Plasma source development for fusion-relevant material testing


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I. INTRODUCTION

The availability of a fusion reactor is determined to a large extent on the lifetime of its plasma-facing components. Developing materials resistant to high erosion and neutron radiation damage is a great challenge that urgently needs to be addressed.1 The materials used in a fusion device must withstand an intense plasma heat flux. The divertor in a tokamak is exposed to plasma heat fluxes of \(10 \text{ MW/m}^2\) for \(10^7\) s, in addition to fusion neutron fluences, which can damage the plasma-facing materials to high displacements per atom (dpa) of \(50 \text{ dpa}\). Materials solutions needed for the plasma-facing components are yet to be developed and tested. The material plasma exposure experiment (MPEX) is a newly proposed steady state linear plasma device designed to deliver the necessary plasma heat flux to a target for testing, including the capability to expose \textit{a priori} neutron-damaged material samples to those plasmas. The requirements of the plasma source needed to deliver the required heat flux are being developed on the Proto-MPEX device which is a linear high-intensity radio-frequency (RF) plasma source that combines a high-density helicon plasma generator with electron- and ion-heating sections. The device is being used to study the physics of heating overdense plasmas in a linear configuration. The helicon plasma is operated at 13.56 MHz with RF power levels up to 120 kW. Microwaves at 28 GHz (\(\sim 30 \text{kW}\)) are coupled to the electrons in the overdense helicon plasma via electron Bernstein waves and ion cyclotron heating at 7–9 MHz (\(\sim 30 \text{kW}\)) is via a magnetic beach approach. High plasma densities \(>6 \times 10^{19}/\text{m}^3\) have been produced in deuterium, with electron temperatures that can range from 2 to \(10\text{eV}\). Operation with on-axis magnetic field strengths between 0.6 and 1.4 T is typical. The plasma heat flux delivered to a target can be \(>10 \text{MW/m}^2\), depending on the operating conditions. An initial plasma material interaction experiment with a thin tungsten target exposed to this high heat flux in a predominantly helium plasma showed helium bubble formation near the surface, with no indication of source impurity contamination on the target. © 2017 American Vacuum Society. [http://dx.doi.org/10.1116/1.4982664]
to explore H-modes using the lower L-H power threshold of helium plasmas. During the active phase of ITER operation (or any fusion reactor), helium (the fusion ash) will be implanted in the divertor in small concentrations. Therefore, an initial PMI experiment in a mostly helium plasma has been performed, and findings from this study are also included.

II. EXPERIMENTAL APPARATUS

A cross-section of the Proto-MPEX is shown in Fig. 1. The device consists of a vacuum chamber with 12 solenoid magnets (M1 through M12), a helicon plasma source, a microwave coupling section, an ICH antenna, and “downstream” and “upstream” target plates. Throughout this paper, upstream refers to the area to the left of the helicon antenna and downstream refers to the area to the right of the antenna. Axial locations are often referenced with respect to the center of the helicon antenna.

The magnets have an inner diameter of 21.7 cm and are made of 40 turns of a water-cooled copper conductor. They were originally constructed for the Elmo Bumpy Torus experiment and are designed to operate continuously at 9000 A. In our experiments, most of the coils typically operate at up to 6500 A, which produces a peak axial magnetic field of approximately 1.5 T. The two magnets around the helicon antenna operate at currents of between 200 and 400 A, with magnetic fields up to ~0.1 T.

