Latest Results From the Hybrid Illinois Device for Research and Applications (HIDRA)

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Abstract— The Hybrid Illinois Device for Research and Applications (HIDRA) is a toroidal fusion device at the University of Illinois at Urbana–Champaign, Urbana, IL, USA. HIDRA is the former WEGA stellarator that was operated at the Max Planck Institut für Plasmaphysik, Greifswald, Germany. The machine is a five-period, $l = 2$, $m = 5$ stellarator, with major radius $R_0 = 0.72$ m, and minor radius $a = 0.19$ m. Initial heating is achieved with 2.45-GHz electron cyclotron resonance heating and an on-axis magnetic field of $B_0 = 0.087$ T that can go as high as $B_0 = 0.5$ T. HIDRA has the ability to operate as both a stellarator and a tokamak, initially operating in the stellarator mode. The focus of research on HIDRA will be doing dedicated studies on plasma-material interactions (PMIs) using the wealth of knowledge and experience at the Center for Plasma Material Interactions, Urbana, IL, USA. In early 2016, the first experiments were performed on HIDRA. This paper presents some of the first results obtained from the machine such as initial magnetic fields' measurements and plasma discharges. It also shows the development of the control system being currently implemented and introduces HIDRA-materials analysis tool, the *in situ* PMI facility that will be mounted on HIDRA in the near future to further enhance the diagnostics and material testing experiments meant to be conducted on the machine.

Index Terms— Control system, diagnostics, electron gun, fusion, Langmuir probe, magnetic field, plasma discharge, plasma materials interaction, stellarator, tokamak.

I. INTRODUCTION

THE Hybrid Illinois Device for Research and Applications (HIDRA) [1] is one of the oldest fusion experiments still operational today. It is labeled "hybrid" because it has the ability to operate as a stellarator and/or a tokamak, a property that makes it unique among the fusion devices [2]. It was first used in 1975 in Grenoble, France as a tokamak under the name WEGA, standing for "Wendelstein Experiment in Grenoble [2] for the application of radio frequency heating." Then, it moved to Germany in 1982, to the University of Stuttgart, Stuttgart, Germany, before moving again to Greifswald between 2000 and 2001, where it was operated by the Max Planck Institut für Plasmaphysik up to the year 2013. While in Germany, WEGA was operated as a stellarator [3]. WEGA was used as a test bed for the Wendelstein 7-X (W7-X) diagnostics, heating and control scenarios. After W7-X became operational, WEGA moved to the University of Illinois at Urbana–Champaign (UIUC), Urbana, IL, USA, in 2014 and was renamed as HIDRA. At UIUC, HIDRA's main research focus will revolve around plasma-material interactions (PMIs) studies, especially those related to the interaction between plasma and liquid metals, specifically liquid lithium.

II. PMI STUDIES ON HIDRA

The most challenging obstacle that needs to be dealt with in order to make fusion a viable energy source is that of the materials and PMI, in particular at the inner wall and divertor [4]. This has a direct effect on the lifetime of the device and its components, as well as the quality of the plasma and the energy being produced [5]. Because of the extremely high temperature needed to sustain a plasma, the materials used at the wall and divertor need to be able to withstand considerable heat fluxes. Nowadays, a heat flux of 10 MW/m^2 is widely used as the benchmark when designing fusion related devices, with tungsten and carbon usually being the materials of choice [6], [7]. Currently, however, solid materials struggle to handle the heat flux on the wall and divertor surfaces, for example, in the case where the surface is hit by an edge-localized mode (ELM). This is why liquid metals are considered today as a serious alternative to solid materials, as they

have the potential to overcome these problems. The continuous flow of a flowing liquid metal acts as a healing process that protects the surface from ELMs and avoids damage from particle or heat fluxes. The most promising candidate among the liquid metals is lithium. It has a low atomic number of $Z = 3$, and contributes to removing impurities and controlling the ELMs [8].

