Plasma diagnostics for the sustained spheromak physics experiment

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In this article we present an overview of the plasma diagnostics operating or planned for the sustained spheromak physics experiment device now operating at Lawrence Livermore National Laboratory. A set of 46 wall-mounted magnetic probes provide the essential data necessary for magnetic reconstruction of the Taylor relaxed state. Rogowski coils measure currents induced in the flux conserver. A CO_2 laser interferometer is used to measure electron line density. Spectroscopic measurements include an absolutely-calibrated spectrometer recording extended domain spectrometer for obtaining time-integrated visible ultraviolet spectra and two time-resolved vacuum monochrometers for studying the time evolution of two separate emission lines. Another time-integrated spectrometer records spectra in the visible range. Filtered silicon photodiode bolometers provide total power measurements, and a 16 channel photodiode spatial array gives radial emission profiles. Two-dimensional imaging of the plasma and helicity injector is provided by gated television cameras and associated image-processing software. An array of fiber-coupled photodetectors with H alpha filters view across the midplane and in the injector region to measure neutral hydrogen concentrations. Several novel diagnostics are being fielded including a transient internal probe (TIP) and an ultrashort-pulse reflectometer (USPR) microwave reflectometer. The TIP probe fires a very high velocity optical bullet through the plasma and will provide fairly nonpertabative internal magnetic field and current measurements to compare with an equilibrium code model fitted to wall-mounted probes. The USPR is being designed to study edge density and turbulent fluctuations. A multipoint Thomson scattering system is currently being installed to give radial temperature and density profiles.
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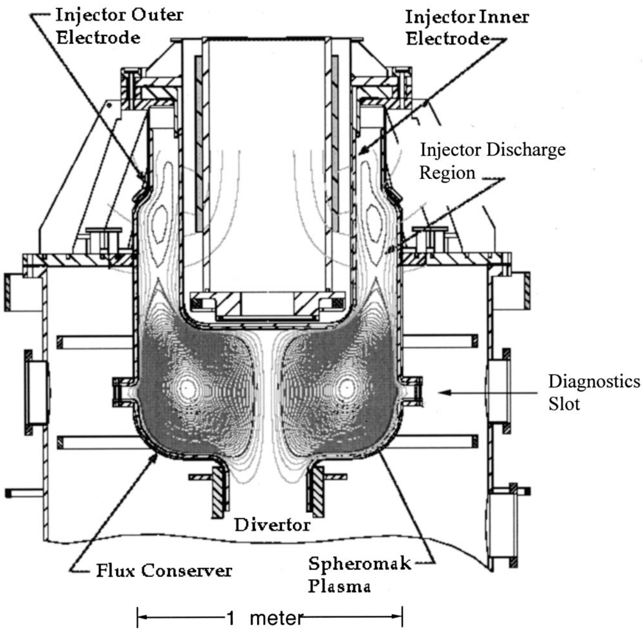

FIG. 1. SSPX with CORSICA modeling of equilibrium field profile.

INTRODUCTION

The sustained spheromak physics experiment (SSPX)[1] device produces spheromak[2–8] plasmas with an outer diameter of 1 m and a plasma minor radius of 0.23 m. A cross section of the device is shown in Fig. 1. Many diagnostics gain access at the slot located at the flux conserver midplane as shown in the figure. The SSPX has a large complement of diagnostics already fielded and several more coming online in the near future, particularly the profile diagnostics to measure the internal density, temperature, and magnetic field of the spheromak. A listing of SSPX diagnostics is given in Table I along with a description of the parameters measured and whether the diagnostic is temporally or spatially resolved. Many diagnostics on SSPX have been installed through collaborations with other institutions. A top view of SSPX diagnostics is shown in Fig. 2 with the major diagnostics labeled along with the collaborating institution. This article describes the diagnostics installed or soon to be installed on SSPX.

BANK DIAGNOSTICS

SSPX has two main capacitor banks, the 10 milliFarad 11 kV formation bank and the 120 milliFarad 5 kV sustaining bank. Both banks are switched with ignitrons. Rogowski loops are used to measure bank dI/dt. The signals are recorded on transient recorders and integrated numerically by the data analysis system to get $I(t)$. Twenty-four RG-218 cables connect the output of the ignitrons to the SSPX electrodes. A high voltage probe is mounted out at the SSPX electrodes where the bank cables tie in. Bank diagnostics provide a measure of input power, energy, and helicity.

