AIP | Review of Scientific Instruments

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Citation: Review of Scientific Instruments **85**, 11D812 (2014); doi: 10.1063/1.4886959
View online: http://dx.doi.org/10.1063/1.4886959
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/85/11?ver=pdfcov
Published by the AIP Publishing

REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 11D812 (2014)

Initial implementation of a Thomson scattering diagnostic for Proto-MPEX[a)]

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(Presented 3 June 2014; received 10 June 2014; accepted 24 June 2014; published online 16 July 2014)

Internal funds have been used at Oak Ridge National Laboratory to enable the initial installation of a laser based, Thomson scattering (TS) diagnostic on the prototype Material-Plasma Exposure eXperiment (Proto-MPEX). Since the funds are limited in amount and duration, the initial TS system has followed a low cost design and rapid implementation. This paper will discuss the design elements of the initial TS configuration on Proto-MPEX and issues encountered during installation. Avenues of response to system limitations will be discussed, along with considerations for further optimization. The laser system will undergo reconfiguration to enable additional project milestones, e.g., laser induced break-down spectroscopy. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4886959]

I. INTRODUCTION

Thomson scattering (TS) of laser photons from plasma electrons is a relatively common diagnostic technique, utilized in fusion grade plasmas to measure electron velocity distribution functions (due to the Doppler shift imparted to scattered photons from moving electrons) and thereby infer electron temperature and density.[1–3] In conjunction, Raman or Rayleigh scattering (RS) of laser photons from neutral particles can be measured to infer the neutral particle density in the same scattering volume as TS.[4] Since the cross-section for TS (and RS, to a less severe extent) is extremely small, the TS "signal" photons must be discriminated against the large number of injected photons from the laser, i.e., the "background." This is typically accomplished by minimizing laser background light with light baffling, choice of viewing geometry, beam polarization, and efficient beam dumping. Hence the vast majority of laser photons are not utilized, but are dumped. This laser power (or a fraction thereof) can be harnessed to enable additional laser based diagnostics, such as Laser Induced Break-down Spectroscopy (LIBS).[5–7] TS, RS, and LIBS measurements can be accomplished with a single laser, if the LIBS impact is time-of-flight delayed relative to the TS and RS measurements.

Typical components of a TS diagnostic system are: (1) the high-power laser and laser coupling (to the plasma device) optics, (2) the scattered light collection optics and routing hardware, and (3) the light detection and digitization instrumentation. Each of these aspects will be discussed in this article for the initial implementation of the prototype Material-Plasma Exposure eXperiment (Proto-MPEX)[8] Thomson scattering diagnostic system.

II. LASER SYSTEM

A central component of the laser-based diagnostics for Proto-MPEX is a high-powered laser. The system utilized here is commercially available from Newport, Inc. as a Spectra Physics Quanta Ray Pro-350.[9] The Q-switched Nd:YAG laser is capable of producing ~3.0 J of 1064 nm light. For this application, the laser is "frequency doubled" to produce 1.4 J/pulse (7–10 ns pulse duration) of 532 nm light at 10 Hz. Any residual power at the 1064 nm fundamental is rejected into an incorporated beam dump in the laser.

For the health and safety sake of the diagnostic operators and ancillary personnel, the Nd:YAG laser beam-line is completely enclosed during standard operating procedures. Hence, this Class IV laser can be treated as a Class Ib "embedded" system by Oak Ridge National Laboratory (ORNL). Only during beam alignment is the enclosure boundary violated. The majority of alignment is performed with a co-linear, low-power helium-neon (HeNe), continuous beam, alignment laser at 632 nm. When necessary, co-linearity of the HeNe and Nd:YAG laser will be verified with "flash paper" prior to the laser beam dump.