The vacuum chamber and the pumping system are composed of a variety of components. Starting from the left-hand side of Fig. 1, a large dump tank is located upstream of the helicon antenna and consists of a 66 cm long, 61 cm diameter stainless steel tank. A small 150 l/s turbo pump is located there as well. The section between the dump tank and the fifth magnet, M5, consists of standard 15.2 cm diameter stainless steel vacuum components. Downstream from that point, the vacuum chamber is formed by the aluminum housing of the magnets and stainless steel spool pieces (~49 cm inner diameter) that connect them. The “central chamber” shown in the figure is an aluminum box which is 41 cm wide, 66 cm high, and 69 cm deep. A 2800 l/s and 1000 l/s turbo pump are located there. A skimmer plate with a 5.8 cm diameter hole is located between the helicon antenna region and the central chamber to provide differential pumping. An additional skimmer plate with an 8.6 cm diameter hole is located on the downstream of the central chamber. Beyond the target plate is a large-volume ballast tank (6.3 m³) that provides effective pumping for pulsed gas operations and includes a 2500 l/s turbo pump. The base pressure is ~10⁻⁶ Torr. There are two primary gas injection points which consist of a gas ring wrapped around the circumference of the vacuum chamber. One injection point is located 14 cm upstream of the helicon window, and the other is 14 cm downstream of the window. Gas flows of up to 10 standard liters per minute (SLM) are possible with flow controllers from MKS Instruments although typical values are between 0.1 and 2.5 SLM.

MKS Instruments model 627 baratrons are used to measure the pressure at four locations (shown in Fig. 1 as P1-P4): 12 cm upstream of the helicon window, 12 cm downstream of the helicon window, in the central chamber, and at various locations between the central chamber and the target. The baratron heads are wrapped with several layers of mu metal and are mounted between 30 and 60 cm from the chamber walls to help mitigate effects of the magnetic field. Pulses of gas only, magnetic field only, and gas plus magnetic field are taken to calibrate out the effects of the field on the measurement. The gas pressure is the highest near the helicon and the lowest near the target for constant flow conditions without a plasma when the gas is injected near the helicon. For example, a constant flow of 0.4 SLM results in a pressure of 10.5 mTorr near the antenna, 5.1 mTorr in the central chamber (0.94 m downstream of helicon), and 1.1 mTorr at 2.17 m downstream of the helicon. The gas pressure typically drops

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**Fig. 1.** (Color online) Cross-section of the Proto-MPEX device and a typical axial magnetic field strength. The coils are labeled M1, M2, etc. For this field calculation, there is no current in coils M2 and M5. Coils M3 and M4 have 310 A, and the remaining coils have 5900 A. The central chamber is between coils M6 and M7 and is the location of Probe A, pressure measurement P3, and the microwave launchers. The direction of the magnetic field is from left to right in the figure.
during the plasma pulse, presumably due to plasma pumping effects.

The helicon plasma source uses a water-cooled double-helix half-turn antenna, as shown in Fig. 2. The antenna is 25 cm long with an inner diameter of 15 cm. The antenna is separated from the vacuum chamber by a cylindrical aluminum nitride window (Ceradyne Ceralloy® 1370 DP) 30 cm long with an inner diameter of 13.8 cm. The antenna is operated at 13.56 MHz at power levels of up to 120 kW using a Continental Electronics model FRT-86 transmitter.

Two different microwave systems are used to create and heat the plasma. An 18 GHz klystron source (Varian model VGA-934) is used to initiate the plasma. A short run of the rectangular waveguide (~1.5 m of WR62), followed by a rectangular-to-circular converter and a smooth-walled, up-taper section, directs the microwaves into the central chamber (see Fig. 1) through a 63 mm diameter, 2.8 mm thick aluminum oxide vacuum window. An internal reflector plate directs the microwaves toward the target side of the central chamber wall, where they are reflected again in the direction of the helicon source. Power levels of 4–8 kW are typically used to create a seed plasma before the initiation of the helicon plasma.