MAGNETIC PROBES AND DIAGNOSTIC SLOT ROGOWSKI COILS

Magnetic fields in SSPX are measured with edge magnetic probes mounted in small holes in the flux conserver. Each probe has two orthogonal windings sensitive to the poloidal and toroidal directions. The two coils in each of the probes are wound on a single Vespel form with 13 turns of No. 26 Kapton insulated wire for each of the coils. The probe

TABLE I. List of SSPX diagnostics including measured parameters and temporal or spatial profiling capability.

Diagnostic	Measures	Time resolved?	Spatial profile?
1 Profile Thomson scattering	ne, Te	Gated-single measurement	yes
2 CO_2 laser	ne	yes	two chords now, more to be added
3 USPR	ne, fluctuations	yes	yes
4 TIP	internal Bt, fluctuations	yes	yes
5 16ch photodiode bolo array	Prad. energy loss distribution	yes	
6 3 channel filtered bolo array	Prad, Wrad	yes	views midplane
7 1 channel thermistor	Wrad	integrating	views midplane
8 SPRED spectrometer	Wrad, Te, Spectral rad	integrating	single chord, can be scanned
9 Ion Doppler spect	Ti, Vi	yes	can view selected chords
10 Wall magnetic probes	Bp, Bt at wall	yes	wall profile in z, theta
11 Flux conserver Rogowskis	Flux cons postcurrent	yes	slot profile in theta
12 Visible spectrometer	Impurities	integrating	single chord
13 Hard x ray	runaway electrons	yes	single point
14 VUV monochrometers	line ratios, impurities, Te	yes	two chords
15 Midplane H alpha array	neutral H	yes	yes–10 chords
16 Injector H alpha	neutral H	yes	single chord
17 Injector TV camera	discharge visible light	gated-single point	yes
18 Midplane TV camera	discharge visible light	gated-single point	yes
19 Bank Rogowskis	cap bank current, input power	yes	na
20 Injector voltage	injector voltage, input power	yes	na
21 Bank room TV camera	monitors for arcs	yes	yes
22 Injector room TV camera	monitors for arcs	yes	yes
23 Residual gas analyzer	vacuum sys-H20, evolved gas	yes	na
24 Vessel pressure	vacuum sys, gas valve ops	yes	na

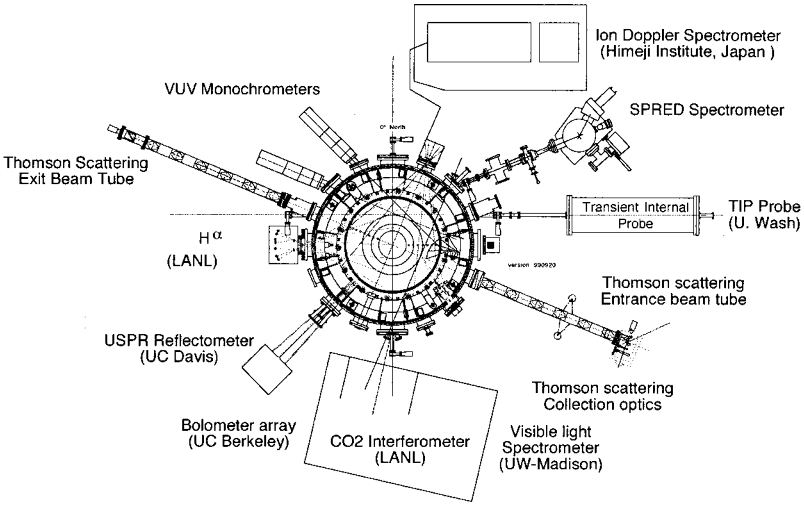

FIG. 2. Top view of SSPX diagnostics.

forms are 0.5 in. in diameter, are protected from plasma with a 0.010 in. hat-shaped stainless steel cover. The probe locations are arranged in three arrays—two axial and one azimuthal. One axial array is located at 90°, and the other at 292.5°. Each axial array has holes for 19 probes with positions extending from up in the injector discharge region, past the diagnostics slot and down to near the divertor region. The azimuthal array has holes for ten probes and is located just above the diagnostics slot. All probe locations are not currently filled with probes. There are ten probes in the axial array at 90° and five probes in the azimuthal array.

