Compact soft x-ray multichord camera: Design and initial operation

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A compact and low cost diagnostic for spatially resolved measurements of soft x-ray or total radiation emission has been designed and realized to be flexibly applied to different plasma physics experiments. Its reduced size (outer diameter=35 mm) makes it suited to a variety of devices. The line integrated emissivity (brightness) has been measured along up to 20 lines of sight, using an array of miniaturized silicon photodiodes. Preliminary prototypes of the diagnostic have been installed in the Madison Symmetric Torus reversed field pinch (RFP) device at University of Wisconsin and in the EXTRAP T2 RFP device at the Royal Institute of Technology in Stockholm. Application of the diagnostic to a gas-fed (argon, helium) magnetoplasma dynamic thruster (MPDT) with an external magnetic field will also be discussed.
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I. INTRODUCTION

The rich variety of MHD phenomena in the reversed field pinch (RFP) calls for advanced, noninvasive imaging systems that allow the diagnostic of the plasma with high spatial and temporal resolution. This is the case, for example, to follow the nonlinear evolution of MHD instabilities, in particular in those regimes where their properties drastically change. This happens, for example, as a result of active fluctuations control techniques like pulsed poloidal current drive (PPCD)[1,2] or in self-organized laminar states as those obtained in the quasi-single helicity (QSH) regime[3] (when a single $m=1$ tearing instability dominates the magnetic fluctuations spectrum).

Soft x-ray (SXR) imaging of the plasma is a very powerful technique for this purpose. A neat example has been provided in the RFX device,[4] where a SXR tomography has been developed.[5,6] This diagnostic enabled the achievement of a large number of new results, including the finding of QSH states. On the basis of these results the RFX group has developed a new, miniaturized SXR probe that can be used to monitor not only the slow evolution of the SXR emissivity pattern, but also its high frequency fluctuations. Given its small size and flexible design, this photocamera is intended to be portable to many different plasma devices. This diagnostic has been designed and fabricated within the framework of the INFM-PAIS project ‘‘Softcam.’’

This article focuses on the prototypes of the SXR probe that have been installed in various experiments, namely the MST[7] and EXTRAP T2R[8] RFPs, and a magnetoplasma dynamic thruster (MPDT).[9] Section II will describe in detail the

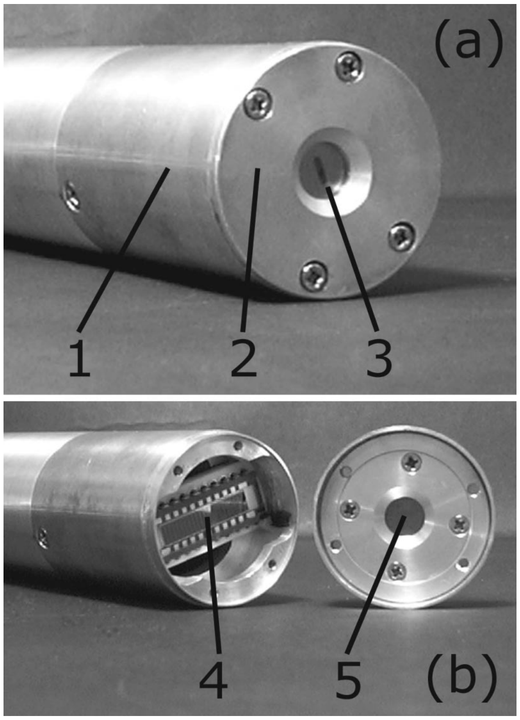

FIG. 1. Images of the SXR photocamera: (a) closed and (b) open.