The Nd:YAG laser is staged in a diagnostic laboratory, adjacent to the Proto-MPEX machine area. The room boundary provides a natural segmentation, useful for the establishment of work areas. Under normal operating conditions, after exiting the laser housing, the laser light encounters a remote-steerable mirror, to be routed vertically upwards. After ~3 m, a second remotely steerable mirror directs the beam horizontally towards the Proto-MPEX device. Both of these steering mirrors are located in the so-called "Tower 1," which supports the elevated laser beam enclosure. The laser light exits the diagnostic laboratory in an enclosed 3-in. diameter pipe through a wall penetration, into the Proto-MPEX machine area. After the wall penetration, the beam enclosure is supported by "Tower 2." After Tower 2, the beam travels overhead, above the machine "control room" to Tower 3. From Tower 3, the beam continues at an elevation of ~ 4 m, above the Proto-MPEX device, until it reaches Tower 4. At Tower 4 there is another remote-operable steering mirror, which directs the

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[a)] Contributed paper, published as part of the Proceedings of the 20th Topical Conference on High-Temperature Plasma Diagnostics, Atlanta, Georgia, USA, June 2014.

[b)] Author to whom correspondence should be addressed. Electronic mail: biewertm@ornl.gov laser vertically downward, transecting the plasma column of Proto-MPEX, before being dumped.

The total horizontal distance traversed from Tower 1 to Tower 4 is ∼ 20 m, in three roughly equal segments. The beamline enclosure is surplus aluminum "waveguide" from ECH transmission line development at ORNL. The enclosed beam line segment between Tower 2 and Tower 3 is designed to be removable, to allow the use of the installed building crane and/or forklift, when transporting large/tall loads from one end of the building to the other. It is expected that these large load transports may be necessary once or twice each year. The environment of the laser beam enclosing pipes is not controlled, i.e., the pipes are naturally filled with "air" at atmospheric pressure and ambient humidity. If necessitated by scattered light considerations, provisions could be taken to slightly pressurize the beam enclosure with "dry" nitrogen gas.

After being vertically directed downward in Tower 4, the laser transitions from propagation in air to propagation in (Proto-MPEX) vacuum by a quartz vacuum window. Calculations show that there will be ∼4% reflection from this window, which could be recovered by tilting to the Brewster angle (∼56°) at the air-vacuum interface.[10] The reflected light is captured within the steering mirror enclosure of Tower 4. If necessitated by laser power optimization needs, a Brewster angle tilt to the entrance window could be engineered at a later date. However, for typical Proto-MPEX operating densities ($\sim 10^{19}$ cm^{-3}), it has been calculated that ∼850 mJ of laser energy (∼1400 mJ/pulse available from the laser) is needed for "single shot" measurements. The normal incidence, 2(3/4) in. conflat, vacuum window is held at the end of a 28 in. "flight tube" that is attached to a Proto-MPEX spool piece flange. This flight tube includes a bellow for vibration isolation and an electrical conduction break (ceramic) or "high voltage stand off" (up to 3 kV), which electrically isolates the beam enclosure and towers from Proto-MPEX. Similarly, after transecting the plasma column directly in front of the target region, the laser beam passes through an "exit flight tube," again with a conduction break and bellows, before exiting through another normal-incidence vacuum window. If stray-light reflections prove to be an issue for light collection, then baffling along the beam path, in the entrance and exits flight tubes, can be added. After exiting the vacuum, the laser light is absorbed on a commercial dump, enclosed by a lower "dump box."

III. LIGHT COLLECTION OPTICS

It is envisioned that the light collection optics will consist of a commercially available "camera" lens, observing the region in front of the Proto-MPEX target plane through the center of a 4.5-in. conflat port. The target face has been designed to sit ∼1 cm behind the center of the ports on the Proto-MPEX vacuum spool piece. There are currently 4 ports on the spool piece. The "top" and "bottom" ports have 2(3/4) in. conflats, and will be utilized by the TS entrance and exit flight tubes. The 2 horizontal ports view the plasma column, for collection of plasma-scattered laser light at a 90° angle. Currently, one of the 4.5-in. ports will be utilized for the collection of plasma light, while the other will contain a re-entrant port for infrared (IR) imaging of the target surface, or for probe insertion.