The two halves of the flux conserver are separated and form a slot where diagnostic access is available. The two halves are connected by 32 posts spaced evenly in azimuth. Sixteen posts have a Rogowski coil for measuring the current flow between the two halves. Each Rogowski coil is 192 turns of No. 26 Kapton-insulated wire wound on a 2 in. Vespel form. Like the magnetic probes, the Rogowski coils are protected from direct contact with plasma by a stainless steel shield.

The magnetic probes are used for several analyses. First, the probes provide input to the CORSICA equilibrium modeling code.[9] This modeling is used to infer the internal fields, currents, and q profile. A second use is mode analysis where the probe signals, coupled with the known spatial distribution of the probes, can be analyzed to explore mode activity such as the central column kinking and the ''dough-hook'' mode seen on SPHEX.[10–12]

CO_2 INTERFEROMETER

Los Alamos National Laboratory (LANL) has collaborated to install the multichord heterodyne CO_2 laser interferometer that was used on the compact toroid experiment (CTX) experiment on SSPX. The system consists of a 40 W pulsed CO_2 laser and other optics mounted on an optical table adjacent to the SSPX vacuum vessel. The CO_2 beam is directed through an array of beam splitters and mirrors, frequency shifted and split into several separate beams, then directed through the SSPX vacuum vessel. Two beams are currently operational. Each beam travels through ZnSe windows on the SSPX vessel to mirrors mounted on the far side of the vessel. The optical table and the mirror mounts on the far side of the machine are tied together mechanically and the whole system floats on air-isolation mounts to avoid vibrations. Two 10 mW class 3 HeNe lasers are used for alignment. Density measurements are presented in a companion article.[13] A typical shot showing SSPX discharge current, voltage, edge poloidal field, and density is shown in Fig. 3.

SPRED SPECTROMETER

The SPRED[14,15] Spectrometer measures radiation in the 10–160 nm spectral region. The instrument has been absolutely calibrated for intensity at the National Institute of Standards and Technology. The diagnostic is mounted at the flux-conserver midplane and has a tangential view along the magnetic axis. The spectrometer recording extended domain (SPRED) spectrometer has shown that the major radiating species in SSPX plasmas are carbon, nitrogen, and oxygen. The instrument has also demonstrated efficacy in several cleanup methods for reducing those impurities by showing

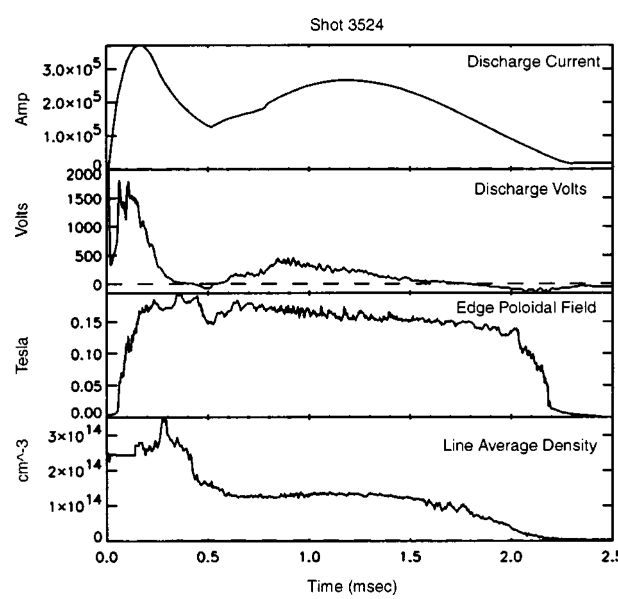

FIG. 3. A typical sustained SSPX discharge showing discharge current, voltage, edge poloidal field, and line average electron density.

large reductions in impurity line radiation after helium discharge cleaning and titanium gettering on the inside of the SSPX flux conserver.[16]