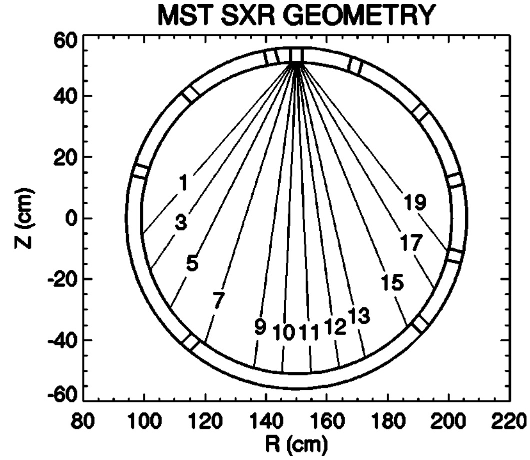

FIG. 2. Scheme of the lines of sight. The corresponding diode number is shown next to each chord.

diagnostic. A short survey of the results obtained in extensive experimental campaigns in the three devices will be reported in Sec. III. Future installation of this diagnostic and new application of the probe will be the subject of the last section.

II. DESCRIPTION OF THE DIAGNOSTIC

The diagnostic can be conceptually subdivided in two units, the detection subsystem and the insertion/support subsystem.

The *detection* subsystem consists of a SXR photocamera, equipped with a total of 20 SXR detectors. The photocamera [see Fig. 1(a)] is an aluminum cylinder (1), diameter=35 mm, closed by an aluminum cover (2) with the pinhole (3) is its front side. The array of detectors (4) [see Fig. 1(b)] is positioned 1 cm away from the pinhole; the front cover also contains a beryllium filter (5). By removing the aluminum top, the pinhole, the Be foil or the array of detectors can be easily changed, without touching the cables or any other part of the probe head. The probe is then attached to one end of a tube (which contains all the cables), and to the insertion/support subsystem, through an adapter.

A rectangular pinhole open (1×4 mm) in the front cover defines the geometry of the lines of sight and allows radiation to impinge on the detectors. A scheme of the lines of sight is shown in Fig. 2 (in this case for the SXR probe installed in the MST device). The angular aperture of the set of chords is defined by the distance between the array of detectors and the pinhole. When this distance is 1 cm, as in Fig. 2, the impact parameters of the lines of sight (the perpendicular distances from the lines to the origin) lay between -35 and 35 cm (which is the order of magnitude of the dimensions of the plasma devices where the SXR probes has been installed).

The SXR radiation has been measured by a set of silicon photodiodes: a linear array of detectors mounted on a Teflon socket has been used for compactness. After a careful searching of various types of detectors, the best choice has been the AXUV-20EL 20 diodes array manufactured by IRD.[10] The diodes, in a common anode configuration, are 0.75×4 mm (roughly the same dimension of the pinhole), with an active thickness of 35 μm; they are used without bias voltage, and guarantees absorption of photons up to 6–7 keV, with a dark current well below 0.1 nA. The photodiodes have flat response over a wide range from visible to x ray, and are therefore very suitable for absolute total radiation measurements (bolometry); see an application in Ref. 11. A special version of the array chip has been ordered with smoothed corners for compatibility with the photocamera dimensions.

A beryllium absorber, also positioned on the aluminum cover, between the pinhole and the diodes, is used to select only the SXR energy range (10 eV–10 keV). The first version of the SXR photocamera (showed in Fig. 1) was equipped with a flat Be filter: in this case all of the lines of sight intersected the filter foil with different angles (up to 40°). As a consequence, each diode ‘‘saw’’ the plasma through a different thickness of Be. Since this revealed a problem when performing a tomographic reconstruction (a necessary condition is that all of the detectors see the radiation emitted by the plasma in the same energy range, see Ref. 6), a new version of the photocamera with a curved Be foil has been developed. The absorber has been included in a curved frame, so that all of the lines of sight are perpendicular to its surface.