Microwaves at 28 GHz are used to heat the plasma electrons, primarily via mode-converted EBWs. The EBW heating approach was chosen because the plasma density in the Proto-MPEX device is much higher than the cutoff density at 28 GHz (~1 x 10^{19} m^{-3}). EBWs are hot electrostatic plasma waves that propagate in the plasma, do not have a density cutoff, and are readily absorbed in Doppler-broadened electron cyclotron harmonic zones. The TE02 output mode of the gyrotron (Varian model VGA-8000, 200 kW) is converted to the HE11 mode via a mode converter tank. A Vlasov launcher directs the microwaves toward a paraboloid reflector, which directs and focuses the resulting HE11 mode to the input of an 88.9 mm diameter section of the corrugated waveguide (with 1.3 mm deep grooves spaced every 1.4 mm). The waveguide run in the experiment consists of 3.2 m of waveguides and two miter bends. The connection to the central chamber is through a corrugated taper to the interface with a 63.5 mm diameter edge water-cooled aluminum oxide vacuum window. An additional section of 63.5 mm diameter corrugated waveguides (1 mm grooves spaced every 1.4 mm) and miter bends with waveguide extension, shown in Fig. 3, is used to direct the microwaves once inside the vacuum chamber. The miter bend/waveguide extension section can be rotated to find the optimum launch angle for EBW coupling. Most experiments have been performed with the launcher pointing in a direction of +20° from the normal (as shown in the figure). Predictions of wave propagation and absorption have been made using the GENRAY-C code which is a modification of the GENRAY code that operates in Cartesian coordinates.

The ICH antenna section is located between the central chamber and the target. The antenna is a 25 cm long double-helix half-turn antenna with an inner diameter of 9 cm, similar in design to the helicon antenna but with the helical twist in the opposite direction. The installed antenna is shown in Fig. 4. The antenna is operated in a vacuum but is separated from the plasma by an 85 mm outer diameter, 80 mm inner diameter, and 61 cm long quartz tube. The antenna is designed to couple energy to the ions via the slow wave magnetic beach approach, where the waves are absorbed at the cyclotron resonance in the expanding magnetic field just downstream of the antenna. The antenna has been modeled using the ANTENA code to estimate loading and wave propagation and using CST Microwave Studio® to verify power handling capability. It is typically operated at 8.5 MHz and at up to 30 kW using a Continental Electronics model FRT-85 transmitter.

The plasma is terminated at both the ends on conducting metal plates. The upstream plate located in the dump tank is 1.5 mm thick stainless steel with a diameter of 40 cm. The plate is large enough to capture the expanding magnetic field.
lines from the plasma. The target plate consists of either a 1.5 mm or a 0.25 mm thick stainless steel plate with a diameter of between 9.5 and 11.4 cm, depending on its location. For most experiments, the target is located 2.57 m downstream of the helicon antenna, but it was located 1.4 m downstream for some experiments. As discussed subsequently, an infrared (IR) camera was used to image the backside of the target plate to obtain an estimate of the deposited heat flux.

III. DIAGNOSTICS

Many different diagnostics are used at several axial and radial locations, including double Langmuir probes, Filterscopes, IR and fast digital cameras, a microwave interferometer, a retarding field energy analyzer, and a Thomson scattering system, some of which are described as follows.

Several double Langmuir probes are used to perform radial profile measurements at various axial locations. The probes consist of two tungsten wires that are 0.25 mm in diameter, 1.2 mm long, and separated by 1.4 mm. The calculated density is within ~10% of the density determined using a 70 GHz interferometer. The sweep voltage was typically a triangle wave swept at ±70 V at a frequency of 200 Hz. Data are shown at three different probe locations, as indicated in Fig. 1. Probe A is located in the central chamber and is 0.94 m downstream of the helicon antenna. Probes B and C are located 1.85 and 2.17 m downstream of the antenna, respectively.

Filterscopes\textsuperscript{16} are used at several axial locations to measure line emission from the plasma at a 100 kHz sample rate. Narrowband D-alpha filters (656, 1 nm wide) are used most often, but various helium, tungsten, and other line filters have also been used.\textsuperscript{17} The emission from the plasma is measured using compact achromatic collimating lenses and is connected to the Filterscope inputs via fiber-optic cable. Up to 24 simultaneous Filterscope measurements are possible. Fiber optic views are located between most of the magnets. When coupled with the fast sampling rate, the temporal and axial variation of the plasma emission can be measured. Applications include the validation of B2-Eirene transport code predictions,\textsuperscript{18} understanding the temporal evolution of the plasma during helicon plasma mode jumps, exploring recombination physics at the target from D-alpha, beta, and gamma emission, and helium line ratio measurements to determine density and temperature.\textsuperscript{17}

