

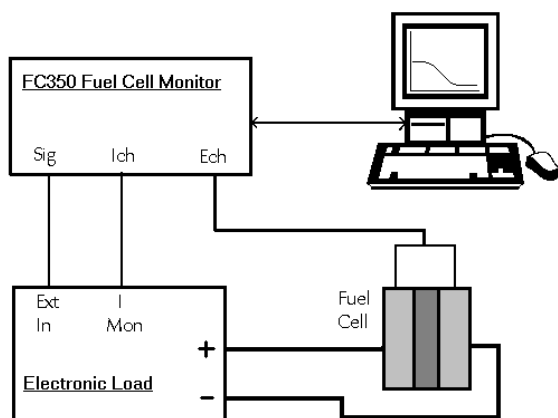
FC350™ Fuel Cell Monitor

Fuel cells are poised to assume a major role in energy storage and conversion. Their success depends on continued improvement in fuel cell performance. The FC350 Fuel Cell Monitor was designed to help you make this improvement possible.

Electrochemical impedance spectroscopy (EIS) is a powerful electrochemical technique, which can be particularly useful for fuel cell development. You can use EIS for materials selection and performance evaluation. Fundamental studies of new approaches and optimization of fuel cell performance can both benefit from EIS testing and modeling.

Gamry's FC350 measures fuel cell EIS better than standard EIS systems designed for the laboratory. Large fuel cells can generate several hundred amperes, well beyond the capability of laboratory EIS systems. Lab EIS systems also cannot handle the large voltages in fuel cell stacks with more than 10 to 20 fuel cells.

The Gamry FC350 Fuel Cell Monitor measures the impedance of fuel cells operating at high current levels. The FC350 consists of a Digital Controller, an Interface, and FC350 software working in conjunction with an Electronic Load (see Systems Information). A schematic of the FC350 is shown below.



The FC350 with an Electronic Load measures the impedance of the fuel cell. The measurement of I and E at a given frequency allows the calculation of the impedance.

The FC350 employs an Electronic Load to sink the current from the fuel cell. The sinusoidal excitation signal from the FC350 is input to the Electronic Load, which modulates the fuel cell current. The current signal from the Load is output to the current input channel of the FC350. The voltage of the fuel cell or stack is measured directly by the FC350 at the voltage input channel. The FC350 processes these signals to calculate an impedance. The FC350 measures EIS in either galvanostatic mode or a novel hybrid mode.

EIS measured with an FC350 can identify problems that limit a fuel cell's efficiency, it can help optimize cell design, and it can determine anodic and cathodic process mechanisms. EIS can be useful in the selection of membranes and the study of membrane impact on performance. Clever placement of reference electrodes in a cell may allow an analyst to separately test subsections of the cell, such as the anode, the cathode, and the electrolyte.

The Gamry FC350 is designed to accommodate the low impedance of fuel cells. It can measure fuel cell impedances as low as $500 \text{ n}\Omega$ ($5 \times 10^{-7} \Omega$)! It can measure complex impedance over a frequency range of $10 \mu\text{Hz}$ to 20 kHz (the upper limit is determined by the Load).

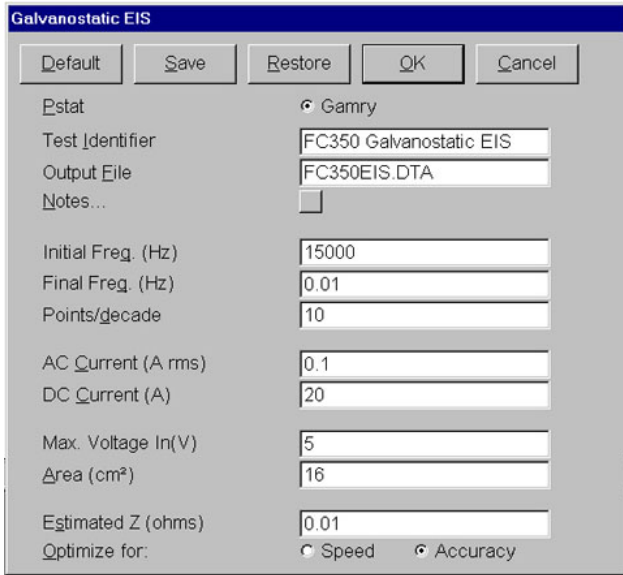
Note that basic physics makes measurement of low impedances at high frequencies impossible. You can measure $100 \text{ m}\Omega$ at 5 kHz , but you cannot measure $1 \mu\Omega$ at 5 kHz . Also, the arrangement of the cables leading to your fuel cell can have a significant effect on your results.

Using the FC350 to Measure EIS of Batteries

The FC350 was designed to measure EIS of fuel cells. Several of our users have found that it also works great for batteries. You can test EIS on primary batteries with an Electronic Load. Substitute a remotely programmed power supply for the Load and you can use the FC350 to measure EIS on secondary batteries.

