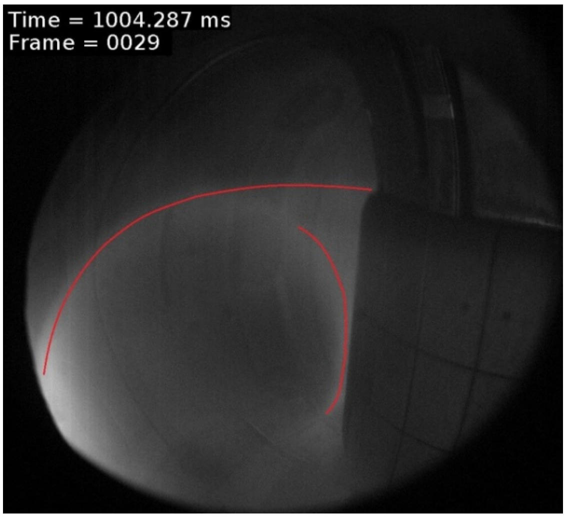

Figure 1. Figure from COMPASS circular shot #7411 with highlighted plasma edges seen by the fast camera.

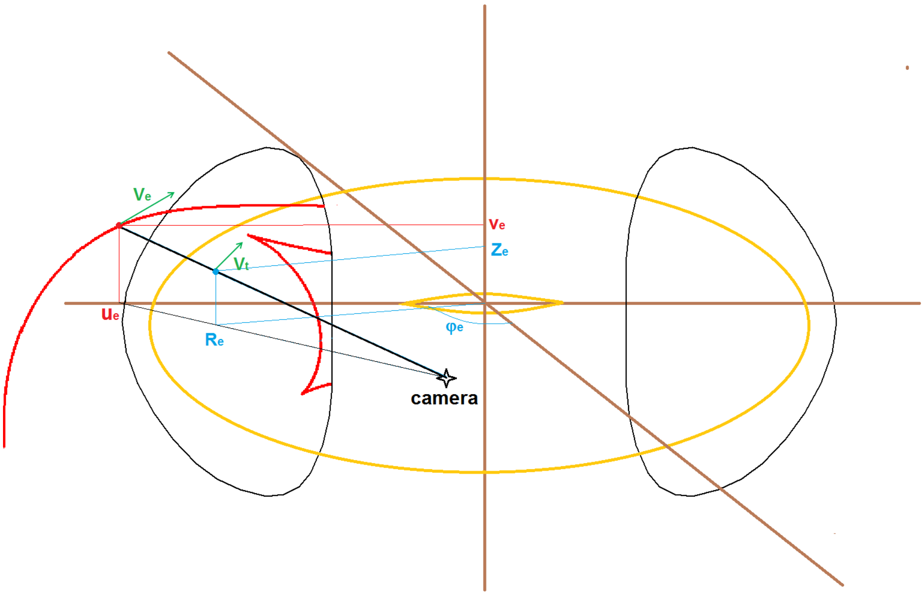

Figure 2. Geometry of the reconstruction method: Projection of plasma edges on the projection plane (red), tangent sightline (black line), tangent point on the plasma surface (blue circle) and corresponding point (pixel) on the projection plane (red circle). Vectors used in the coordinate transform shown in green.

Detection of the plasma edge on camera images

To automatically detect the edge pixels on a camera image, we make use of magnetic reconstruction of the plasma boundary. The last closed flux surface calculated by EFIT code is used as the first estimation of the optical plasma boundary. Assuming that plasma is toroidally symmetric with poloidal cross section shaped according to EFIT, we calculate the points on this three-dimensional surface, to which there exists a tangent sightline from the camera. Then, using inverse coordinate transform from tokamak to image coordinates $(R_e, Z_e, \varphi_e) \rightarrow (u_e, v_e)$ we get the image of the plasma edge given by EFIT. For usual COMPASS plasmas, the fast camera cannot see the lower low field side (LFS) part of the plasma edge and for elongated plasmas also the topmost part usually cannot be seen (see Figure 3). It is given by the fact that no tangent sightlines from the camera to that parts of the plasma surface exist. This results in appearance of several (typically two) edge curves on the camera image.