VUV MONOCHROMETERS

SSPX has two Acton Research Model VM-502 monochrometers installed. The instruments have a nominal 0.2 meter focal length, aberration-corrected concave holographic gratings, nominal $f/4.5$ aperture ratio, and a precision micrometer for slit adjustment. A manual sine drive mechanism provides a linear wavelength change with a rotation of a precision lead screw. The spectrometer housing is sealed with o rings, and bakeable to 150 °C. The detector system uses a magnetically shielded photomultiplier (PM) tube with a sodium salicylate coated window (ARC Model DA-781). The instruments are usually tuned to specific lines identified by the SPRED spectrometer. This then provides a time-resolved measurement of the line radiation. The monochrometers are mounted on adjacent ports and view along a tangent to the magnetic axis. The visible ultraviolet (VUV) monochrometers have shown oxygen and carbon radiation measurements temporally consistent with total radiation as measured by the bolometers.

VISIBLE SPECTROMETER

The SSPX visible spectrometer is a 0.5 m Jarrell–Ash model 82-000 installed by the University of Wisconsin.[17] It is capable of operating with high resolution ($\Delta\lambda<0.015$ nm) or large bandpass (110 nm range w/$\Delta\lambda<0.3$ nm) by changing the grating. It is capable of measuring emission line broadening (Ti) and performing emission line surveys (impurity composition) from UV to near infrared. The charge coupled device detector is a Santa Barbara Instrument Group, Inc. (SBIG) model ST-6V. An electromechanical shutter limits temporal resolution to 2 ms exposure times. Light is collected by a telescope that views a diametrical chord through the plasma. This light is coupled to spectrometer by a fused silica fiber optic bundle. The input slit is 25 μm. Data is acquired by computer over a fiber optic link.

ION DOPPLER SPECTROMETER

This diagnostic is being fielded in collaboration with the Himeji Institute of Technology. The system is similar to the visible spectrometer discussed above, but uses a larger 1 m spectrometer and a 16 element Hamamatsu R5900 photomultiplier tube for light detection. The grating is 1800 l/mm blazed at 300 nm. The detector has a UV window that provides good sensitivity from 185–650 nm. Each channel of the PM tube is recorded on a digitizer and provides a time-resolved record of the spectra. Light is coupled to the spectrometer with a fiber optic. A collimating telescope can be aligned to view one of five different angles through the plasma. The overall resolution of the instrument is 0.025 nm. H beta as well as oxygen and carbon impurity lines are typically measured and used to infer plasma flow and ion temperature.

H-ALPHA ARRAY

The H-alpha array has been installed in collaboration with LANL. This system is comprised of PM tubes with H-alpha filters, fiber optics for light transport, and lenses to collimate views through the plasma and couple light into the fibers. Seven chords are viewed at the midplane. An eighth channel views up in the injector region. The seven viewing chords at the midplane provide a fairly coarse profile from one edge of the flux conserver to the other edge.

BOLOMETER

The bolometer system has been installed in collaboration with the University of California, Berkeley. The instrument contains three subsystems: a 16 channel absolute-intensity soft x ray and ultraviolet (AXUV)[18] silicon photodiode array for profile measurements; three single AXUV silicon photodiodes that view a large section of the plasma with two of the diodes filtered to provide energy resolution; and a thermistor-based integrating bolometer to measure total energy. The 16 channel array views 16 chords through the plasma starting near the vertical geometric axis and spreading out toward the outer edge of the flux conserver. In the three single diode section, one diode is bare, the second diode is filtered with glass, and the third is filtered with lithium fluoride. The bolometer section has two thermistors in a bridge circuit with one thermistor exposed to plasma radiation and the other blinded. All sections of the bolometer are mounted in a single package, positioned in the diagnostics slot, and view the SSPX midplane. A unique feature of the bolometer is the ability to pulse a quantity of gas, such as hydrogen, into the bolometer internals to attenuate charge exchange neutrals. This provides the potential for measuring the energy and power loss due to charge exchange as well as radiation. As stated above, the bolometer has shown radiation measurements temporally consistent with oxygen and carbon radiation as measured with the vacuum monochrometers.