A McPherson 2051 high-resolution spectrometer is available for use on the Proto-MPEX device. The spectrometer is a 1 m Czerny-Turner configuration with gratings ruled at 1800, 1200, and 300 grooves/mm. A Princeton Instruments PhotonMAX 512b EMCCD camera is used as a detector. The system is used to measure the Doppler-broadened spectra of plasma impurity ions (typically Ar II from injecting ~1% argon in a deuterium plasma) with a 10 ms framing rate on five simultaneous lines of sight, using the same collection optics as are available for Filterscope measurements.

A Thomson scattering system is used to measure the density and temperature in front of the target plate. It uses a Spectra Physics Quanta Ray Pro-350 Q-switch Nd:YAG laser. The laser is frequency doubled to produce 532 nm light at 10 Hz pulses. A Kaiser Optical Systems Holospec f/1.8 spectrometer with a PI-Max3 intensified CCD camera is used to measure the Thomson scattering signal. The details of the system can be found in Ref. 19.

The heat deposition profile at the target plate is measured by viewing the backside of the target using a FLIR A655sc IR camera. The target image is seen through a 4.6 cm diameter ZnSe window and is reflected from a gold-coated mirror to the camera. A fiducial pattern on the backside of the target is used to help focus the camera. An example view of the backside of the target is shown in Fig. 5. The details of the IR imaging system can be found in Ref. 20. For thicker target plates (1.5 mm), the temperature was measured using a thermocouple inserted into the edge of the plate. For the thinner plates (0.25 mm), a thermocouple was attached 2.5 cm from the center of the plate. The plates were either bead-blasted or water-jetted to produce a dull surface finish. The target emissivity was estimated based on the thermocouple measurement and was calibrated with a heat gun during benchtop testing, with typical values of 0.33 for the thick plate and 0.26 for the thin plate. The target plates were supported and kept rigid with four 1.25 cm diameter aluminum rods attached to the edges of the plate, as can be seen in the figure. Note that the camera optics are such that the heat pattern seen in Fig. 7 corresponds to what would be observed when viewing the target from the helicon antenna.

IV. INITIAL EXPERIMENT RESULTS AND DISCUSSION

The Proto-MPEX device has been operated with several different gases—including hydrogen, deuterium, helium, and argon—although most efforts focus on deuterium plasmas because of their high relevance for fusion plasma material...
interactions. The plasma is pulsed, with the 18 GHz system coming on first for preionization followed by a pulse from the helicon source. The helicon pulse length is typically ~150 ms, but 1 s pulses have been obtained. The pulse length is primarily restricted by the lack of water cooling on the helicon vacuum window although a new water-cooled window is being designed that will allow for much longer pulse operation. Microwaves at 28 GHz (30–60 ms pulse) and ICH power (30–60 ms pulse) near 8.5 MHz are initiated in the middle of the helicon pulse. A typical pulse, showing the timing of all the power system triggering, is shown in Fig. 6.