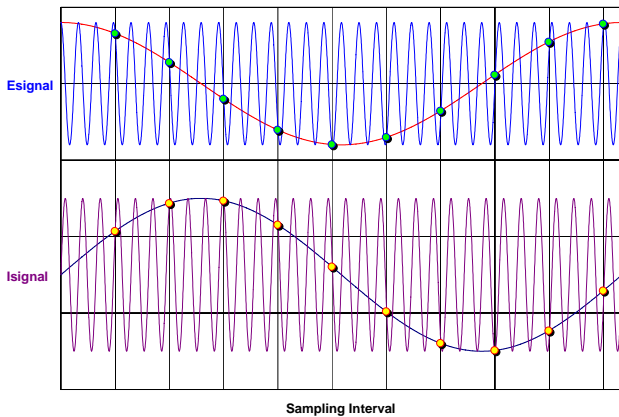
Galvanostatic EIS

Galvanostatic EIS involves the application of an AC current and measurement of the resulting AC potential. Galvanostatic EIS is the most common EIS technique for fuel cell studies.



Setup Window for Galvanostatic EIS. Every parameter required to make the EIS measurement is available on the single Setup Window.

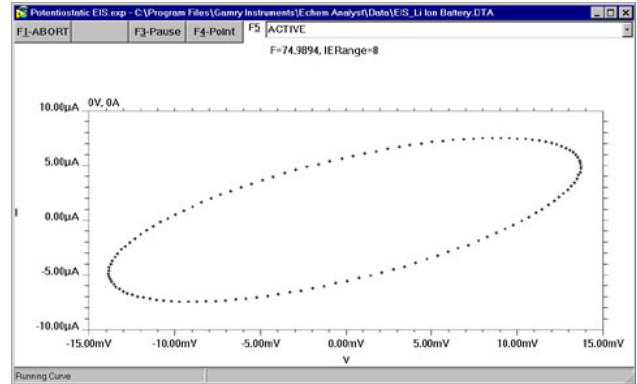
The FC350 uses Sub-Harmonic Sampling to make the EIS measurement. This technique was developed by Gamry in 1995. The AC waveform is generated using Direct Digital Synthesis (DDS) circuitry built into the FC350. DDS employs digital signal processing techniques to generate a low-distortion, true sine wave excitation at the desired frequency.



Sub-Harmonic Sampling transforms the high-frequency voltage and current signals to a lower frequency while maintaining the amplitude and the phase relationship.

Gamry's unique circuit design insures that the excitation waveform from the DDS is precisely synchronized with the data acquisition. The FC350's Analog/Digital Converter samples the current excitation and voltage response waveforms at many points on different cycles of the waveform. The exact sampling position on the waveform is precisely controlled because the data acquisition frequency is an exact sub-harmonic (fractional harmonic) of the excitation waveform.

The result is a sine wave of lower frequency but with the same amplitude as the original current or voltage waveform. The relative phase shift between voltage and current is also preserved in these lower frequency curves because current and voltage are synchronously sampled.

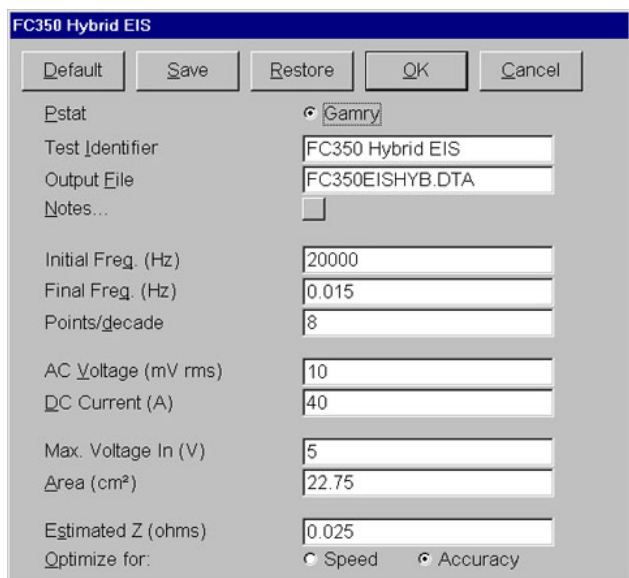


A Lissajous Figure Displayed During Data Acquisition provides a snapshot of the data quality and instrument performance. The Lissajous can quickly identify stability issues with a fuel cell.

The sampled current and voltage curves are each transformed into the frequency domain using a discrete Fourier Transform. The impedance is calculated from the voltage and current signals.