The *support/insertion* subsystem is used to position the SXR photocamera in its measuring location (which is usually a few centimeters from the plasma). Two version of this subsystem have been produced: one (manipulator) which allows for the movement of the photocamera, and the decoupling from the vacuum of the device through a gate valve, and

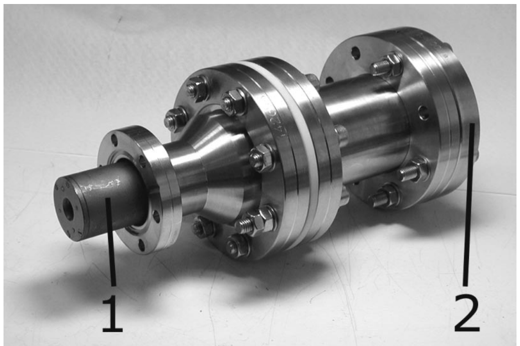

FIG. 3. Image of the fixed version of the SXR probe.

another, more compact, which place the SXR probe in a fixed position, without any valve.

The layout of the first version of this system was adapted from a MST type of manipulator, used for positioning magnetic probes, and has been chosen to allow for all kind of mechanical and electronic tests (use of different pinhole or thickness of Be, switching of cables, etc.) without breaking the machine vacuum. The insertable system enables to insert, extract or move the diagnostic, and to rotate it around its axis (to change the orientation of the lines of sight).

The fixed version of the support subsystem, shown in Fig. 3, inserts the photocamera (1) in a permanent position, directly connect to the vacuum of the machine; all the signals are extracted in the flange (2) through a 25 pin connector. This version of the diagnostic has been designed and produced after the first results of the SXR insertable probe, when a more clear range of parameters, such as dimensions of pinhole, thickness of Be filter, was available.

The currents produced by the detectors, which are proportional to the absorbed SXR power and normally of the order of tens to hundreds of nA, are processed through current to voltage amplifiers, with transimpedances ranging from 10^4 to 10^8 V/A. Both commercial (Femto DPLCA-200[12]) and custom developed (Elad[13]) amplifiers have been used, with bandwidth varying between 10 and 500 kHz (which allows for fluctuation studies if the signals are high enough to require less gain). The signals have been then digitized with a sampling rate of 1 MS/s in CAMAC-type digitizers.

III. EXPERIMENTAL RESULTS

The MST RFP represents a flexible and easy-to-use experimental RFP facility. A SXR photocamera has been installed in one 1.5 in. portholes of the MST vacuum vessel, positioned at 90° poloidal; a Be filter 16 μm thick has been used. The manipulator described in Sec. II supported the probe. With the above-described geometrical layout (see Fig. 2), two consecutive viewing cones (the volume defined by one diode and the pinhole, and whose axis is considered as the line of sight) overlapped up to the 50%. This could be a problem for a tomographic reconstruction, and the idea was to consider only every second detector. The number of chords was then reduced to 12 (actually four diodes, looking at the plasma core, have overlapped cones of sight, but this was done to increase the spatial resolution in the center). The poloidal coverage of the fan of chords is about 70% of the MST cross section: this and the time resolution are sufficient to detect localized, rotating structures in the plasma core of MST, corresponding to quasisingle helicity states.

