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HIDRA control system (HCS): A LabVIEW-based program to control the Hybrid Illinois Device for Research and Applications

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ABSTRACT

With a semi-complex research device such as the Hybrid Illinois Device for Research and Applications (HIDRA), there comes a need for an efficient program that can be used to control the machine. Such a program must be able to safely and effectively control all aspects of the machine from a remote location to provide maximum safety for the operators. This control system must be able to control the toroidal and helical magnetic fields, magnetron, plasma diagnostics, and more. Along with controlling the machine comes the need to monitor and collect data during operation. Motivated by these needs, we present the HIDRA control system (HCS), an open source program to control HIDRA. This software fills the critical void of safe and effective control software for the machine.

1. Introduction

The Hybrid Illinois Device for Research and Applications (HIDRA), seen in Fig. 1, is a newly assembled toroidal magnetic fusion device at the University of Illinois at Urbana-Champaign (UIUC). HIDRA used to be the WEGA stellarator that was located at the Max-Plank Institute for Plasmas Physics (IPP) in Greifswald. At the IPP, WEGA was used as a testbed for various W7-X components, as well as its control system [1].

HIDRA is a unique, educational, and student-friendly tool for future fusion scientists and engineers as well as an important research device for fusion science [2]. The main purpose that HIDRA will be used for is running plasma material interaction (PMI) studies as well as developing plasma facing component (PFC) technology for larger devices such as the EAST tokamak in China [3]. PMI at the inner wall of the vacuum vessel and divertor is one of the major issues in fusion research, as there currently exists no materials that can withstand the energy fluxes that are incident on the plasma device's components [4]. Solving the issue of materials is crucial in order to have a viable operational fusion device. One potential solution to that problem is the use of liquid metals at the plasma-material boundary [5,6]. Having this in mind, the Center for Plasma Material Interactions (CPMI) at UIUC will use HIDRA to move materials research forward in the field of liquid metals, and specifically liquid lithium. Two PFC designs, the Liquid Lithium Metal Infused Trenches (LiMIT) [7–9] and the Flowing Liquid Lithium (FLiLi) [10] will be tested inside of HIDRA to study the feasibility of flowing liquid lithium at the inner wall and divertor interface.

The hybrid aspect of HIDRA, which allows it to run as both a stellarator and/or a tokamak makes it a unique machine among the fusion devices. HIDRA, as a stellarator, is able to operate at steady-state (pulse lengths < 60 min), but has a central solenoid allowing tokamak operations. This allows studies of the plasma and PFC with transient plasma events. This means that control of the machine is very important. In the next sections of this paper, the development of the control system of HIDRA will be presented and discussed.

2. The Hybrid Illinois Device for Research and Applications

HIDRA is a 5 period, $l = 2$, $m = 5$ classical stellarator. It has a major radius $R_o = 0.72$ m and a minor radius $a = 0.19$ m. There are 40 toroidal field coils and 4 helical coils that wrap around on the outside of the vessel as well as two vertical field coils that help shape the plasma as seen in Fig. 2. The device is designed to operate up to a magnetic field of $B_o = 1$ T, but values of $B_o = 0.087 - 0.5$ T are more typical. There is an iron core that runs through the center of HIDRA. This solid core that has two solenoids allows HIDRA to operate as a tokamak, thus giving it the ability to operate as a hybrid device. Heating of the plasma is performed using two magnetrons of 6 kW and 20 kW giving a total of 26 kW of 2.45 GHz heating. When operating as WEGA, typical temperatures around $T_e = 20$ eV and densities of $n_e = 1 \times 10^{18}\,\mathrm{m}^{-3}$ were obtained with Bernstein wave heating (OXB) [11,12]. The power to the coils is supplied from two 20 kV transformers, one supplying the toroidal coils and the other the helical coils. These transformers are

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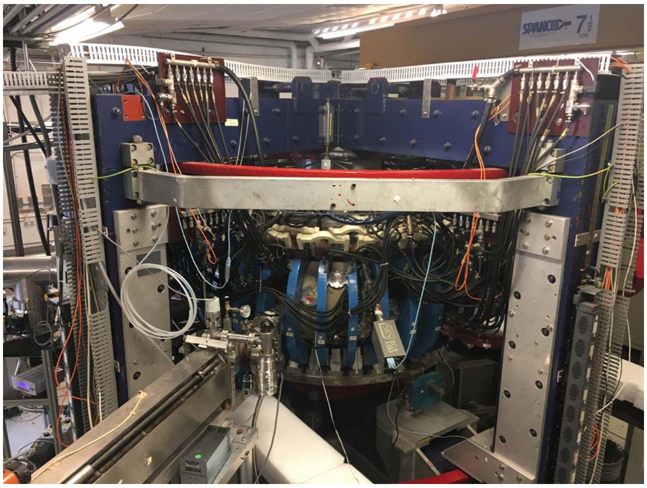

Fig. 1. HIDRA.

connected to rectifiers which allows for steady state operation. Diagnostics for initial operation include a Langmuir probe mounted on a fast reciprocating arm (FRA). The FRA allows the probe to travel to the center of the plasma and retract in 200 ms. This will allow T_e and n_e profiles of the plasma to be obtained. Langmuir probes at the minor radius will measure the edge plasma parameters and help determine the flux to the surface. Four visible light spectrum cameras with no filters will help monitor the plasma. Typical operation times are from tens of seconds to tens of minutes. Table 1 shows a summary of the basic parameters of HIDRA.

