TECHNICAL NOTE

Broadband extreme-ultraviolet survey spectrometer for short-time-scale experiments

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A fast and inexpensive spectrometer system has been developed to record extreme-UV impurity spectra in a magnetic-fusion-research device. To simplify the vacuum system, light is passed out of the spectrometer's vacuum to the detector with a sodium-salicylate-coated, fiber-optic coupler. This coupler is positioned so that the focal field is nearly flat over its aperture. The system's detector is a microchannel-plate-intensified, linear, self-scanning photodiode array. The 1024-pixel array covers a bandwidth greater than 80 nm and is read out once every millisecond. The readout, which is four times faster than the manufacturer's maximum rating, is fully synchronized to the experiment by a locally designed control circuit.

Key words: EUV spectrometer, flat focal field, fiber-optic coupler, photodiode array, synchronization, control circuit.

Many modern applications of spectroscopy require millisecond to submillisecond temporal resolution combined with a large spectral bandwidth. This is the case in magnetic fusion plasma research. One is often required to measure simultaneously the rapidly changing intensities of many different spectral lines from impurities in the plasma.

We have developed an extreme-ultraviolet (EUV) impurity monitoring system for use in the Madison Symmetric Torus (MST)[1] magnetic-fusion-research device. The system is based on a 0.2-m-focal-length spectrometer with an intensified, linear, self-scanning photodiode array as the detector. The array is an EG&G Reticon product, part 1024SAF-011. Although this detector is of a common type, the system as a whole features improvements on past systems: (1) a nearly flat focal field, (2) elimination of an *in vacuo* detector assembly, (3) increased time resolution, (4) precise synchronization of the array readouts to external events. The flat focal field minimizes off-center defocusing and is achieved by appropriate positioning of the detection plane (determined by optical ray tracing). A sodium-salicylate-coated, fiber-optic coupler permits placement of the detector outside the spectrometer's vacuum. Increased time resolution is achieved with a simple modification of the electronics accompanying the array, while synchronous operation is achieved with an inexpensive control circuit. Instructions for the Reticon modification and a detailed schematic of the control circuit are provided in this note.

Detectors similar to the one in this system were first described by Riegler and More[2] and later by Sandel and Broadfoot.[3] Specific aspects of the arrays alone have been discussed by Talmi and Simpson.[4,5] Applications of this detector in fusion plasma diagnostics have been described by Bell *et al.*[6] as well as by Fonck *et al.*[7,8] Hodge *et al.*[9] as well as Beiersdorfer *et al.*[10] describe extensions of this type of system to the soft-x-ray region of the spectrum.

Our spectrometer is a converted commercial monochromator, the Minuteman 302-VM (see Fig. 1). It utilizes a holographic, aberration-corrected, 1200-groove/mm, concave grating that is rotated on its own fixed axis to focus different wavelengths on the exit plane. To match the nominal location of the exit focal plane, the detection plane is tilted relative to the optical axis at an angle θ. The focal field of this spectrometer has a natural curvature, but defocusing over the detection plane, which is a problem common to all 0.2-m systems with this type of grating, is largely avoided by optimizing θ and the distance from the center of the grating to the center of the detection plane. Thus, while normal-incidence systems suffer from substantial defocusing at the edges of the detec-