The collection lens will image an array of fibers through the plasma column. These fibers will serve a variety of purposes, including TS, RS, and optical emission spectroscopy (OES). While the OES sightlines are "chord integrated," the TS and RS collection volumes are limited to the intersection region between the line of sight and the laser path in the plasma (in the standard way). As such, ∼15 (600 μm core diameter) plus ∼25 (300 μm core diameter) fibers will form two vertical fans (arbitrarily above and below the machine axis), which will allow a radial profile of measurements to be made across the diameter of the plasma column, which is roughly 3 cm, depending on the magnetic field configuration. These collection fiber bundles are legacy equipment at ORNL. After initial operation, the light collection efficiency of the bundles will be assessed, and an optimized (e.g., 1000 μm diameter core) collection bundle procured, if the budget allows.

Light collected from the imaged fibers will be routed from the Proto-MPEX machine area to an adjacent optical "patch panel." At the patch panel, the fibers will encounter other fibers, which gather light from other locations along the axis of the Proto-MPEX device, e.g., for OES. "Transfer fibers" will route the collected light from the adjacent machine area patch panel, through underground conduit over a distance of ∼20 m, into the diagnostic laboratory for distribution (at another patch panel) to detection instruments. The transfer fiber bundles consist of twenty-four 1000 μm diameter core fibers and forty-eight 600 μm diameter core fibers. Transmission losses through these fibers, and at the fiber junctions (at the patch panels), must be measured but are estimated to be within acceptable bounds.

IV. INSTRUMENTATION

A variety of instruments are being staged in the diagnostic laboratory of Proto-MPEX. These include a low-resolution survey spectrometer, a high-resolution (Czerny-Turner) tunable grating spectrometer, and a high-throughput transmission grating spectrometer, as well as traditional ORNL "Filterscope" channels for time-resolved digitization.[11] To save cost, all of these have been repurposed from ORNL legacy hardware stocks. Of these, it is envisioned to dedicate the high-throughput, holographic transmission grating spectrometer (Kaiser Optical Systems, Inc. model Holospec f/1.8)[12] for TS and RS measurements. Coupled to the spectrometer will be an intensified CCD camera, the PI-MAX III 1024 with a Gen III intensifier, made by Princeton Instruments.[13] The fiber-coupled intensifier can be gated to ∼2 ns (or greater) resolution, which is more than sufficient to capture the ∼8 ns Nd:YAG pulse, without significant amount of plasma bremsstrahlung emission.

The short-focal length Holospec spectrometers are subject to significant image plane curvature for a "straight" entrance slit. To effectively eliminate this, the entrance slit (and fiber array) can alternatively be curved at the appropriate radius, as has been accomplished in Ref. 14. Curved fiber bundles are available at ORNL for "low" and "high" resolution, fixed gratings. The low resolution bundle is configured for 10

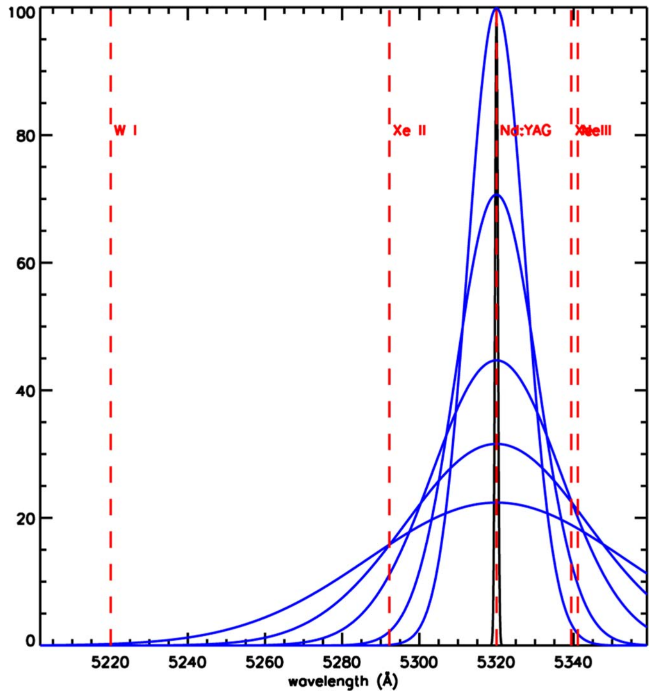

FIG. 1. Calculation of the expected spectral response for a given channel of the TS diagnostic being implemented on Proto-MPEX. The narrow (black) curve at 532 nm represents the instrumental width expected from RS scattered photons. The progressively wider (blue) curves are simulated spectra for 1, 2, 5, 10, and 20 eV electrons, at constant arbitrary density.