With a research device such as HIDRA, there exists a need for an efficient program that can be used to control the machine. The HCS must be able to control several aspects of the machine including the toroidal and helical magnetic fields, magnetron, and more. Along with controlling the machine comes the need to monitor and collect data during operation. We need a control system that can acquire data from the several diagnostics of the machine all at the same time and alert the operator in real time if any problem arises. The system should be able to record and store all of these collected data during a run. This program must also be able to control all aspects of the machine to provide maximum safety for the operators from a remote location. In the case of the Nuclear Radiation Lab, we have set up a control room near HIDRA. The control room is separated from HIDRA by an electrically grounded fence enclosing the machine. No one is allowed within the fenced off area while the machine is running. Currently, the gate to the cage is locked via a key, and the operator holds the key and makes sure no one is in the cage. There is a provision, within the control panel to have an automatic interlock that will be implemented in the future (Fig. 3).

This paper is organized as follows: Section 3 is a discussion on the magnetic field control, the most important control of the HCS. In Section 4, we discuss the implementation of the software itself. Section 5 is a discussion on initial calibration results of HIDRA. In Section 6, we discuss the future of the HCS.

Table 1
HIDRA parameters.

Parameter	Stellarator	Tokamak
# Toroidal coils	40	40
# Helical coils	4	–
l, m	2, 5	–
R_0	0.72 m	0.72 m
a	0.19 m	0.19 m
Aspect ratio	3.8	3.8
a_{plasma}	0.11 m	0.11 m
V_{plasma}	0.17 m^3	0.17 m^3
B_0 (cw)	< 0.5 T	–
B_0 (pulsed)	–	< 1.0 T
t_{pulse}	< 60 min	15 ms

3. Magnetic field control

One of the most important aspects of the HCS is the control of the high currents generated from the rectifiers to generate the magnetic fields. In order to efficiently confine a plasma, we must have precise control over the magnetic fields produced by our magnets. The toroidal field is generated via 40 toroidal magnet coils. The toroidal coils are in a “Pancake Coil” configuration with an azimuthal flow as shown in Fig. 4. There are 13 windings and the width of a single coil is along the axial (toroidal) direction. The inner and outer diameters are 0.58 m and 0.80 m respectively. The coils are set in series and the on axis toroidal field is given by

$$B_o = \frac{0.144I}{1000} \tag{1}$$

where I is the current in the coils and B_o is the on axis magnetic field. This was originally determined in France and Greifswald and has been verified in HIDRA [13]. This follows the well known $1/R$

$$B(R) = \frac{B_o R_o}{R} \tag{2}$$

where $B(R)$ is the measured magnetic field at a major radial position R. Here, B_o and R_o are the on axis magnetic field and major radius respectively. Surrounding the vacuum vessel is a set of four helical coils. These are embedded within a resin that covers the outside of the toroidal vacuum vessel. The current in the coils generates the twisting poloidal field. This in conjunction with the toroidal field generates the confining helical field. The coil currents are externally generated via two transformer/rectifier sets; one each for the toroidal and helical coils. The high voltage supplied at UIUC is $V = 12.47$ kV and a step up transformer supplies 20 kV into the lab. Here, the two transformers step

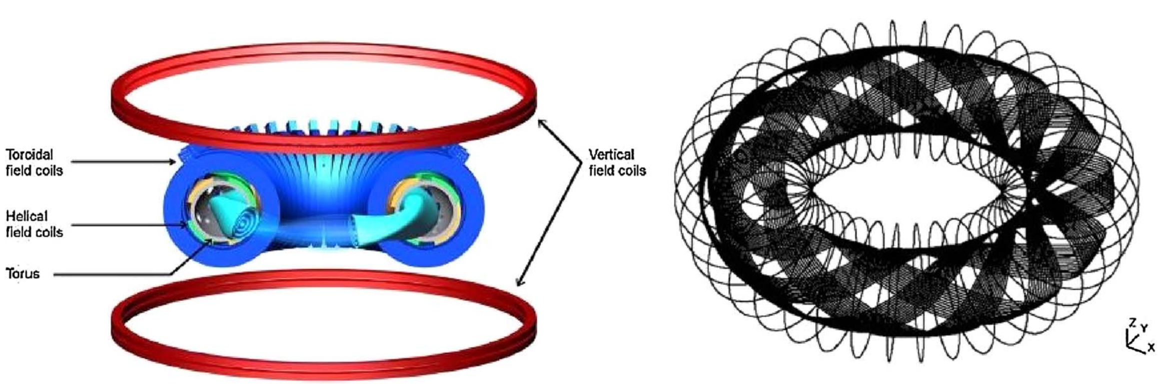

Fig. 2. HIDRA coil structure.