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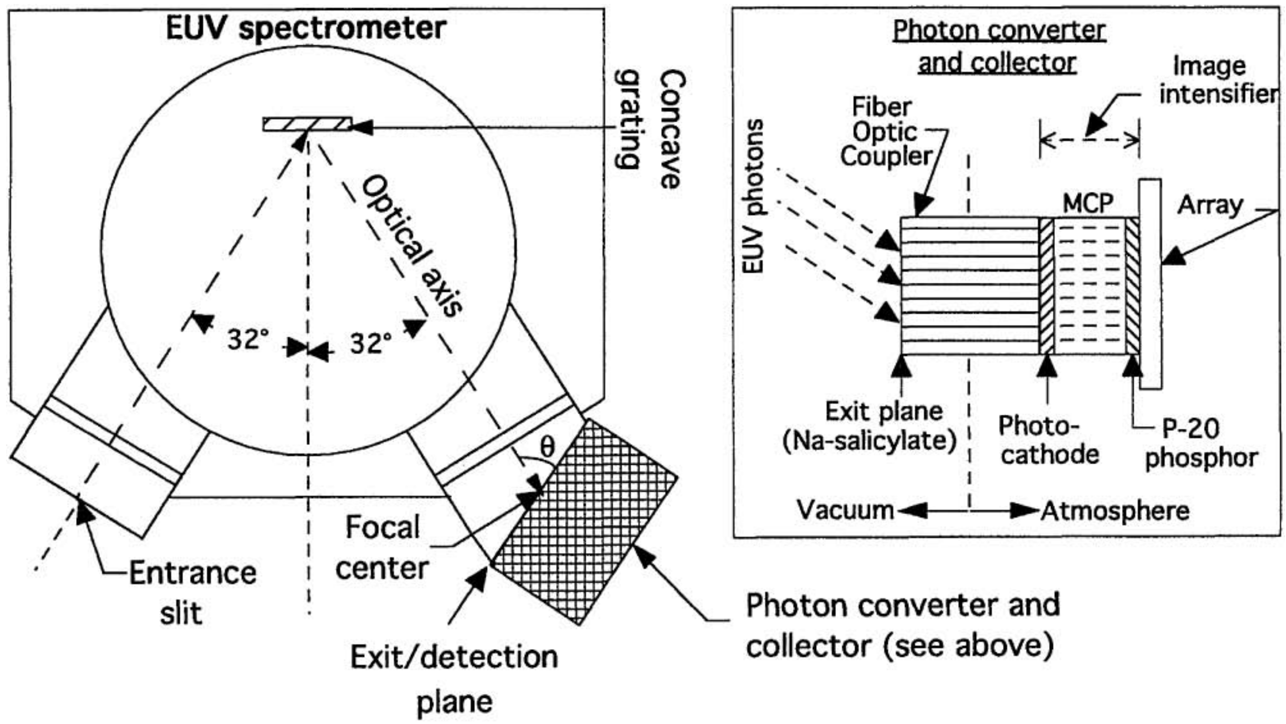

Fig. 1. Layout of the EUV spectrometer. The angle θ between the optical axis and the focal plane is 57.8°. The distance from the center of the grating to the center of the focal plane is 185.6 mm.

tion field,[7] this system provides a nearly flat focal field over the detector's aperture. In the central region of the detection plane the focal field is tangent, while at the edges the focal field bends away, decreasing the nominal resolution (see below) by less than 0.1 nm. The optimum θ and grating-to-detector distance vary with different central wavelengths. For a θ of 57.8° and a grating-to-detector distance of 185.6 mm, this system is optimized for a central wavelength of 100 nm. While this system can actually operate as high as ~300 nm, it is primarily intended for wavelengths between 50 and 200 nm.

The first part of the detector assembly (also shown in Fig. 1) is a fiber-optic coupler available from Schott Glass Technologies. One face of the coupler lies in the detection plane and is coated with sodium salicylate; the coating was applied in-house. The coupler passes visible photons to the rest of the detection apparatus, which is located outside the spectrometer's vacuum. This coupler minimizes vacuum constraints and simplifies the system design.

On leaving the fiber-optic coupler, the visible photons encounter an image intensifier, which is a Varo product, Model 9323. Here they strike a photocathode and are converted to electrons. These electrons are then multiplied in a microchannel plate. Finally the electrons are converted back to visible photons by a layer of P-20 phosphor. The photons are then collected by the fiber-optically coupled photodiode array. The 25-mm apertures of the coupler and image intensifier are large enough to illuminate the entire array. To maximize efficiency, an optical-coupling gel was applied at the coupler–intensifier and intensifier–array interfaces.