HIDRA will allow running PMI studies of liquid lithium within a fusion environment utilizing both the stellarator and the tokamak modes. UIUC has its own design for flowing liquid lithium inside a fusion device, called LiMIT [9], which stands for liquid lithium–metal infused trenches. Similarly, the Princeton Plasma Physics Laboratory (PPPL), Princeton, NJ, USA has another design named FLiLi for flowing liquid lithium [10]. Both LiMIT and FLiLi are plates' designs, and are to be tested inside HIDRA early 2018. According to simulations using edge Monte Carlo 3-D and EIRENE, the 26-kW heating source of HIDRA will translate into heat fluxes up to $1\,MW \cdot m^{-2}$ on an inboard limiter, up to $0.2 MW \cdot m^{-2}$ on an outboard limiter, and up to $0.15 MW \cdot m^{-2}$ on a trench limiter. Similarly, upper limits of $4.7 \times 10^{22}, 5 \times 10^{21}$, and $5.6 \times 10^{21}\ m^{-2} \cdot s^{-1}$ for the particle fluxes of, respectively, an inboard, outboard, and trench limiter have been determined.

Also, the development of the HIDRA-materials analysis tool (HIDRA-MAT), which will be further described in Section IX, will allow the study of solid facing components, and therefore diversify the research to solutions different than liquid metals.

III. HIDRA SPECIFICATIONS

HIDRA is a medium-size classical stellarator having a major radius of $R_0 = 0.72$ m and a minor radius of $a = 0.19$ m. It is a five-period device, with a poloidal period number $l = 2$ and a toroidal period number $m = 5$ [1], [3]. For its main operation at UIUC, HIDRA will be used in the stellarator mode, taking advantage of the steady-state operation that can go up to 60 min at low field (0.087 T) and tens of seconds at high field (0.5 T). The tokamak ability of the machine will eventually be used in order to simulate transient operations and instabilities by sending a pulse through the central coil.

In addition to having 40 toroidal field coils and four helical coils, HIDRA has two vertical field coils that help in shaping the plasma. These coils allow to run a toroidal on-axis magnetic field B_0 between 0.087 and 0.5 T. Fig. 1 shows a sketch and CAD drawing of HIDRA's magnetic coils.

Heating is performed using electron cyclotron resonance heating with the aid of two magnetrons of 6 and 20 kW, respectively, adding up to a total power of 26 kW at 2.45 GHz. When operating as WEGA, a gyrotron source at 28 GHz and power between 10 and 40 kW was used, leading to electron temperature of $T_e = 20$ eV. Electron temperatures in HIDRA are expected to stay below the mark of 25 eV when running in the stellarator mode. As a tokamak, with ohmic heating, these temperatures can go as high as 900 eV. Table I sums up the different heating techniques used on WEGA and HIDRA in both stellarator and tokamak modes, and shows the resulting electron temperature T_e, ion temperature T_i, and plasma density n_e.
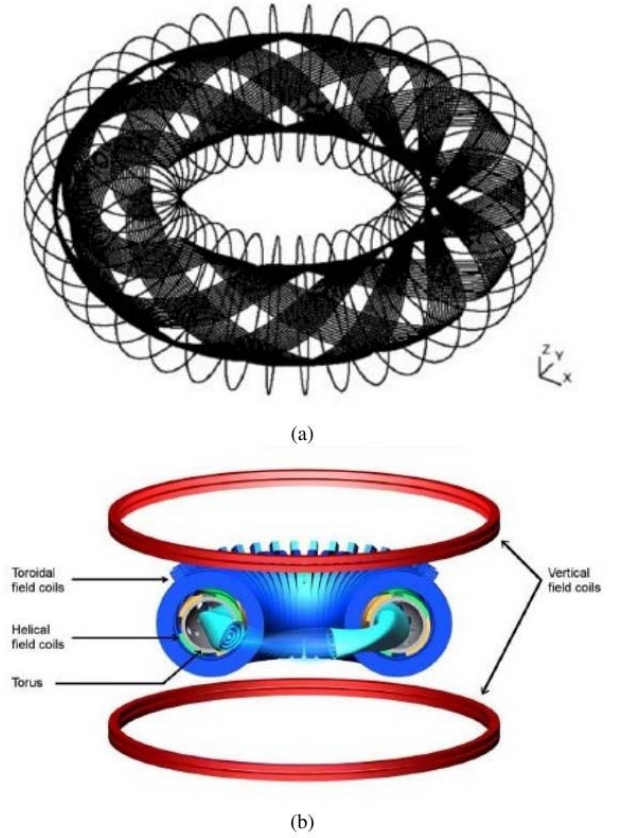

Fig. 1. (a) Sketch of the toroidal and helical magnetic field coils wrapping around the HIDRA torus. (b) CAD drawing showing one of the two halves of HIDRA's vacuum vessel. The position of the two vertical coils, as well as the distribution of the toroidal and helical coils are shown around the torus.