The plasma parameters can vary depending on the magnetic field configuration, helicon power, gas pressure, and additional auxiliary heating power (e.g., EBW or ICH). Two primary helicon operating modes have been observed, with one being dominated by power coupling in the edge of the plasma and the other showing evidence for power coupling to the core of the plasma. The edge-coupled mode seems to be supported by a Trivelpiece-Gould mode.\(^2\) The plasma density measured 1.36 m downstream of the helicon can vary from 1 to 2\(\times\)10\(^{19}\)/m\(^3\) in the center of the plasma, with an electron temperature that can vary from 2–4 eV in the center to >7 eV in the edge (radius > 2 cm). An example of the heat deposition pattern (shown as the change in the temperature) on the thin target plate (0.25 mm) located 2.5 m downstream of the helicon antenna is shown in Fig. 7(a), where two thin regions of high temperature are typically seen in the edges. Near-field capacitive coupling or inductive coupling could also be a contributing factor to this edge heating pattern. Similar edge heating patterns have been seen in visible light images in Ref. 22 as the plasma starts in the E-mode before it transitions to the H-mode. In general, the electron temperature increases and density decreases as the operating pressure decreases (e.g., from 10 to 2 mTorr in the central chamber). The density and electron temperature decrease as a function of distance from the source, with the density dropping 10%–20% from 1.5 to 2.1 m away and the electron temperature dropping 40%–50%. When combined with a focusing magnetic field to make a smaller diameter plasma (lower magnetic field in the helicon antenna region) and low gas flow (<0.1 SLM, fill pressure <2 mTorr), the peak plasma heat flux deposition on a target located 1.4 m downstream from the antenna can be concentrated and exceeds 10 MW/m\(^2\) in a small area on the target, based on IR camera measurements of the temperature change of the target (>300°C). For this condition, the electron temperature in the high heat flux region can be >20 eV. An example of the target heat flux pattern for this configuration is shown in Fig. 7(b) for the thick target plate (1.5 mm).

When the helicon RF power exceeds a threshold level, typically >105 kW, the plasma experiences a mode jump that increases the core plasma density by more than a factor
of 2. These center-coupled plasmas are much more quiescent compared with the edge-coupled mode plasmas. Electron densities greater than $7 \times 10^{19}$/m$^3$ have been measured with a double Langmuir probe located 2.1 m downstream of the helicon source, which is 0.4 m from the target, while the electron temperature for this mode is 1.5–2 eV at this location. These values are consistent with the requirements of the helicon source for MPEX. The probe results are consistent with the Thomson scattering results of $7.6 \times 10^{19}$/m$^3$ and 1.5 eV measured 0.1 m in front of the target. An example of the heat deposition on the thin target plate (0.25 mm) for this mode is shown in Fig. 7(c), where core power deposition is seen. The temporal behavior of this mode jump is shown in Fig. 8. For this condition, deuterium gas is injected 14 cm downstream of the helicon antenna at a flow rate of 2.4 SLM at 300 ms before the helicon power pulse and is then reduced to a rate of 1.7 SLM at 50 ms before the application of a helicon power of 110 kW. For this shot, the peak magnetic field was 1.3 T, the magnetic field around the helicon antenna was 0.05 T, the 18 GHz microwave power was 3 kW, and the central chamber pressure was $\sim$2 mTorr during the plasma pulse. The timing of the mode jump is influenced by the input power level, gas flow level/timing, and gas fueling location. Increased pumping in the central chamber and the use of smaller diameter skimmers could increase the downstream electron temperature and are being explored. The details of the helicon mode jump physics are given in Ref. 23.

Typical density and temperature profiles are shown in Fig. 9 for several axial locations. Probes A and B were scanned vertically, and Probe C was scanned horizontally. The experimental conditions were the same as for Fig. 8. The density is broader for Probe A because of the flux tube expansion in the central chamber. The central density does not vary much on axis, but the electron temperature tends to decrease further downstream. This temperature decrease might be caused by collisions with neutrals. The temperature profiles tend to be fairly flat in the center and peaked at the edges ($>2$ cm). The density is not radially symmetric, which is consistent with the heat deposition pattern shown in Fig. 7(c). Increasing the magnetic field in the helicon antenna region leads to larger diameter plasmas at the target, but more RF power will likely be needed to maintain the core-coupled mode and will be the subject of future experiments.

The microwave power at 28 GHz has been coupled to the plasma during overdense conditions. Most experiments have used the O-X-B mode conversion scenario, where an ordinary mode is launched from the waveguide at a tangential angle with respect to the magnetic field. The O-mode converts to the slow extraordinary mode near the upper hybrid resonance, where it then converts to the Bernstein wave. The Bernstein wave then propagates perpendicular to the magnetic field, where it is damped on the Doppler-broadened electron cyclotron harmonic surfaces.

