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UTILIZING PYTHON TO PREPARE THE VENUS ION SOURCE FOR MACHINE LEARNING*

A. Kireeff†, D. S. Todd, M. J. Regis, M. Salathe, L. Phair
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

The fully-superconducting electron cyclotron resonance (ECR) ion source VENUS is one of the world's two highest-performing ECR ion sources, and a copy of this source will soon be used to produce ion beams at FRIB. The tuning and optimization of ECR ion sources is time consuming and there are few detailed theoretical models to guide this work. To aid in this process, we are working toward utilizing machine learning to both efficiently optimize VENUS and reliably maintain its stability for long campaigns. We have created a Python library to interface with a programmable logic controller (PLC) in order to operate VENUS and collect and store source and beam data. We will discuss the design and safety considerations that went into creating this library, the implementation of the library, and its some of the capabilities it enables.

VENUS OVERVIEW

VENUS (Versatile ECR for NUclear Science) is a third-generation superconducting electron cyclotron resonance (ECR) ion source at Lawrence Berkeley National Laboratory, and it is used as one of the three injector ion sources for the 88-Inch Cyclotron [1], see Fig. 1. In VENUS, like in all ECR ion sources [2], an ion beam is extracted from a confined plasma, as shown in Fig. 2. Axial confinement of the plasma in VENUS is provided by a combination of three NbTi superconducting solenoids: two larger end solenoids and a smaller center coil with reversed polarity that affects the resultant axial field well depth. A sextupole made up of six NbTi superconducting racetrack coils is used for radial confinement. The superposed field of these coils produces a "B_{min}" structure where the magnetic field is a minimum at the center and increases in all directions. Closed surfaces of constant magnetic field magnitude surround this minimum, and electrons are resonantly heated by the injection of microwaves of frequency that correspond to these closed surfaces and satisfy the cyclotron frequency equation $w_c = \frac{eB}{\gamma m}$, where B is the magnetic field, γ is the Lorentz factor, and e and m are the electron charge and mass, respectively. The two frequencies injected into VENUS, 18 GHz and 28 GHz, resonantly heat non-relativistic electrons at magnetic fields of 0.64 and 1.0 tesla, respectively. Beam and support material are introduced to the plasma through a combination of gas injection, ovens, and sputtering, depending on what ion beam is being extracted.

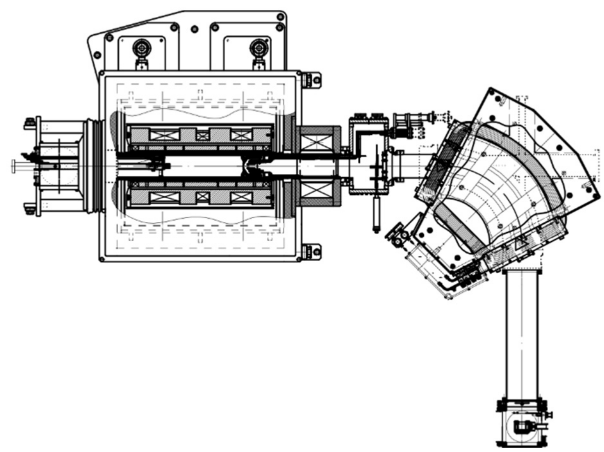

Figure 1: Aerial view of the VENUS Ion Source (left) and its low energy beam line showing the analyzing dipole magnet (upper right) and beam analysis box which includes a faraday cup and vertical and horizontal emittance scanners (bottom right). A second dipole (not shown) follows that directs the selected beam down toward the 88 Inch Cyclotron center.