For the edge-plasma parameters, a simulation for the electron temperature at the plasma edge shown in Fig. 2 was obtained assuming a 10% efficiency from the 26-kW input, to emulate radio frequency (RF) deposition inefficiencies and radiative energy losses. The drop-off observed is stronger than what was reported from WEGA, but the temperature in the edge region between 5 and 10 eV matches the experimental results in magnitude.

IV. INITIAL MAGNETIC FIELDS AND IOTA MEASUREMENTS

Back when HIDRA was still running as WEGA in France and Germany [11], measurements of the magnetic fields found that the on-axis toroidal component B_0 at the position $r = R_0$ where r is the radial coordinate and R_0 is that corresponding to the axis of the torus, is given as follows:

$$B_0 = \frac{0.144 I}{1000}. \tag{1}$$

In (1), B_0 is given in tesla and I is the current in the toroidal coils given in amperes. At any position $r = R$ across the vacuum vessel, the toroidal magnetic field $B(R)$ is given by the following:

$$B(R) = \frac{B_0 R_0}{R}. \tag{2}$$

TABLE I
HEATING TECHNIQUES, RESULTING TEMPERATURES, AND DENSITIES

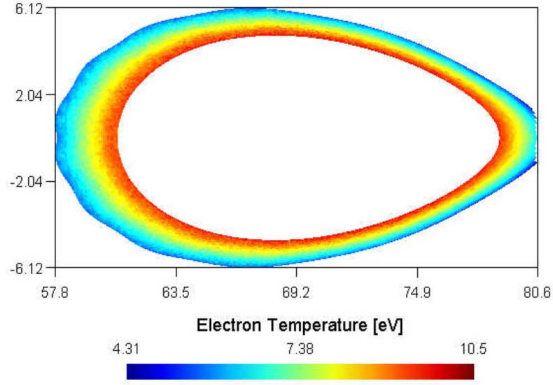|	Stellarator	Tokamak
Magnetron (cw and modulated) at 2.45 GHz	6 kW	—
Magnetron (cw) at 2.45 GHz	20 kW	—
Gyrotron (cw, pulsed) at 2.8 GHz (as WEGA)	10 kW, 40 kW	—
Plasma Current	—	< 60 kA
Ohmic Heating	—	100 to 130 kW
T_e	< 25 eV	600 to 900 eV
n_e	5×10^{18} m^{-3}	1.6×10^{19} m^{-3}
T_i	< 2 eV	150 to 250 eV

Fig. 2. T_e for 10% RF efficiency with a 26-kW discharge and a 0.5-T axial magnetic field.

The measurements of the toroidal magnetic field on HIDRA agree with previous ones taken on WEGA [11]. The resulting plots of these new measurements are shown in Fig. 3.

Also, the rotational transform ι (iota) has been measured and compared to the modeling performed by Marcinko and Curreli at UIUC. The rotational transform is given by (3), where B_H is the helical magnetic field, B_T is the toroidal magnetic field, r is the radial coordinate across the vacuum vessel, $R_0 = 0.72$ m is the major axis radius, and $a = 0.19$ m is the minor axis radius

$$\iota = 2\pi \frac{1-l}{m} \frac{R_0 B_H}{B_T r} \left(\frac{a}{r}\right)^{2l-4} . \tag{3}$$

The plots of the rotational transforms obtained from measurements and modeling are shown in Fig. 4. Although the results are close, they do not match and diverge slightly. The experimentally obtained iota is offset a clear 50% higher than the value coming from modeling. Potential misalignment in the coils could be the reason behind this mismatch.

V. PLASMA DISCHARGE AND CONFINEMENT

Several plasma discharges were done on HIDRA, aiming at observing the evolution of the plasma with the magnetic fields
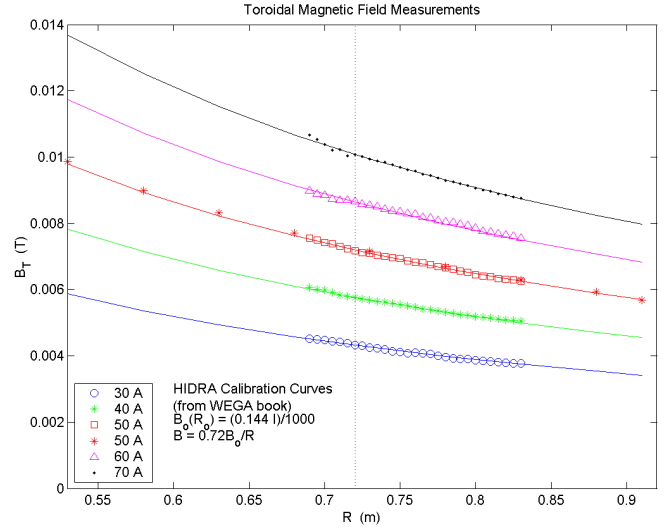