A plot of the electron temperature and density as a function of time during a 28 GHz microwave pulse is shown in Fig. 10. These data were measured 1.85 m downstream of the helicon antenna (0.9 m downstream of the microwave launcher) in a deuterium discharge at a radius of 2 cm, with a launch angle of $+20^\circ$ from the normal (as shown in Fig. 3).
and a coil current of 4700 A. The peak magnetic field was 1.0 T, the helicon antenna field was 0.05 T, and the field in the central chamber was ~0.3 T. The helicon power was ~110 kW, the 18 GHz power was 3 kW, and the central chamber pressure during the plasma pulse was ~2 mTorr. A modest increase in the electron temperature was observed (~25%) at this radial location during the microwave pulse, where the electron temperature increases from ~3 to ~3.8 eV. GENRAY-C modeling predicts that the power absorption should be near the upper hybrid layer at the plasma edge (radius of ~3 cm in the central chamber) but with areas of better core coupling existing at certain values of the magnetic field where Doppler-broadened resonances are accessible. The modeling suggests that the edge coupling will be dominant as a result of collisional damping, which is consistent with experimental observations of power deposition in the edge; however, the situation should improve at lower neutral density and higher electron temperature. Recently, it has been observed that longer plasma pulse lengths result in lower neutral pressure (<1 mTorr during the plasma pulse) near the EBW launcher because of plasma pumping in the central chamber. This pressure reduction and the use of improved (smaller diameter) skimmer plates for better differential pumping are being explored as a way to improve EBW core coupling, along with increasing the power level and pulse length of the microwave system.

The ICH antenna has been operated at 8.5 MHz and at up to 25 kW for 60 ms pulses into a helicon plasma with deuterium plasma densities of 2−6 × 10^{19}/m^3 and coil currents of 5900 and 6400 A. These conditions correspond to drive-frequency-to-ion-cyclotron-frequency ratios (Ω/ω ci) of 0.85 and 0.79, respectively. Operations thus far have focused on measuring the antenna loading to determine power-handling limits, but some initial heating experiments have also been performed. The predicted loading of the antenna (real part of the antenna load impedance) by the ANTENA code is shown in Fig. 11 as a function of plasma density and the gap between the antenna and the plasma edge. The measured load impedance of 4–5 Ω is somewhat higher than that predicted for the measured gap of 2–2.5 cm. Contributing factors for this difference include the one-dimensional assumptions in ANTENA, the actual radial density profile, and the changing magnetic field. We are in the processing of modeling the antenna in 3D using COMSOL Multiphysics, which should help to address these factors. For this load range, the estimated voltage and current (<~2 kV, <~80 A) at the antenna are well within the design limits of the moderate power vacuum feedthrough being used, as shown in Fig. 11. Peak voltages in the matching network are ~2 times higher and are within the 25 kV rating of the tuning capacitors. When the plasma is seeded with a small amount of argon (~1%), the Doppler-broadened 480.6 nm Ar II ion line, measured using a McPherson spectrometer 0.1 m downstream of the ICH antenna, shows a broadening of the line profile with RF power, which is indicative of ion heating. In addition, preliminary measurements of the ion energy distribution with a retarding field energy analyzer show a broadening in the distribution at larger radii, which indicates some edge power deposition. Efforts are focused on quantifying the amount and the location of power coupling and will be reported in future publications.

V. INITIAL TUNGSTEN EROSION EXPERIMENT

An initial PMI experiment exposed a sample of tungsten to a plasma of 95% helium and 5% deuterium. The purpose of this experiment was to determine whether the plasma conditions in Proto-MPEX could potentially be used for high-flux/low-fluence material tests. It has already been found that helium can lead to a change in the microstructure of the material. This could affect the transport of hydrogen in
tungsten, form nanostructure extrusions like fuzz, and change the thermal conductivity of tungsten.