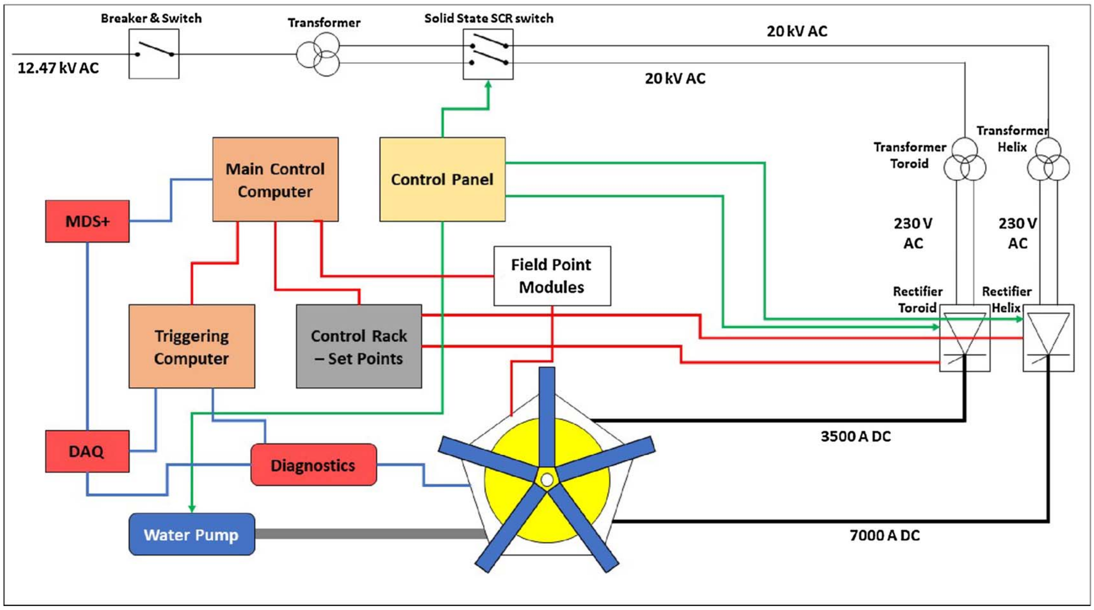

Fig. 3. Components of HIDRA.

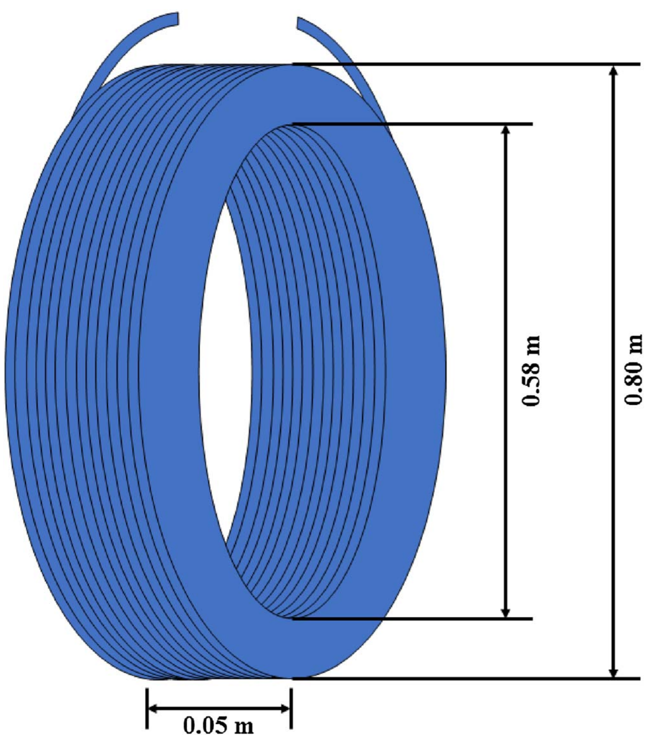

Fig. 4. Toroidal coil.

the 20 kV down to 230 V and rectifiers convert the AC voltage into DC for continuous operation. The rectifiers through the HCS can drive currents up to 3500 A in the toroidal coils and 7000 A in the helical coils. The main power frequency in the US is 60 Hz. Since the rectifiers are taking a 60 Hz voltage and rectifying that, any ripple in the current will be at 60 Hz. This is verified with a Rogowski coils on the toroidal current line. The current ripple is about 16–20 A peak to peak when we run a toroidal current for 600–700 A shown in Fig. 5. This is about a 2.5–3% ripple and does not seems to affect the confinement.

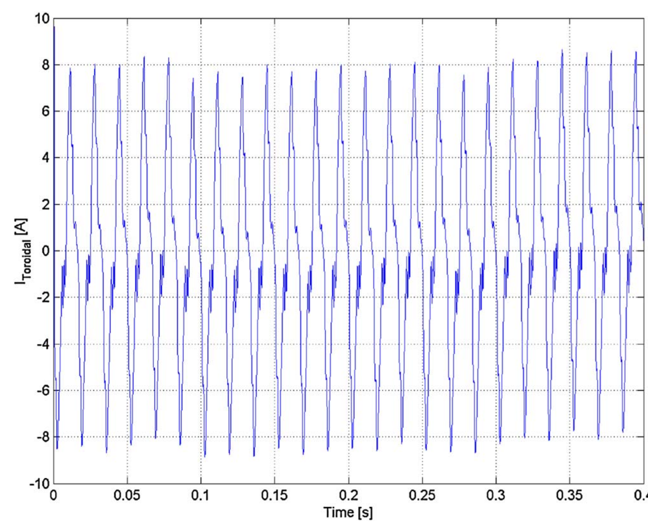

Fig. 5. Current ripple at 600 A–700 A.