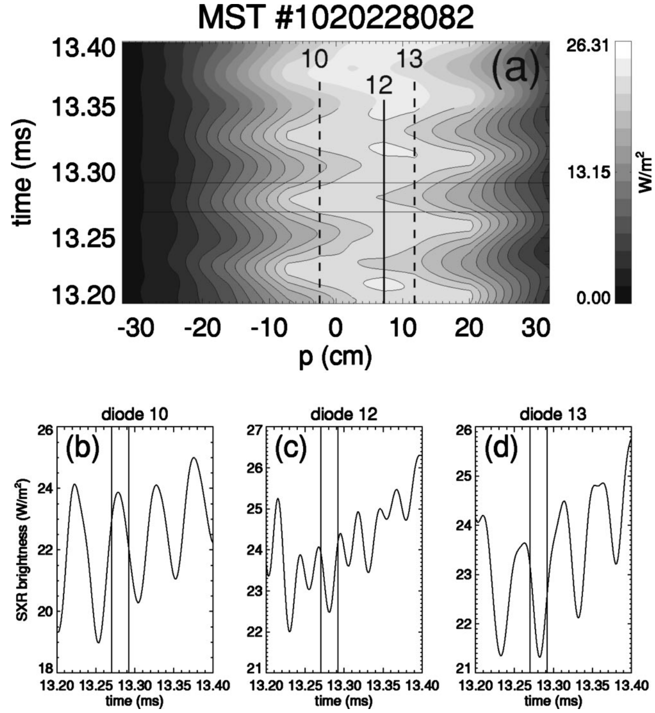

FIG. 4. (a) Contour plot showing the evolution of the SXR brightness (line integrated emissivity), as a function of time and of the impact parameter p, for a MST discharge. (b)–(d) Expanded insets showing the time signals for three diodes, marked as vertical lines in (a).

An $m=1$ structure has been detected on the SXR signals during enhanced confinement (PPCD) experiments, in particular when the magnetic fluctuations spectrum is dominated by a single $m=1$, $n=6$ mode. Figure 4(a) displays a contour plot of the line integrated (brightness) SXR profile, where the horizontal axis is the impact parameter of each line of sight and the vertical axis is the time. The SXR brightness of the chords looking at the periphery of the plasma core is dominated by a 20 kHz oscillation, which is in counterphase in the inner and outer section of the plasma. Figures 4(b) and 4(d) show the time evolution of this oscillation for two of these chords, corresponding to the two dashed lines in Fig. 4(a). It is interesting to note that this oscillation frequency corresponds to the rotation frequency of the dominant $m=1$, $n=6$ magnetic mode, measured by a set of pickup magnetic probes. Figure 4(c) shows the oscillating behavior in the central chord, which corresponds to the solid line in Fig. 4(a): in this case the frequency is around 40 kHz, about twice as the frequency seen in the adjacent chords. These evidences can be explained with the presence of a rotating, localized structure in the SXR emissivity caused by a QSH state. Considering the outer chords, frames (b) and (d), the impact parameter is greater than the radial position of the $m=1$ structure, and this island intercepts these lines of sight only once in a rotation period, therefore the fluctuation seen in the SXR signal is approximately equal to the rotation frequency of the

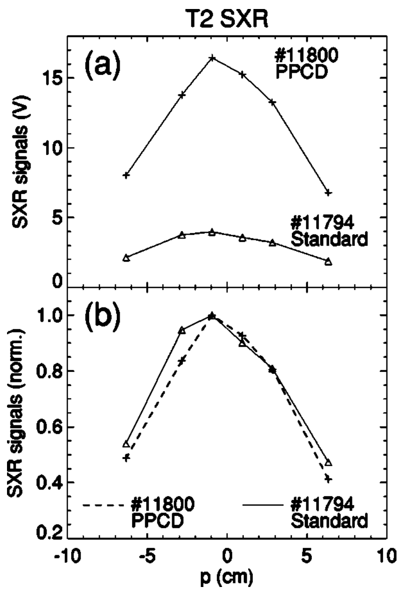

FIG. 5. (a) Signals from the six-diode SXR camera, for a fixed time instant, as a function of the impact parameter *p*, in a non-PPCD (No. 11794) and PPCD (No. 11800) T2R discharge. (b) The same SXR profile, but normalized to the maximum value; the SXR profile for the PPCD is the dashed line.

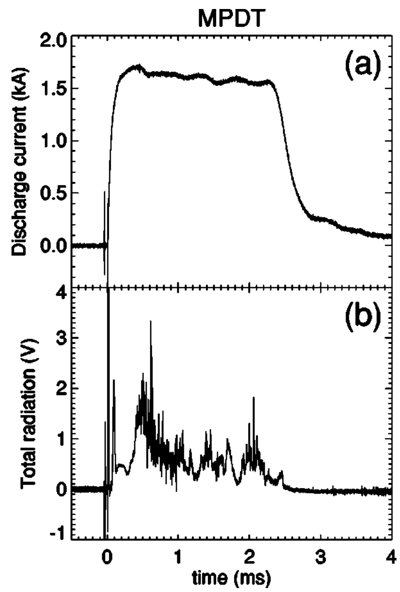

FIG. 6. Example of measurements performed on the MPDT of Centrospazio, (a) arc current and (b) line integrated radiation along a chord viewing the core of the plasma.