fibers (1000 μm core diameter) on each of 2 entrance slits. When coupled with a narrow band-pass filter around the frequency doubled Nd:YAG line at 532 nm, this effectively allows 20 channels to be accommodated on a single CCD camera. For the PI-MAX III 1024 implemented here, each fiber is binned "on chip" to reduce the read noise, allowing the entire frame to be read out with at 100 Hz (i.e., a 10 ms framing period.) Alternatively, a 17 fiber (600 μm core diameter) bundle is available for a "high resolution" grating configuration. The fiber bundles, gratings, and narrow band pass filters were all previously utilized on JET as part of the CHERS diagnostic (operating at 529 nm).[15] New entrance slits (of ~20 μm width, rather than 75–250 μm) will need to be fabricated for this TS application.

Figure 1 shows a simulation of the expected spectral response of the instrument configuration that was discussed above. Multiple curves are plotted for TS measured apparent electron temperatures ranging from 1, 2, 5, 10, and 20 eV (at constant, arbitrary electron density). Also plotted is the expected instrumental width for the Raleigh scattered light from neutral deuterium in the plasma. The height of the RS peak is indicative of the neutral concentration in the plasma column at the volume (intersection of the line of sight with the laser path) of measurement, when the system is fully calibrated. Given appropriate concentrations of neutrals, the RS peak should be readily discernable from the broader, TS peak. Also shown in Fig. 1 are the rest locations of certain emission lines, e.g., W I, which may be present from the solid tungsten Proto-MPEX target, and Xe I lines which can be used from a "pen lamp" source to calibrate the diagnostic. While the TS spectrum centered on 532 nm is offset from the center of the detector, both sides of the spectrum can still be measured. Though this grating was chosen for the 529 nm C VI line of CHERS on JET, it can also be re-appropriated and used for these TS measurements on Proto-MPEX.

V. ADDITIONAL MEASUREMENTS

In the process described above, the majority of laser photons are not utilized, and are instead "dumped" after passing through the plasma. It is envisioned that a fraction (1%–10%) of these photons could be diverted by inserting a partial beam splitter in front of the laser dump. These diverted photons could be refocused onto a fiber bundle and redirected to the Proto-MPEX spool piece, where they could be directed onto the solid W target surface. With sufficient laser power, Laser Induced Break-down Spectroscopy (LIBS) can be performed, utilizing the same collection optics for TS, RS, and OES, as described above. By appropriate choice of the beam-splitter parameters, the laser power can be varied. Moreover, by appropriate choice of the return-fiber, the arrival of the laser light for LIBS can be time-of-flight delayed, so as not to interfere with the collection of TS photons. It is estimated that a return-fiber of ~3 m is sufficient to introduce ~10 ns delay between TS and LIBS laser photons. Ideally, a second gateable CCD camera can be purchased to make LIBS measurements on one of the spectrometers discussed above. The design of the LIBS system for Proto-MPEX is discussed in greater detail in Ref. 7.

VI. SUMMARY AND FUTURE WORK

A diagnostic system has been designed for the Proto-MPEX device and is currently undergoing implementation. The diagnostics system is based on a high power Nd:YAG laser, frequency doubled to emit light in the visible spectrum at 532 nm. These laser photons when Thomson scattered from the plasma electrons give information indicative of the electron temperature and density. Laser photons when Rayleigh scattered from the neutral particles give information indicative of the neutral density. It is anticipated that radial profiles of all these quantities can be accomplished simultaneously at 10 Hz to characterize the performance of the Proto-MPEX device under various operational conditions. These measurements have not yet been made, but are expected in the near future. Following initial measurement attempts, the limitations of the current system design will be assessed, and further optimization may be required.

ACKNOWLEDGMENTS

The authors would like to gratefully recognize the work of the many support personnel at ORNL that contributed to the construction of this diagnostic system.

This work was supported by the U.S. D.O.E Contract No. DE-AC05-00OR22725. Research sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy.

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