4. HIDRA control system software

The HIDRA Control System is an open source LabVIEW program that satisfies the needs of a control system discussed in Section 2. The program is written mostly in LabVIEW with some scripts written in a few different languages. We chose LabVIEW because it is the standard in the lab in which we work and on many other similar machines in similar environments. LabVIEW is a systems engineering software developed by National Instruments. We use LabVIEW 2017 to run the program. HCS can be obtained at:

https://github.com/dsjohns2/HCS

The user can then run the program by running **HIDRA.vi**.

4.1. Program work flow

The program work flow is divided into four main phases: program setup, machine setup, shot, and shutdown. Each phase is further divided into a number of sections to make sure HIDRA is able to successfully run a plasma shot. The work flow is shown in Fig. 6.

In the first section of the program setup phase, the program disables

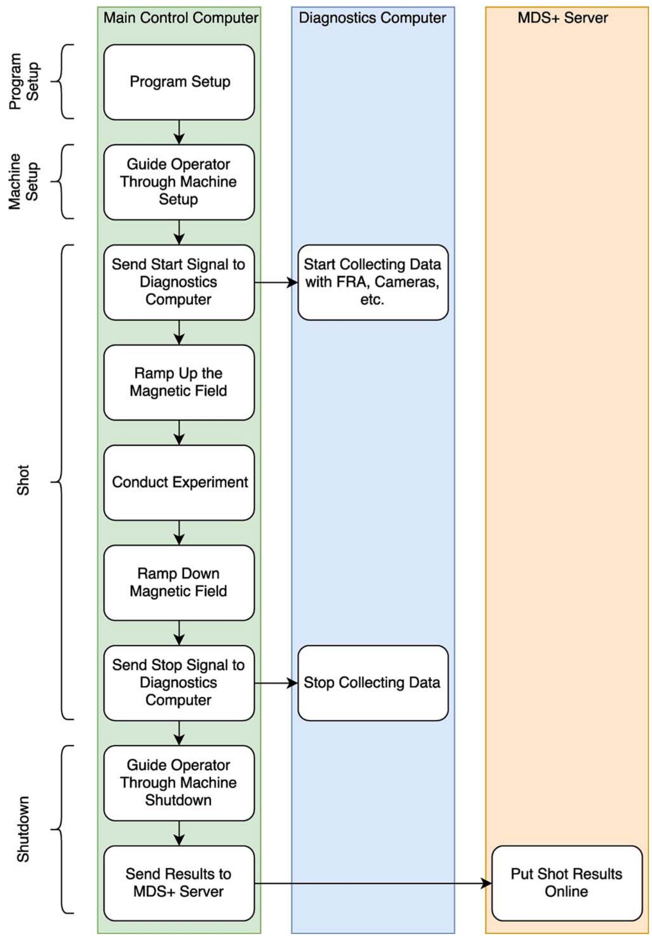

Fig. 6. HCS work flow.

Table 2
Steps in the machine setup phase.

Step number	Operation
1	Check vacuum vessel pressure
2	Turn on control rack fuse box breakers
3	Turn on 480 V breakers
4	Turn on 400 V transformer breakers
5	Verify toroidal rectifier is ready
6	Verify helical rectifier is ready
7	Turn on water cooling pump
8	Make sure all personnel are out of cage and lock cage
9	Turn on the helical and toroidal rectifiers
10	Set profile of shot pulse
11	Verify that displayed profile is correct and begin pulse

Table 3
Steps in the shutdown phase.

Step number	Purpose
1	Turn off the helical and toroidal rectifiers
2	Turn off the breakers on the 400 V transformer
3	Turn off the water cooling pump when appropriate

the LabVIEW default option of aborting the program. This is done because the default abort option does not clean up after itself in a suitable way. An abort button is placed on the main user interface panel that safely shuts done the machine and closes all files to ensure there is no corruption. The panel is maximized and unable to be closed until the program runs until completion or until the abort button is pressed. This is a safety precaution that makes sure that the program is not closed while the machine is running and that makes sure that all files are saved appropriately. The program also disables the scrollbars as the panel is designed to fit on the screen all at once. The program prompts the operator for their name, the purpose of the experiment they are about to run, and the diagnostics that will be used to evaluate the shot. This ensures that we are able to keep track of the details of the individual experiments. The program concludes the setup phase by automatically acquiring the shot number and by creating a new folder where all of the shot data will be stored along with the experiment metadata. The system produces a metadata file for information about the experiment and a data file that contains the feedback currents from the machine. This data file will also contain diagnostics data as more are added. The data file is typically a few megabytes while the text file is a few hundred bytes.