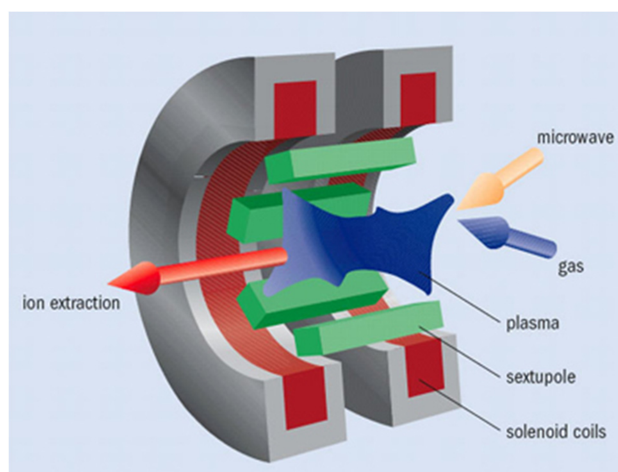

Figure 2: A simplified view of ECR ion source operation. Solenoid coils (middle coil not shown) and sextupole magnets axially and radially confine the plasma, respectively. Gas is injected into the source, it is ionized by microwave-heated electrons, and ions are extracted by establishing a potential difference between the source and beam line.

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† akireeff@lbl.gov

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Between plasma confinement, beam extraction, and system optimization, over 20 input variables are set by the source operator. For VENUS, this is done using a programmable logic controller (PLC) interface. Additionally, this interface constantly reads and displays over 80 source and beam line diagnostics. Beam optimization is challenging for human operators as the tuning space is large and transitioning from a local maximum to a higher maximum is difficult when faced with twenty possible adjustment variables and tens of diagnostics. Additionally, the 88-Inch Cyclotron and its users require that the source deliver stable beams for weeks-long campaigns. Maintenance of this stability is labor intensive [3] as the source must be monitored and corrective actions must be taken when control parameter drift occurs.

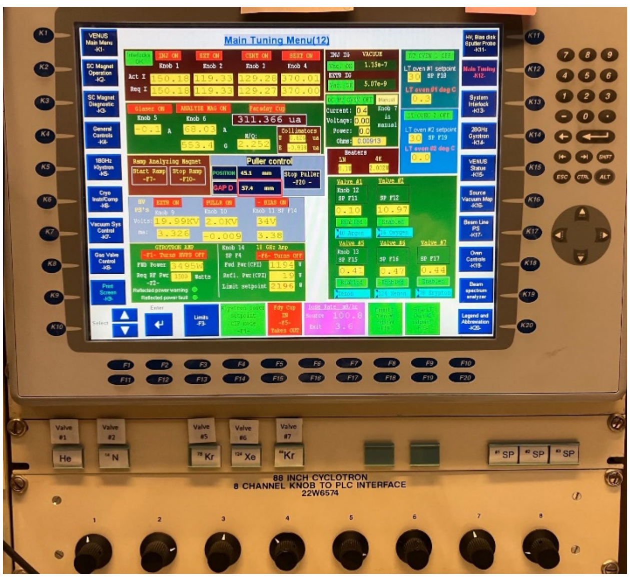

Figure 3: VENUS Panelview Plus 1500 PLC display showing the main tuning screen. The Panelview is touchscreen, has buttons and a numeric keypad to change or set parameters, and a collection of knobs below that allow for tactile fine-tuning.

For the above reasons, we strive to establish a machine learning system that can be used to both maximize beam output and maintain long-term stability without the need for frequent human intervention. The backbone of this effort is a Python based computer-VENUS interface that will permit computer control of the source while being general enough to handle future VENUS enhancements and other ion sources, similar to [4]. A description of the Python library developed for this purpose, its operation, and the safety considerations that went into it are given below.

CODE OVERVIEW

A human operator of VENUS tunes the source through an Allen Bradley ControlLogix 1756 PLC. A Panelview Plus 1500 serves as the interface for users with the PLC, and it has multiple screens that give constant readings of the cryostat system, the vacuum system, and many other parameters having to do with both the plasma and the beam line, as can be seen in Fig. 3. The screens have buttons and allow touch screen data entry for operators to set parameters that will affect the plasma and its produced beam. Additionally, the system has been designed with knobs that allow users to make fine adjustments in a more tactile way than numerical input. A computer that is going to run the source needs to be able to read all of this data from the PLC, write values to control the plasma, and save arbitrary data, but will not need the ability to turn knobs as numerical input is the more logical means of changing parameters.