For this test, a thin piece of tungsten (50 × 50 × 0.25 mm) was placed on a grounded sample holder at a location 1.4 m downstream of the helicon antenna. The plasma conditions were similar to those for the IR camera condition shown in Fig. 7(b), where the magnetic field was configured such that the peak plasma heat flux was focused on a small area, with a peak magnetic field of 0.7 T. The helium gas flow was 0.05 SLM, and the central chamber pressure was ~2.5 mTorr. The sample was exposed to 55 pulses of 100 kW helicon plasmas (130 ms pulse length), with an additional 4 kW of 18 GHz power (240 ms) and 25 kW of 28 GHz power (30 ms). Based on Langmuir probe measurements, the flux is estimated to be 1–2 × 10^23/m^2s and the fluence is estimated to be ~1 × 10^23/m^2. Ion energies are estimated to be >40 eV because of the high electron temperature in this region (>20 eV).

Scanning electron microscopy images from the sample, taken from the area of maximum heat flux, are shown in Fig. 12. The area evidences large grain growth and recrystallization, which typically takes place for temperatures exceeding 1400 °C for tungsten. Although the temperature was not measured on this sample, it can be estimated based on the similar experimental conditions from those shown in Fig. 7(b), where the temperature exceeded 300 °C on a thicker (1.5 mm) 304 stainless steel target. When scaled to the thinner target and corrected with the heat capacity of tungsten, the calculated temperature exceeded 2000 °C in this area. A pitted surface can be clearly seen in the close-up view, which would be consistent with helium bubble formation. Possibly because of the low fluence of this experiment, there was no evidence of tungsten “fuzz” growth, which has been seen in other helium plasma exposure experiments.

A transmission electron microscopy image of the sample is shown in Fig. 13. A protective layer was deposited on the surface before the sample underwent focused ion beam (FIB) milling. Bubble (cavity) formation can be seen throughout the sample, including cavities on the order of 50 nm in diameter. The bubble location is within 100 nm of the surface.

The analysis results from the surface interface using energy-dispersive x-ray spectroscopy (EDS) are shown in Fig. 14. The elemental analysis showed no materials from the plasma chamber, such as stainless steel (from stainless steel chamber wall/skimmers) or aluminum (from the chamber wall or the helicon ceramic). Only elements from the FIB sample preparation or the TEM specimen holder were seen, assuming that impurities of 0.1–1.0 wt. % should be visible. This finding is important for future PMI experiments because any surface modifications must be attributable only to the specific plasma being used (e.g., helium or deuterium) and not to the material eroded from surfaces to which the plasma is in contact in other parts of the chamber.

VI. SUMMARY AND CONCLUSIONS

The Proto-MPEX device has been successfully operated using deuterium and helium plasmas at peak magnetic fields of 1.5 T. In deuterium operations, the electron density and temperature near the target have reached ~8 × 10^19/m^3 and 1.5–2 eV, respectively. The plasma has been observed to experience a jump from an edge-coupled mode to a center-coupled mode at sufficiently high helicon input power (>105 kW). Initial EBW experiments have shown that the electron temperature in the edge can increase up to 25% at densities above the cutoff for some experimental conditions. GENRAY-C modeling indicates that core coupling will improve at lower neutral densities, which can be achieved.
for longer plasma pulses and better differential pumping. The first ICH experiments have shown good antenna loading, which is consistent with modeling predictions, and quantification of ion heating is ongoing. The performance of the helicon source matches the needs of the MPEX device, and the focus of subsequent research is to demonstrate the needed electron and ion heating of the core plasma. When exposed to a high heat flux helium/deuterium plasma ($/C24 \times 10 \text{ MW/m}^2$), a thin tungsten sample showed evidence of high-temperature-induced recrystallization and helium bubble formation near the surface. No plasma source contamination was noticed on the sample surface, such as stainless steel or aluminum, which is important for the future needs of the MPEX device.

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**FIG. 14.** (Color online) EDS of the surface interface from the tungsten sample from the high heat flux region. There was no evidence of impurities from the plasma source.

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