The system then moves on to the machine setup phase. In this phase, the operator of the machine goes through step by step to ensure that HIDRA is ready for experimentation. At each step, a window pops up showing a physical procedure that must be done to start HIDRA. A diagnostic relating to the procedure may also be shown if available. The operator performs the physical action, ensures that the related diagnostic is at a specified value, and then continues on to the next step. The program is formatted in a modular fashion so that any step and associated diagnostic can be added easily to the work flow. The reasoning behind this is that we have plans on incorporating field point modules in the future to measure the cooling system temperature and flow rate. After each step is performed, the operator has the option of continuing to the next step or returning to the previous step. The order of the steps has been designed to specifically meet the safety operating procedure of the machine. Table 2 shows the machine setup step number and the general operation of each step.

Once the machine setup is complete, the HCS is now able to run a shot in the shot phase. A shot is the procedure of creating, heating, and magnetically confining a plasma and recording the results of the confinement. The program uses the DAQmx Assistant VI to get the installed PCI board to send a certain voltage to the control rack. The control rack forwards the signal to the rectifier to set a specified current within the magnets. As HIDRA is a stellarator, the operator must be able to easily set current profiles where the current going through the magnets changes over time. The HCS accomplishes this by letting the operator chose the current in the toroidal magnets and helical magnets individually at specified times. The program then linearly interpolates the operator's input current specifications over time, displays the profile that is about to be run, and asks the operator to confirm the profile. Once the operator confirms the profile, the profile is run with a time step of 0.1 s. This is a small enough time step that ensures the jump between the current levels is at most about 30 A. We want to avoid larger current step jumps to avoid overshooting the target current. The ramp up in the fields allows the operator enough time to manually bring up either the magnetron or glow discharge. We are in the process of implementing the plasma and heating startup to be automatic. The program then allows for the operator to run as many shots as they desire and it saves the records of the shots after each one.

Once the operator has completed the shot phase, the program enters the shutdown phase. This phase simply walks the operator through turning the machine off in a safe way. The steps included in this phase are shown in Table 3.

At any point, in case of a hardware failure, there is an emergency stop button that can be pressed. This button will rapidly shut down the coil systems.

4.2. Front panel

The HCS was designed in such a way that controlling the machine feels intuitive. The main front panel, HIDRA.vi, is where the program is started. This panel contains the current experiment information, the

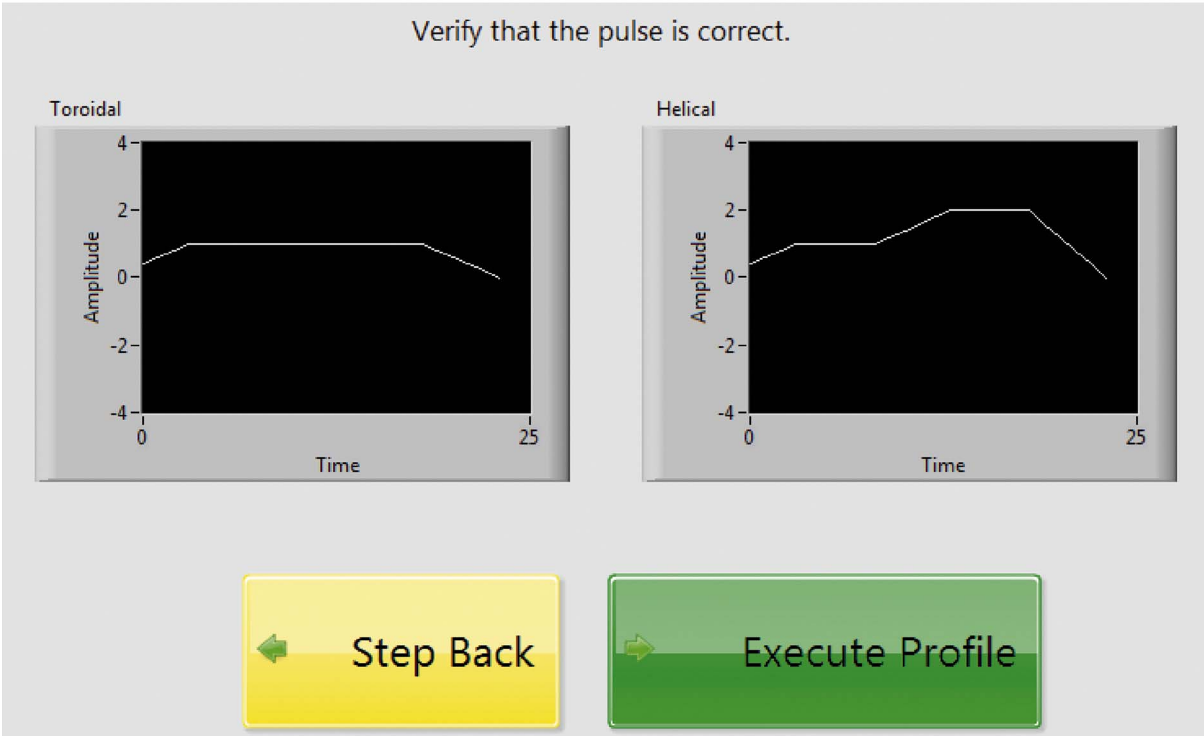

Fig. 7. In this step, the profile is generated by linearly interpolating the data points set in the set profile step. The operator then verifies that this is the desired profile and begins execution.