The resulting system bandwidth is slightly less than 80 nm (see Fig. 2 for a sample spectrum). Use of the fiber-optic coupler and microchannel plate does not seriously degrade the system's resolution. For an entrance-slit width of 40 μm, the full width at half-maximum of a narrow line in the EUV was measured to be slightly greater than 0.3 nm, covering ~4 pixels on the array.

Two additional features of this system, both electronic in nature, are of particular note and merit description; see Fig. 3 for a general schematic of the system electronics. The first feature is the quadru-

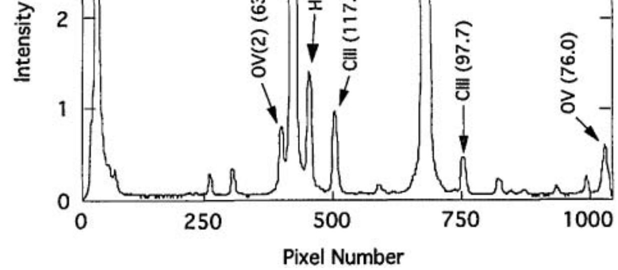

Fig. 2. Single spectrum from EUV spectrometer. The central wavelength is 116.0 nm.

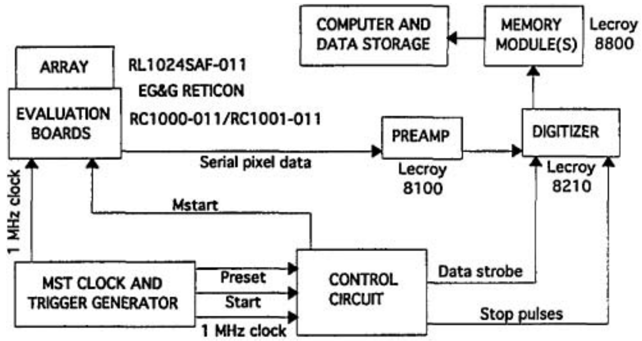

Fig. 3. Block schematic of the EUV system electronics. Note that the preamp, digitizer, and memory modules are housed in a local Camac crate.

pling of the system's speed. The photodiode array is accompanied by two evaluation boards, the motherboard, part RC1000-011, and the satellite board, part RC1001-011. These boards provide the signals and video processing necessary to operate the array and, as shipped from Reticon, permit a maximum clock rate of 250 kHz. Thus, as 1 pixel is read out with each clock pulse, back-to-back scans of the array result in a pixel integration time (the time between successive readouts of a particular pixel) of ~4 ms. To achieve an integration time near 1 ms, the time scale of many phenomena on the MST, the system must be clocked at 1 MHz. We found that a simple modification of the motherboard permits operation at 1 MHz. Specifically, one replaces the timing components of three one-shot oscillators (monostable multivibrators); see Appendix A for the specific changes.

Clocking the array at 1 MHz (from the MST's master clock) with only this modification did not affect the linearity of the array response, as was verified with a set of neutral-density filters. However, the saturated-signal level from the array dropped by a factor of ~2.5. To offset this drop, we use a Lecroy 8100 preamplifier (see Fig. 3). We also installed a BUF-03-FJ line driver to better drive the array data into 50-Ω coaxial cable.

External synchronization of the array readout to our experiment is also required, and we have designed and implemented a control circuit (see Fig. 4 for a detailed schematic), the second electronic feature, to achieve this end. In contrast to past Reticon systems[11] the current system provides for a relatively simple external control of the array readout. One merely sets two jumpers on the motherboard (see Appendix A) to bypass the board-generated clock and Mstart pulses. One Mstart pulse is needed to begin each readout of the array. The control circuit provides the Mstart pulses as well as the triggers necessary for the system's digitizer, a Lecroy 8210, while carefully synchronizing the array readouts to each plasma discharge in the MST; refer to Appendix A for a circuit startup procedure necessary to ensure internal synchronization of the different circuit sections. To collect all the data in a typical 60-ms discharge, the control circuit is designed for continuous or back-to-back scanning of the array. The functions of the control circuit are described below.