Fig. 3.   Toroidal magnetic field measurements across the HIDRA vacuum vessel. The data are compared to the calibration curves from the WEGA book.
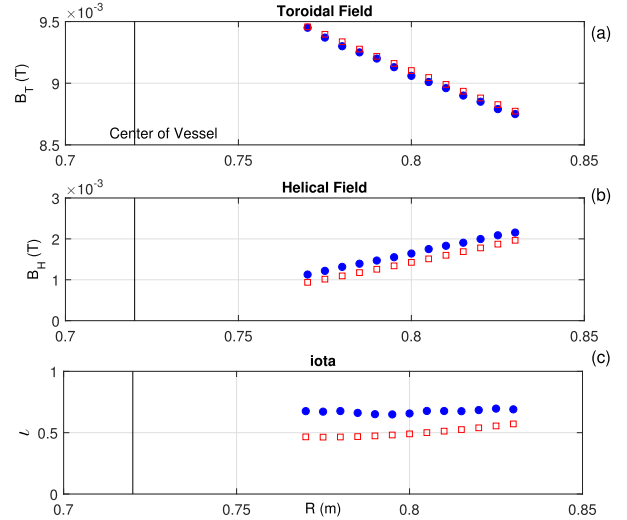

Fig. 4.   Rotational transform as obtained from modeling and measurements. (a) Toroidal field. (b) Helical field. (c) iota values.

applied. The following results presented were obtained using an argon plasma. These initial discharges were performed in argon to understand the machine's operation. Eventually, helium and then hydrogen will replace argon as the working gas as they are more relevant to the fusion environment than argon due to its low mobility.

In Figs. 5–7, the top plot shows the toroidal magnetic field's current, the middle plot shows the helical magnetic field's current, and the bottom plot shows the plasma floating potential V_f, obtained from a Langmuir probe placed at the plasma edge, about 5 mm away from the wall. This positioning of the probe allows us to detect when confinement is reached.

In Fig. 5, ramping both the toroidal and helical fields leads the plasma floating potential to eventually vanish, which indicates that the plasma moved away from the wall and got confined. As the fields are ramped down, the floating potential reappears, as confinement is lost.
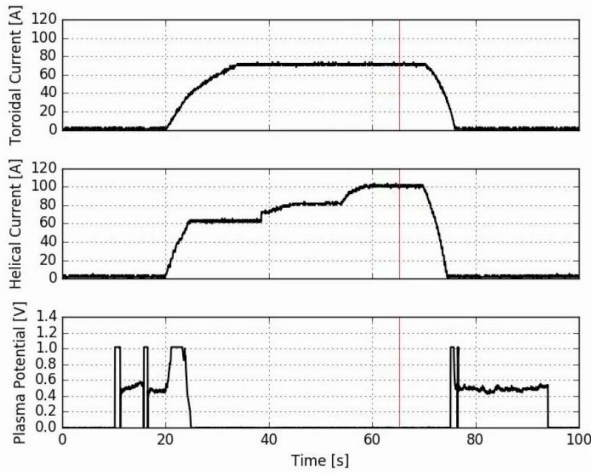
Fig. 5. Oscilloscope readings during the plasma discharge using argon. Here, both the toroidal and helical fields were ramped up, leading to the plasma floating potential to vanish.
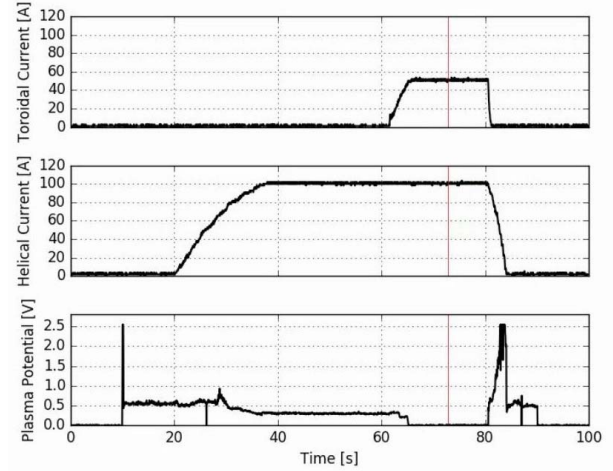