Fig. 8. In this screen shot, the profile is being executed as shown in the set point plots. The other plots will also respond when they are turned on.

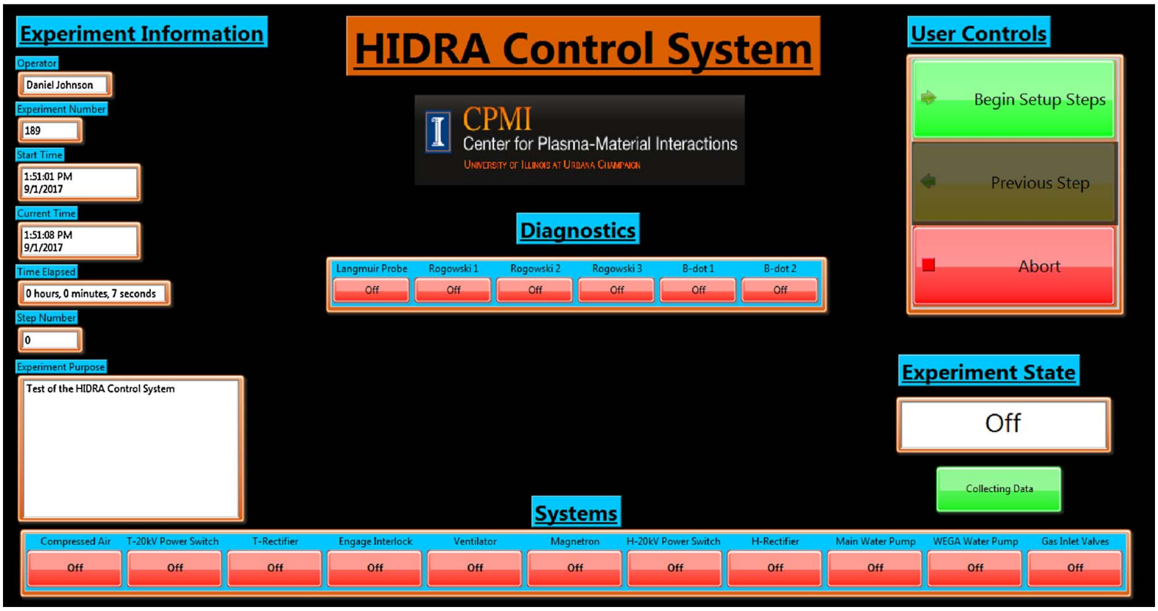

Fig. 9. The main front panel of the control system serves as a display of important information as well as the main control of the system.

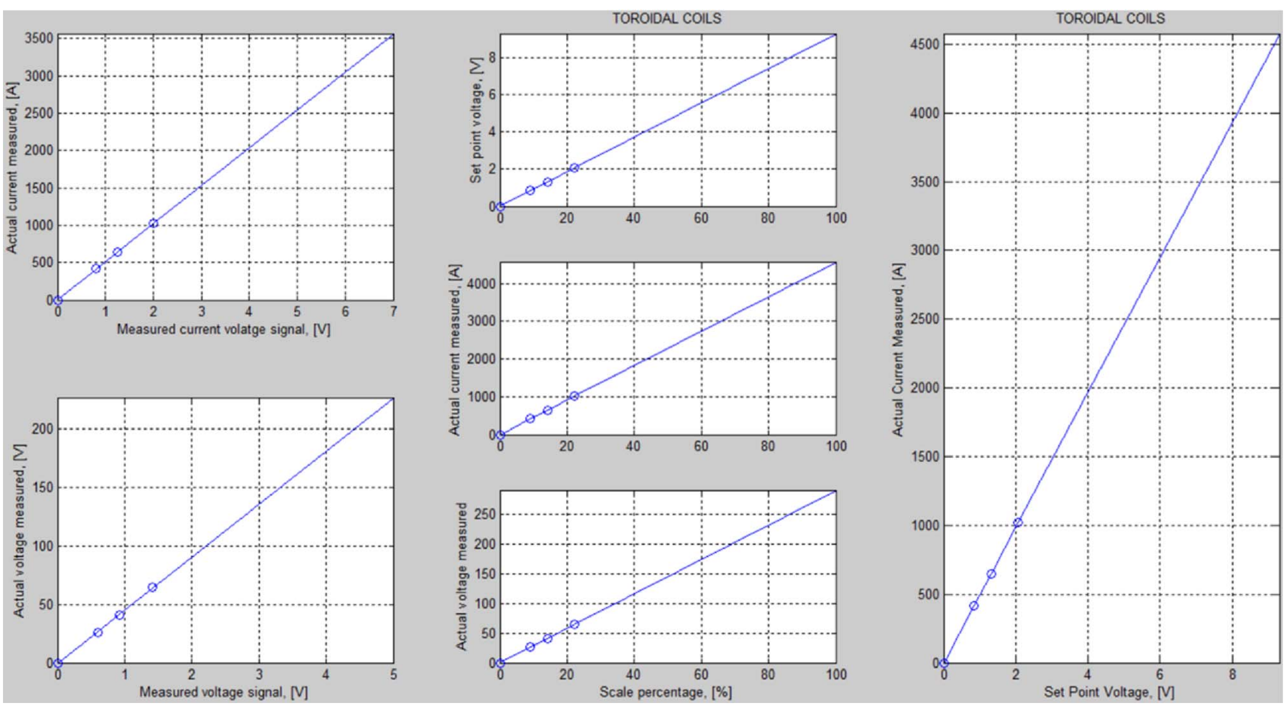

Fig. 10. Calibration curve for the toroidal current with respect to the set point values set from the control software.