(1,6) mode. In the case of a central chord, frame (c), the same structure intercepts the chord twice, and this explains the double frequency. See also Ref. 14 for a brief summary of the results obtained with this SXR probe.

Another SXR photocamera, fixed version, has been installed in the 165° poloidal porthole, in the same toroidal location of the previous probe; the thickness of the Be filter is the same of the SXR insertable probe (16 μm). Preliminary measurements have proved that the new probe is working reliably.

A SXR diagnostic, of the type of Fig. 3, has been recently installed and put into operation in the EXTRAP T2R reversed field pinch, in one of the equatorial porthole. The photocamera has a curved Be foil, 9 μm of thickness (the filter has been chosen thinner because of the lower level of the SXR signals, due to the lower plasma current of this device). The amplifiers have been installed near the machine, and the output signals have been transmitted to the digitizers, located in a different room, along 40 m long fiber optics. For these initial experiments six chordal measurements were available for each shot, which should allow for a reconstruction of the brightness profile in the plasma core. Various plasma conditions have been investigated, with plasma current ranging from about 80 to 100 kA. Useful information on the plasma core has been obtained in PPCD discharges: a significant increase of the measured SXR brightness during the application of the PPCD is observed and this corresponds to an increase of the SXR emission in the whole plasma core. A comparison of the SXR profiles in a non-PPCD and PPCD cases is shown in Fig. 5(a). Normalizing these values to the maximum, the shapes of the SXR profiles seems also to change [Fig. 5(b)].

A third prototype of the SXR probe has been used to analyze the plasma produced by the gas-fed (argon, helium) magnetoplasma dynamic thruster (MPDT) of Centrospazio, Pisa, Italy. The photocamera has been used without Be filter (the temperature of the plasma, in this device, is of the order of few eV, thus no SXR are detectable) and has been installed inside the vacuum chamber to view the plasma exiting the thruster from above. A simple aluminum bar supported the probe; the cables have been extracted through a vacuum feedthrough and the signals (only six diodes have been measured) have been amplified and then sent to a digital scope. Due to the high level of the radiation (up to the ultraviolet range) emitted by the plasma, lower gains of the amplifiers have been used, thus increasing the time resolution (300 kHz and more) of the measurements and allowing to follow the very rapid events of this type of plasma. The thruster has been operated in different conditions, namely low and high discharge (arc) current (between 2 and 10 kA), with and without the application of an external magnetic field up to 100 mT. An example of measurements is shown in Fig. 6. The analysis of these preliminary data is under investigation.

IV. FUTURE DEVELOPMENTS

The positive results obtained with this relatively simple and cost effective instrument have encouraged an investigation of possible upgrades and of new kinds of applications. The SXR probes can be used, in fact, in a variety of modes and could lead to the realization of a flexible and multipurpose facility for the measurement of plasma radiation.

The first upgrade could include the installation of new SXR probes in the abovementioned devices, maintaining the present design of the probe: two or more SXR photocameras, viewing the plasma through different directions, allow for SXR tomographic reconstruction. An option like this allows not only to study with great detail large $m=1$ coherent structures but also individual islands and their nonlinear interaction. Since soft x-ray emissivity is directly linked to internal plasma quantities, such as electron and ion density and electron temperature, fast multichord measurements will allow characterizing the turbulence of these basic quantities. The analysis will concern the study of line integrated signals to characterize the correlation between adjacent and crossing chords. Finally, SXR and total radiation measurements using 2D array of photodiodes is under study.

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