VENUS has been in operation for two decades, and in that time the PLC has been outfitted with a wide array of safety interlocks and controls to ensure safe operation of the source. Our approach in this work has been to control VENUS by interfacing with the PLC, much as a user sitting in front of the PLC would, so that the already-developed safety mechanisms would apply to computer control and prevent mistakes being made in computer operation that could damage the source. This has the further benefit that a smooth transition between computer operation and human operation can be made since both users are running the source directly through the PLC.

To achieve this, we chose to use the Python programming language as the backbone and would use pylogix to interface with the VENUS PLC. Pylogix is a Python communication library that lets users easily read and write values from tags in Alan Bradley PLCs over EtherNet/IP. The storage of the generated data was done using sqlite3 (similar to the databases used in [5, 6]), a C-language library (with Python bindings) that implements a relational SQL database engine, as it has high throughput and is easy to use.

We created a PLC interface class in Python that has a function which allows the program to query a read variable and subsequently returns the variable's value. Ths PLC interface class also contains a write function that allows a program to write a specific value to a variable on the PLC and return whether the write was successful or not. We implemented generalizable, table-like functionality as a separate class that initializes a relational database file and table in the database file by taking in arbitrary column names and their types (string, integer, etc.). It can also write a row of data to the database. Since the database class can take arbitrary names and their types, we aren't limited to only using this code for logging for VENUS and can use it for any type of data storage. Further, we don't have to worry about modifying the database class when adding new variables to VENUS because the class takes the variable names as a parameter, which means we only have to modify the parameter instead of the whole class.

SAFETY AND SECURITY

Interfacing with a machine as complex as VENUS comes with various safety and security concerns for if something goes wrong, the results could be catastrophic for the ion source and significantly reduce the capabilities of the 88 Inch Cyclotron. There are two main sources of concern: people accessing the operation controls who are not authorized to do so and those authorized to access VENUS causing it to operate outside its safe operational range.

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Unauthorized access has been addressed by utilizing a secured server as an interface between the VENUS PLC and the remote user. This server has a firewall on it and can only be logged into by users with accounts, making it an effective means of limiting access to the VENUS network and explicitly restricting who can control VENUS.

To ensure VENUS is operated within established parameters, a sanity check for specific components and a range for the values that can be written to the PLC are checked before sending requests for new values. Some VENUS components require that certain conditions are met in order to function properly. For example, microwave power can not be injected if the magnetic field configuration doesn't produce a resonance zone. Therefore, before writing to a variable, the library verifies that all necessary conditions are met. However, it should be noted that this serves as a second layer of safety as the established PLC interlocks and safety mechanisms should prevent out-of-range requests from being sent to power supplies.

APPLICATIONS AND NEW ABILITIES

This interface with the VENUS PLC has allowed us to perform research and take measurements that could not or were not done before because it would have been too tedious for a human operator to perform. There are actions such as the measurement of charge state distributions that require minute-timescales to complete, and therefore are not performed with great frequency. The computer does not grow impatient with repeated, slow measurements, so a charge state distribution can be measured after every control parameter change giving a full picture of the effects to all beam species and not just the one being measured on the faraday cup.

Using this code we have collected second-by-second data from all VENUS variables [7, 8, 9], which is incredibly useful to understand and model VENUS and how it operates. An example of something we found is that a number of power supplies show an increase in variation during the afternoon and early evening but are stable the rest of the day. This is still being investigated but we hypothesize this is due to power grid instability in the heat of the day (though our electrical technicians think the supplies should not show this). This power supply variance leads directly to both source and beam instability, but was too subtle for anyone to notice without the data collection and analysis. With all this data, we can also begin to optimize the beam output for certain subsets of variables and even train machine learning models to directly optimize over these variables, which will alleviate some of the burden from the operators.

FUTURE WORK

We introduce a simple Python interface to the PLC controlling the VENUS ion source at Lawrence Berkeley National Laboratory that allows us to efficiently read, write and save data. This has allowed us to garner insights that were not possible to detect before, collect vast amounts of data about VENUS and how it works, and readies us to apply machine learning methods to further our understanding and optimization efforts. Future work with VENUS entails creating a graphical interface (analogous to [10]) to access historical data, processing all the data we've collected, analyzing it, and applying machine learning methods to it.

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