information about various diagnostics on the machine, and the general control of stepping through the program. This is also the location of the aforementioned abort button. The experiment information displays the name of the operator, the current shot number, the start and current times, the current step and step instructions that the user is on, and the purpose of the experiment. The user controls give the operator three options at any time: continue to the next step, go back to the previous step, or abort the program altogether.

Another optional panel, **Control_Rack_Controller.vi**, can be displayed on a second monitor at all times or will pop up automatically during the shot if no second monitor is available. This panel displays the information pertaining to the voltage and current running through the magnets in real time. In the Nuclear Radiation Lab, where HIDRA is located, this panel is also displayed outside of the control room on an auxiliary monitor for guests to monitor the state of the machine.

4.3. Optimizations

The HCS was designed to run without using up a lot of the computer's resources. Thus, a number of optimizations were included to make sure that this happened. The optimization with the largest impact was replacing all of the while loops containing wait statements with while loops containing event structures. This is a better coding practice for two reasons: (i) the machine waits until the user clicks a button to continue the program in order to avoid using the computer resources; and (ii) the user does not have to wait the remainder of the wait call as the program immediately continues.

The program also utilizes a parallel while loop purely for data

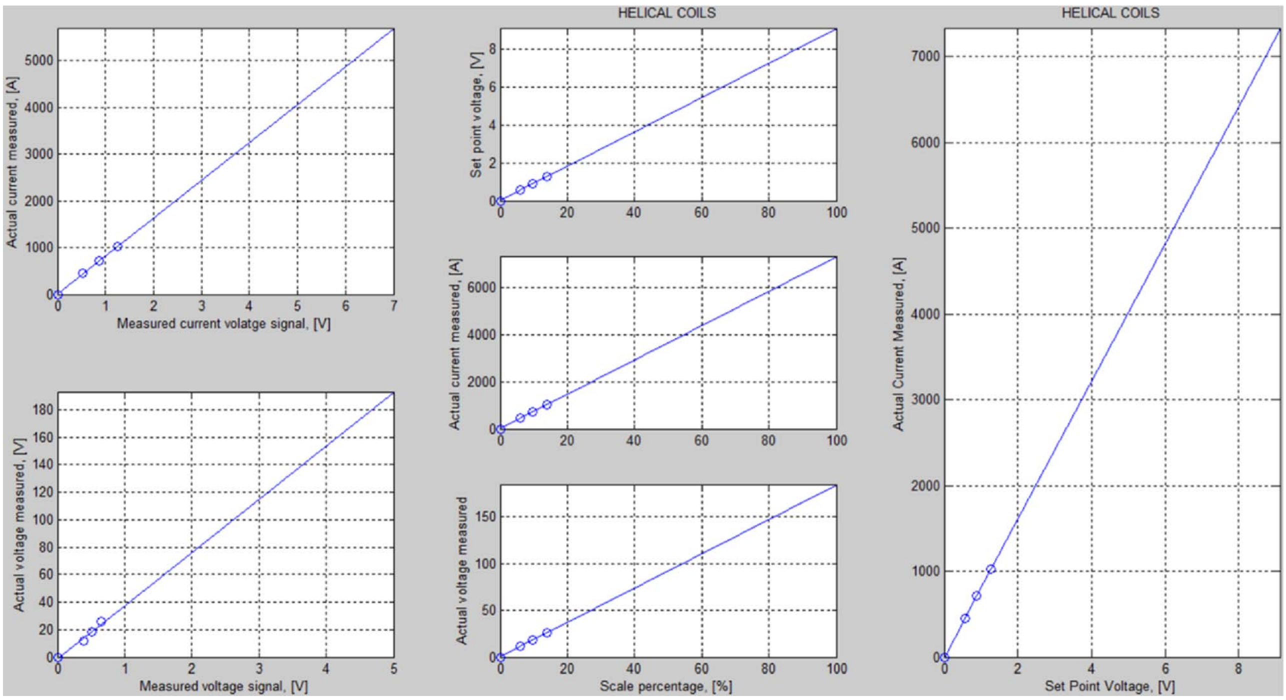

Fig. 11. Helical current calibration curve.