The array requires 1028 (the number of pixels + 4) clock cycles between Mstart pulses in the continuous-scan mode. Thus the control circuit produces an Mstart pulse every 1.028 ms. The control circuit also provides triggers, the data strobe and the stop, to the Lecroy 8210. The 1-MHz strobe pulses, each of which causes a pixel datum to be recorded and digitized, are input at the external clock port of the digitizer. To avoid recording pixel-to-pixel switching noise, the strobe pulses are phased relative to the clock pulses so that a datum is recorded only when it is stable. The stop trigger, which causes the 8210 to exit the digitizing mode, is generated at the end of a complete data-taking cycle. In the design shown here, stop pulses are available at 32, 64, and 128 ms after the start of the plasma discharge.

One other circuit function is to use MST-generated triggers to initiate readout of the array at pixel 1 precisely at the beginning of each plasma discharge (fully synchronized readout). The relevant MST triggers are called preset and start. The preset trigger, which one sets to arrive 3–4 ms before the discharge, permits the circuit to prepare itself and the array for the start trigger, which arrives precisely at the beginning of the discharge. Immediately after the start trigger an Mstart pulse is generated. The array readout, which stops at pixel 1024 after receipt of the preset trigger, then begins again at pixel 1. Readout continues until the next preset pulse, although data taking ends with the stop pulse.

The exact timing of the preset pulse relative to the start pulse is not critical; nevertheless it is somewhat constrained. The array readout ceases between the two triggers; thus, if the time between the two pulses is too long, dark signal will build up on the array, resulting in the contamination of the first array scan after the start pulse. The time must be long enough, however, to permit the readout in progress when the preset pulse arrives to finish; 3–4 ms is a good range for the time between pulses.

The design of this control circuit has many advantages. It is relatively simple and inexpensive to build. It uses standard transistor–transistor-logic-based components and can be constructed with the wire-wrap method. The circuit has a minimal dependence on external signals, limiting its susceptibility to line noise. Past designs for similar circuits (e.g., Ref. 11) utilize the end-of-scan pulse generated by the Reticon evaluation circuitry at the end of each array readout to trigger each subsequent readout. The circuit here is independent of such external signals.

The combination of a nearly flat focal field, fiber-optic coupler, fast photodiode array, and synchronous operation makes this EUV system a simple and effective means of monitoring line radiation in short-time-scale experiments.

Appendix A

To permit 1-MHz operation, the changes to the motherboard, where Reticon's board notation is used,