GATED CAMERAS

Two gated cameras are installed on SSPX to observe the discharge. One camera is color and the other is black and white. The minimum gating time is 65 μs. There are two viewing locations for the cameras. One is a side view of the flux conserver. The other uses a convex mirror at the bottom of the flux conserver and looks upward through the opening of the flux conserver to view the end of the inner electrode and the gap between the inner and outer electrodes. These cameras have proved very useful for studying localized arcing on the electrodes. They also give a qualitative indication of the breakdown symmetry in the interelectrode gap. The color camera also gives an indication of the gas species especially when changing the injected gas from hydrogen to helium and vice versa.

PROFILE THOMSON SCATTERING

The SSPX Thomson scattering system consists of an 1.4 J pulsed Nd:YAG laser mounted on an enclosed table in an enclosed room located on the first floor of the experimental building. A series of beam tubes and mirrors transport the beam up to the SSPX vessel on the second floor. The entrance and exit beam tubes mounted on the SSPX vessel are baffled to reduce stay light. A beam dump is positioned at the far end of the exit tube where a remote television (TV) camera monitors alignment. A visible HeNe laser is used to alignment. Ten locations along a radius are imaged onto ten optical fibers by collection optics. These fibers transport the light to polychrometer boxes on the ground floor beneath the experiment. The polychrometer boxes are commercially produced by General Atomics[19] and are configured with filters to split the incoming light into four wavelength ranges. The light transmitted through each filter is detected with an avalanche photodiode. the first wavelength range is the laser wavelength and is used for calibrating the system. The other three ranges are selected to provide temperature measurements from 2 to 2000 eV. The overall sensitivity of the system is designed to measure a minimum density of $5 \times 10^{18}\ \mathrm{m}^{-3}$. The diagnostic is in the initial stages of startup.

TRANSIENT INTERNAL PROBE

The transient internal probe (TIP) is installed on SSPX in collaboration with the University of Washington, who also developed the diagnostic.[20] The TIP provides a localized internal measurement of magnetic field by firing a small, terbium-doped glass bullet, clad with sapphire, through the plasma at a velocity of 2000 m/s. The path length through the plasma is 0.73 m so the residence time in the plasma is 365 μs. The bullet has a large Verdet constant and the polarization of light passing through the bullet is rotated in proportion to the component of magnetic field along the bullet's axis. An argon-ion laser beam illuminates the front side of the bullet during its flight. The backside of the probe has a retroreflector attached and light is reflected back through the probe to an ellipsometer where it is analyzed for rotation. A two-stage gas gun is used to accelerate the bullet. A sacrificial mirror is used to illuminate the path of the bullet and is destroyed after the measurement. The time response of the system is better than a microsecond and can therefore resolve fast fluctuations and spatially profile the field and field fluctuations inside the plasma. Additional details on this diagnostic are provided in a companion article.[21]

ULTRASHORT-PULSE REFLECTOMETER

The ultrashort-pulse reflectometer[22] (USPR) was built and installed in collaboration with the University of California, Davis.[23] In this system, a short pulse from an impulse generator is propagated though a dispersive waveguide that spreads the signal out into frequencies ranging from 7 to 18 GHz. These signals are filtered into eight frequency bands that are then mixed with six other higher frequency signals to produce 48 total discrete frequency channels ranging from 33 to 150 GHz. These signals are sequentially switched through six overmoded wave guides mounted in vacuum and launched by microwave horns at the edge of the SSPX plasma in the diagnostics slot. Each discrete frequency will reflect from plasma at a critical density given by the plasma frequency. The electronics measures the time between outgoing and reflective signal and translates this into a distance to the reflective layer. For the frequencies of this system, density can be measured in the range from $1.3\times10^{19}\ \mathrm{m}^{-3}$ to $3\times10^{20}\ \mathrm{m}^{-3}$. This system samples each frequency every 18 μs and is fast enough to observe some classes of density fluctuations.

SUMMARY

SSPX has a complete set of plasma diagnostics either currently operating or coming online in the near future to meet the goals of the experiment. Several novel diagnostics such as the gas-puffed bolometer, the transient internal probe, and the ultrashort-pulse reflectometer are being fielded and will provide internal profiles of radiated power, charge exchange power, magnetic field, and density. They will also provide fluctuation data. These new measurements will be coupled with more standard diagnostic such as Thomson scattering and laser interferometry to provide measurement redundancy. Many diagnostics on SSPX are the result of collaborations with other institutions and additional details are available in the cited references.

ACKNOWLEDGMENT

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