Fig. 7. Oscilloscope readings during the plasma discharge using argon. The helical field is set at an even higher value which did push the plasma away from the wall as can be seen from the decreasing value of the plasma floating potential. However, complete confinement only occurred after ramping the toroidal field.
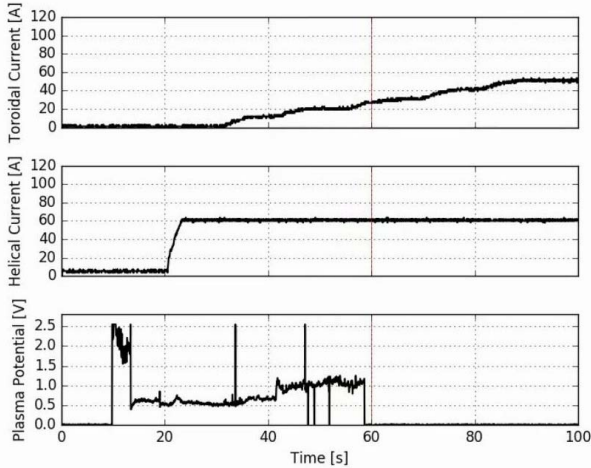

Fig. 6. Oscilloscope readings during the plasma discharge using argon. The helical field is maintained at a constant value, while the toroidal field is slowly ramped up. The plasma floating potential only vanished after the toroidal field reached its threshold value.
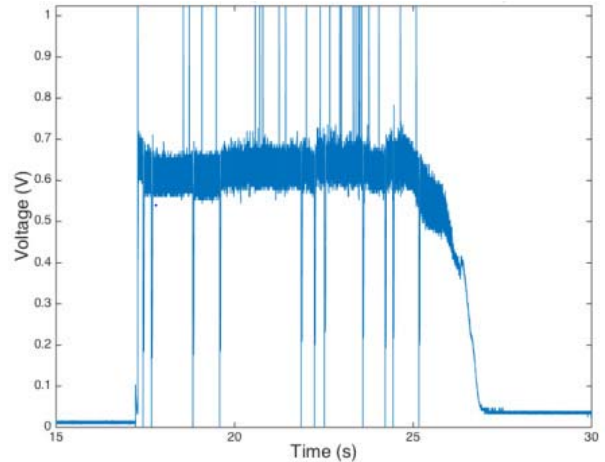

Fig. 8. Floating potential of HIDRA's first plasma. The signal goes to zero near the end, as the toroidal magnets were turned ON and started confining the plasma near the wall.

VI. Diagnostics: Langmuir Probe and Fast Reciprocating Arm

Figs. 6 and 7 show a more interesting result. From those plots, it appears that the helical field is not sufficient to confine the plasma, and that confinement is in fact achieved thanks to the toroidal field.

Holding the helical field's current at 60 A in Fig. 6, the plasma potential kept being measured. It vanished only when the toroidal field's current hit a value of roughly 30 A. This is the same value of the toroidal field current where confinement was observed in Fig. 5.

In Fig. 7, the helical field's current was ramped all the way up to 100 A. Even though the plasma potential seemed to get weaker, it only vanished when the toroidal field's current was ramped up, and hit the same threshold of 30 A. This suggests that there is a minimum toroidal field required for confinement to happen.

The Langmuir probe used to determine the floating potential of the argon plasma which results are shown in Figs. 5–7, was built and tested specifically for being used on HIDRA. The probe has a tungsten rod of 1 mm diameter for its electrode, shielded by alumina, and having an exposure length of 6 mm.

When HIDRA's first plasma was obtained on April 22, 2016, the floating potential was measured to be 0.6 V as shown in Fig. 8. Figs. 5 and 6 both show a floating potential in agreement with this value, whereas Fig. 7 shows that for a helical field current above 70 A, the plasma floating potential decreases to about 0.4 V, because the high helical field does push the plasma, even if slightly, away from the wall.