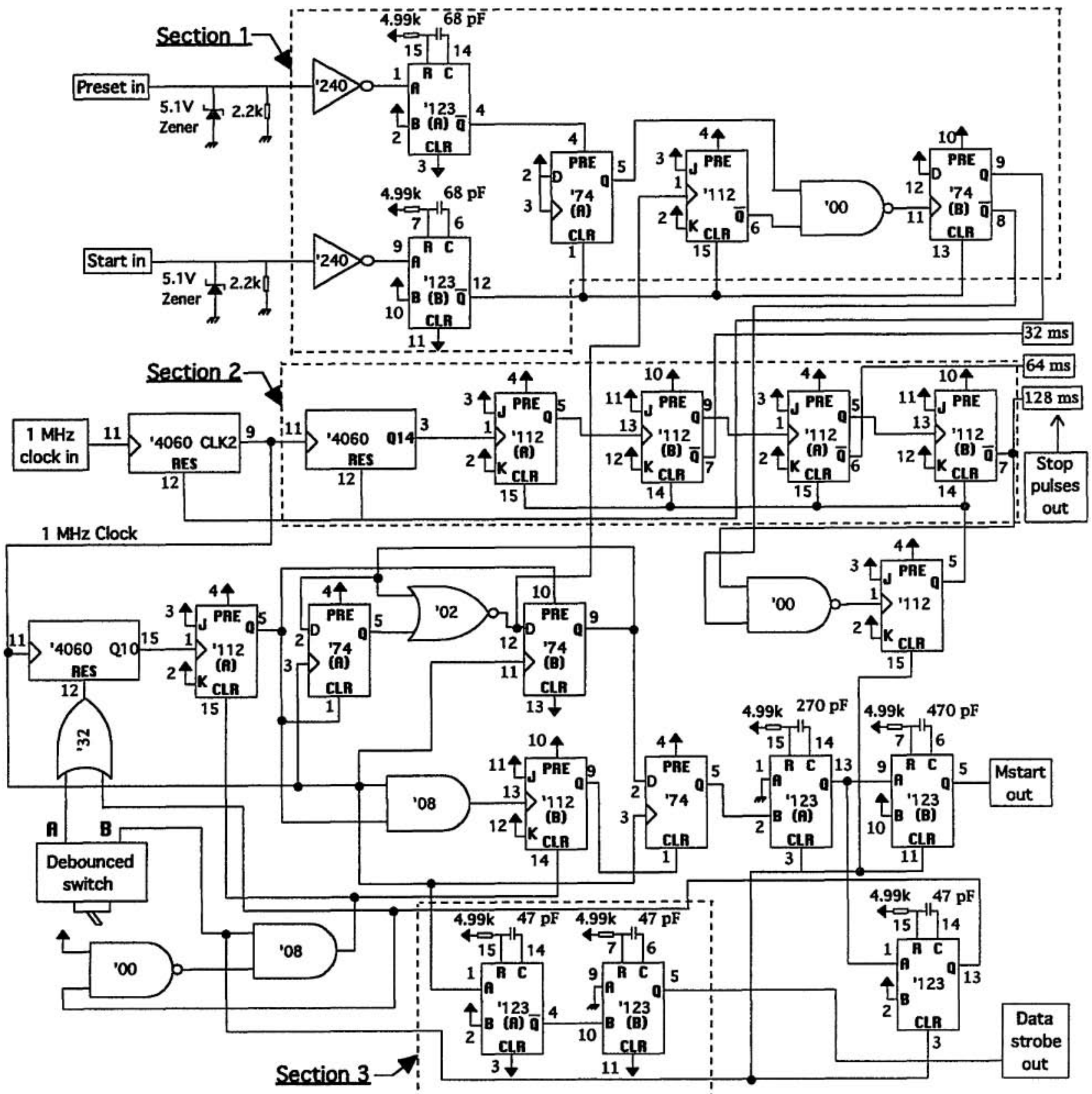

Fig. 4. Control circuit schematic. Section 1 uses the preset and start pulses from the MST trigger generator to synchronize the array readout to the plasma discharges. Section 2 produces stop triggers for the 8210 digitizer. Section 3 provides the data-strobe pulses for the digitizer. Most of the remaining circuit components are dedicated to producing an Mstart pulse after each cycle of 1028 clock pulses.

are as follows:

Chip U11(2): R40 becomes 5 kΩ; C58 becomes 270 pF.
Chip U12(1): R41 becomes 5 kΩ; C59 becomes 180 pF.
Chip U12(2): R47 becomes 5 kΩ; C88 becomes 68 pF.

To bypass the motherboard-generated Mstart and clock pulses, one sets jumpers E2–E3 and E8–E9, respectively, on the motherboard.

To ensure proper circuit operation, the following circuit startup procedure is necessary: (1) apply power (+5 V) with the external clock connected and the debounced switch enabled; (2) apply a start pulse; (3) disable then reenable the circuit with the debounced switch. When enabled, output A of the debounced swtich (Fig. 4) is at ground, while B is at +5 V. When disabled, the polarities are reversed.

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