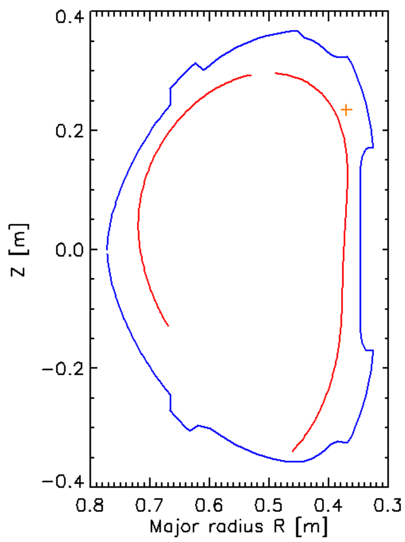

Figure 3. Poloidal cross section of the COMPASS tokamak showing LCFS points from EFIT (COMPASS shot #7145), to which a tangent sightline from the camera exists. Projection of the camera position to *(u,v,0)* plane is depicted by orange cross.

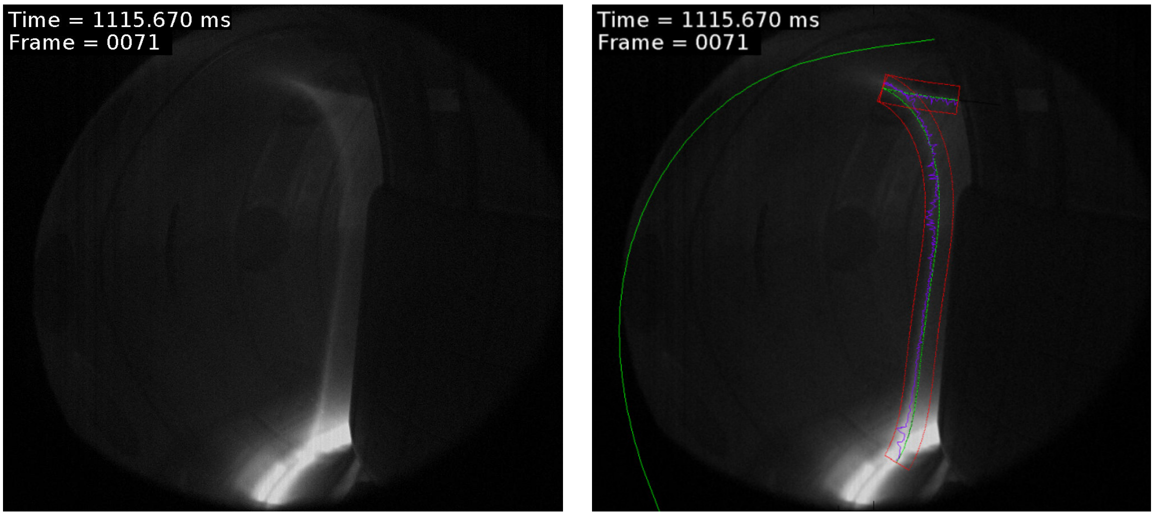

Figure 4. Camera images from COMPASS #7145: (left) Raw camera image. (right) Camera image showing projection of LCFS from EFIT (green curves), ROIs, in which we look for light peaks (red rectangles) and detected plasma edge (violet).

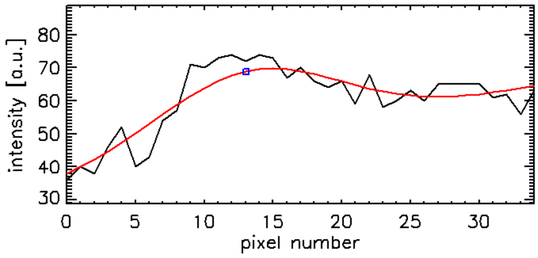

Figure 5. Example of a profile of light (black) in the ROI of Fig.4 along a line perpendicular to the green curve and a gaussian-polynomial fit with detected peak (red + blue square).