In addition, a fast reciprocating arm (FRA) was designed to have a Langmuir probe mounted on it. The FRA is able to
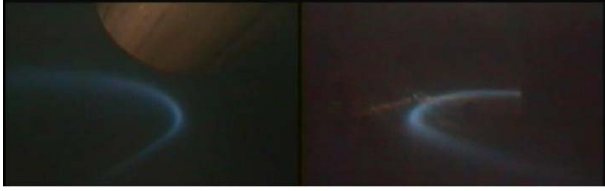
Fig. 9. Observed profile of a helium plasma using the HIDRA electron gun at a depth of 19 cm into the vacuum vessel. The pressure inside the vessel was of 4.8×10^{-2} Pa at the time the profile was taken.

insert the Langmuir probe in and out of the plasma in 200 ms. This allows for the measurement of the plasma parameters at various radii. While the Langmuir probe at the plasma edge will allow measurement of the edge-plasma parameters necessary to determine the surface fluxes, a Langmuir probe mounted on the FRA will help to determine the electron density and electron temperature profiles in the plasma as a function of the radial position.

VII. DIAGNOSTICS: ELECTRON GUN

A simple electron gun has been designed for HIDRA, to do magnetic field and flux line mapping. The filament of a halogen lamp rated at 20 W and 12 V is used as the cathode with an accelerating voltage provided by the negative 300-V bias voltage applied at the Wehnelt cylinder.

The emitted electrons follow the magnetic field lines from a set position, and are visualized with cameras. Fig. 9 shows the observed profile using a helium background gas at an operating pressure of $P = 4.8 \times 10^{-2}$ Pa and 70-A current running through both the toroidal and helical field coils. The filament was fixed at a depth of 19 cm into the vessel. The toroidal field's contribution is responsible for bending the profile of the plasma, whereas the helical field determines the intensity of the curvature.

Some radial scans of the vacuum vessel were also done, running the filament across the vessel and back to its original position. This will help to determine experimentally the rotational transform of the machine and compare it to its known modeled prediction and previous experimental measurements.

The flux lines will eventually be visualized via a mesh with fluorescing powder and with dedicated cameras, to allow a full mapping of the magnetic field inside HIDRA.

VIII. DEVELOPMENT OF THE CONTROL SYSTEM

The HIDRA control unit is linked to the main control computer via a LabVIEW interface operating on a trigger in and out basis. Three oscilloscopes, connected to three dedicated computers, are used to run the various data acquisitions from the multiple diagnostics to be used on HIDRA. The communication between the oscilloscopes and respective computers is done via a python script which allows transmission of the recorded data instantaneously to the diagnostic computers.

The data recorded this way are then automatically transferred and saved to an MDSplus server. The data, thus stored in a well-organized tree, are easily accessible for later use.

IX. HIDRA-MAT AND FORTHCOMING PMI STUDIES

HIDRA is soon to be loaded with the new HIDRA-MAT facility, which is essentially an extension that will enhance the material testing capabilities of the machine. HIDRA-MAT is based on the material analysis and particle probe facility installed on the lithium tokamak experiment and later in the National Spherical Torus Experiment Upgrade at the PPPL [12].

HIDRA-MAT is an *in situ* PMI facility equipped with X-ray photoelectron spectroscopy, thermal desorption spectroscopy and direct recoil spectrometry [12]–[14]. It will allow running diagnostics in and out of the vacuum vessel without the need to shut HIDRA down. This would make it possible to have experiments and plasma diagnostics in extreme conditions. HIDRA-MAT will also be a great tool to study plasma-edge properties and plasma-material interface in real time, making it an important asset for determining the best way to integrate liquid lithium in the inner wall and divertor designs.

In conjunction to this, HIDRA will be used to develop the technologies that are LiMIT [9] and FLiLi [10]. Corresponding plates are planned to be designed, developed, and perfected before being installed in the Experimental Advanced Superconducting Tokamak (EAST), Hefei, China. This paper is being performed as part of a collaboration with PPPL and the Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China for developing a flowing lithium limiter system at the midplane of EAST.

X. CONCLUSION

HIDRA is a classical stellarator that can also operate as a tokamak. Understanding how crucial the materials' issue is when dealing with fusion related technologies, HIDRA will be primarily used at UIUC to run PMI studies and develop plasma-facing component (PFC) technologies. Initial experiments are under way to determine the magnetic field structure inside the vessel and to get a better understanding of plasma operations. The first results agree with past measurements that were done when the machine was still running as WEGA.

Already, HIDRA is involved in the development of PFC technologies in the shape of LiMIT and FLiLi. Also, with the imminent addition of HIDRA-MAT, the machine's ability as a PMI studying facility will only improve.

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Authors' photograph and biography not available at the time of publication.