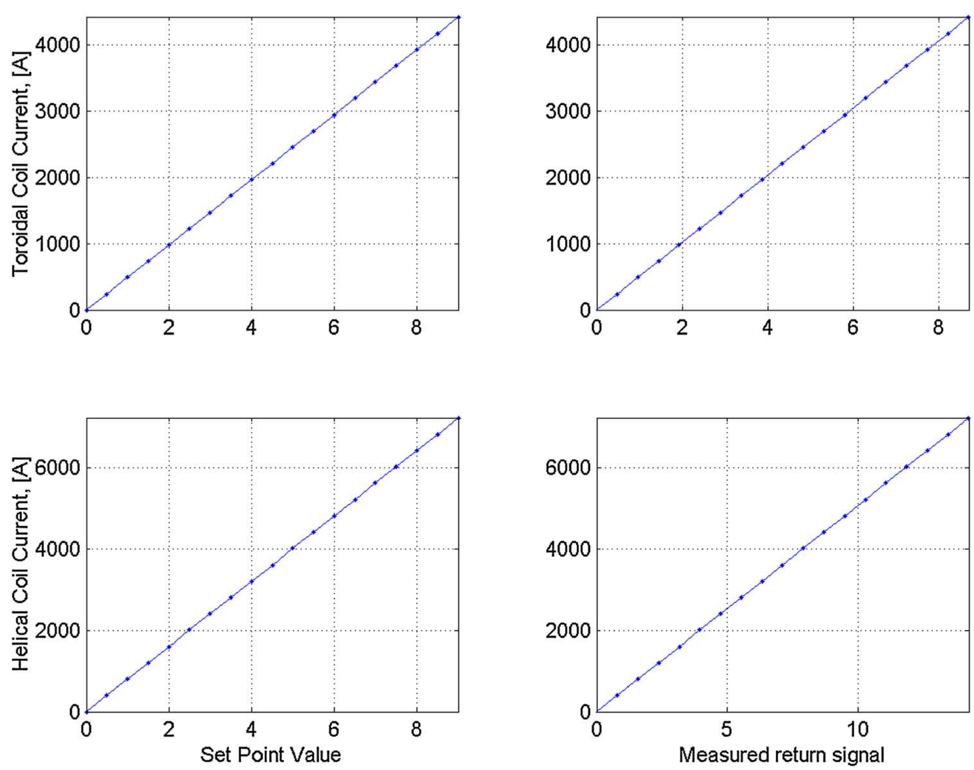

Fig. 12. Calibration of the return signals from the rectifiers with respect to the set point and measured current values. (a) and (b) are for the toroidal coils, (c) and (d) are for the helical coils.

acquisition. This side loop runs every second to display and record auxiliary data such as the pressure of the vacuum vessel. By running the data acquisition loop in parallel, the front panel can display this information even while it is running a different operation. It is very important to point out that while the HCS is a control system, it must also monitor various aspects of the machine at all times to make sure that everything is running smoothly. If the main control loop is in the middle of some process and a part breaks on the machine, we will be able to see the evidence of this immediately rather than waiting until the control process completes. This is very important from a safety point of view (Figs. 7–9).

5. Calibration

Control of the current that is generated from the rectifiers is done via the control system described above. However, the signals used to communicate with the rectifiers needs to be calibrated with the actual current output. The control system provides a maximum voltage of 9.3 V to the rectifiers. This corresponds to the maximum current value generated by the rectifiers. A series of dry runs were performed at different values of the input voltage and a DC current meter was used to measure the actual current that was generated by the rectifiers. This was done for both rectifier sets, toroidal and helical, and is shown in Figs. 10 and 11 respectively.

A straight line fit can be applied to the data and extrapolated for the maximum voltage of 9.3 V. For the toroidal current a maximum current of 4578 A can be generated at 9.3 V. This agrees with what the operating parameters were in IPP Greifswald. For the helical rectifier a maximum current of 7331 A can be generated at 9.3 V. This also agrees with the maximum operating parameters used at IPP Greifswald.

A voltage signal is sent back by the rectifiers to the control system. These voltage signals were also calibrated back to the current that was measured and scaled. Even though the initial set point values that are sent to the rectifiers have a maximum voltage of 9.3 V, the return measured voltage for the rectifiers in fact is more. Fig. 12 shows this clearly. The set point values for the current both run to a maximum of 9.3 V, however the maximum returned values are 8.7 V and 14.2 V respectively. Knowledge of these set point and return values means that within the control system software it is relatively easy to know which values to set for the current. In fact, we have embedded, within the software itself, the calibration factors needed to run the currents. The HCS accounts for this when setting the input voltages. The measurement system has been tested for all reasonable experimental input values.

6. Conclusion

The newly running toroidal device HIDRA is a student friendly fusion device that will explore the intimate relationship between plasmas and materials for fusion applications. It is also is an excellent educational tool to develop the future generations of fusion scientists and engineers. With that in mind a user friendly control system based in LabVIEW software has been written, implemented, and tested. It has been used to run the transformer/rectifier systems that supply the current to the toroidal and magnetic coils and with that a calibration has been performed that allows that current to be directly set from the software through a series of set points.

The next steps for the software is to integrate new diagnostics into it which will consist of a triggering computer that can have individually timed outputs that are programmable at different times. This will all be integrated eventually with an MDSplus data visualization and database systems that will allow multi-user access to experimental data.

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