Now, having the curves corresponding to the expected plasma edge from EFIT on the camera image, regions of interest (ROIs) are appointed in the image having a shape of curved rectangles around those curves (Figure 4). Pixels corresponding to the plasma edges seen by the camera are determined by fitting of the signal along lines perpendicular to given curves in the ROI. As there is no underlying theory for the shape of the emission layer profile, several fitting functions were tried. A sum of gaussian and second order polynomial function was chosen for the fit, as it featured the lowest fitting error. (Figure 5)

There are several limitations to the mentioned method. Optical system vibrations during plasma operation can increase the width of the observed plasma edge emission layer and thus reduce the accuracy of the edge detection. Plasma edge curves seen by the camera have usually sharp corners, where the fitting method fails to make difference between near parts of the curves (see overlapping ROIs in Figure 4). Plasma-wall interaction, especially in the divertor region, can be too intense to allow us to identify the edges on the camera image. Intensively shining dust particles can cause the same problem. Finally, the reflections from the tokamak wall and in-vessel components can severely affect the reconstruction.

Example of plasma edge reconstruction from camera image

Discharges on COMPASS can be circular, elongated or D-shaped with lower divertor. Either ohmic or neutral beam heated high-confinement mode discharges can be standardly reached in the divertor configuration. As a first result of the described method, optical plasma boundary reconstruction for H-mode COMPASS shot #7145 is presented. In this discharge, camera was operated in full resolution with 1 ms exposure time. During the 213 ms shot with 80 ms long flat-top phase (50 ms in H-mode), 200 camera frames were acquired. For the demonstration of capabilities of the reconstruction method, one camera frame during the H-mode plasma phase was processed. For the

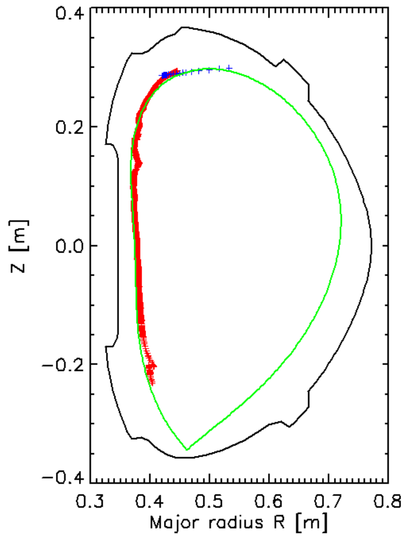

Figure 6. Poloidal plasma cross section showing the reconstructed plasma boundary points for the COMPASS shot #7145 from the camera image (red and blue crosses) and LCFS from EFIT (green curve).

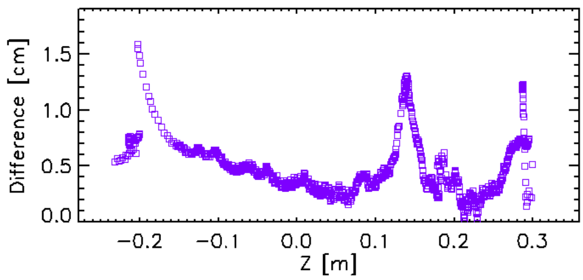

Figure 7. Plot of difference between EFIT and camera reconstruction along the Z axis for #7145.

given image, the plasma edge in the LFS region cannot be reconstructed, as the plasma visible light emission is suppressed there due to transport barrier formation. However, the optical plasma boundary can be nicely seen on high field side (HFS) and top plasma region (Figure 4). The reconstruction of the detected plasma edge is done using the above described coordinate transform. The comparison between reconstructed plasma edge points from the fast camera and EFIT code shows qualitative agreement (Figure 6) with differences not bigger than 1.6 cm and average difference of 0.5 cm (Figure 7). The agreement of both methods can be considered very good as the error of EFIT code itself is approximately 1 cm and the error of the optical reconstruction arises from the width of the emission layer, which is also in the order of several mm to few cm.

Conclusions

An optical plasma boundary reconstruction technique using a fast framing visible-light camera diagnostics on the COMPASS tokamak has been developed. The technique is proposed as an independent measurement to complement the standard EFIT magnetic reconstruction method. As a first result, application of the method on D-shaped COMPASS shot #7145 and its comparison with magnetic reconstruction from the EFIT code is given. Both methods show very good agreement with average difference 0.5 cm.

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