Hybrid EIS

Galvanostatic EIS is a valid technique for EIS, but it must be used carefully. The sample can encounter voltage levels during Galvanostatic EIS that threaten the integrity of the experiment. For example, a fuel cell impedance of 10 mΩ with 1 A excitation at 10 kHz will cause a 10 mV AC voltage. If the impedance increases to 500 mΩ at 10 Hz, the voltage will be 500 mV, almost certainly outside the linear range.



Setup Window for Hybrid EIS. The FC350 uses the Estimated Z for to set the initial AC current, then adjusts the AC current continually throughout the measurement to control the AC Voltage.

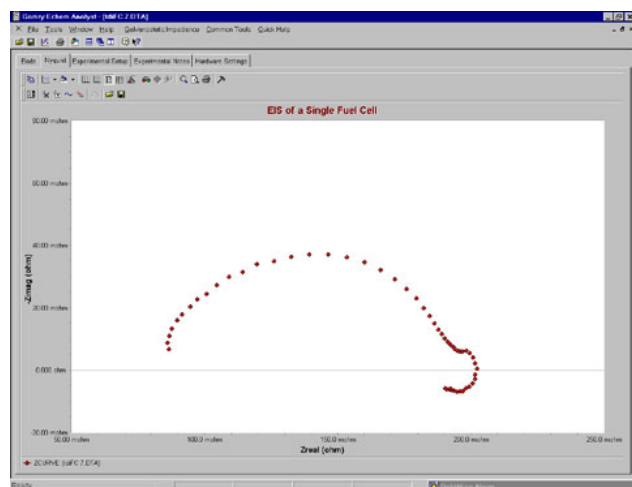
Hybrid EIS¹ overcomes this problem by continually adjusting the applied current during the experiment. During Setup, the user enters an "AC Voltage" and an "estimated initial impedance", from which an AC Current is calculated and applied to the fuel cell. The AC current is tuned throughout the impedance measurement so that the measured AC voltage remains as close as possible to the entered "AC Voltage". In this manner, the amplitude of the AC current is regulated so that the AC voltage does not extend beyond the linear range.

¹ Orazem *et al*, Electrochimica Acta, 41, 977 (1996).

FC350 Features

The accuracy of an EIS measurement at high frequencies is dependent upon the bandwidth of the instrument. EIS measurements are usually made at a maximum frequency of 10 kHz. The FC350 has a bandwidth of 20 kHz. The critical specification is the bandwidth of the Electronic Load. The Load bandwidth will determine the upper frequency of the EIS measurement. Contact Gamry regarding the bandwidth of your Load.

The precision of a dynamic electrochemical measurement such as EIS is an important issue. The Gamry FC350 performs a statistical analysis of the data at each frequency during acquisition. The data is accepted only after the precision criteria are met. The precision criteria can be adjusted by the user.



A Nyquist Plot of a Single PEM Fuel Cell. This data is plotted in the Echem Analyst. Note the negative impedances at low frequencies

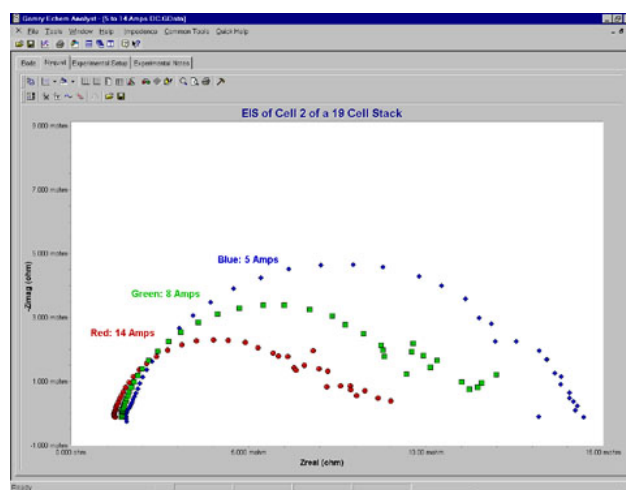
A fuel cell is a dynamic sample and it can be important to make the measurement quickly. The FC350 user has a choice of optimizing Speed or Accuracy during acquisition. When Speed is selected, the precision criteria are relaxed and a minimum amount of information is displayed during the experiment. The measurement time for an EIS measurement

in High Speed mode is over three times faster than in High Accuracy mode.

When used to study fuel cells, EIS is *always* measured in the presence of a significant DC current. The FC350 System offsets these DC levels to zero so that the AC values can be measured at a high gain for maximum accuracy.

Data Presentation and Analysis

Presentation and analysis of your FC350 data is done in the Echem Analyst. Bode and Nyquist Plots are standard and other plotting formats are available through the Curve Selector. Multiple EIS curves can be easily overlaid. Place the cursor over a data point and detailed information (frequency, Zreal, Zimag, etc.) is displayed, particularly useful for Nyquist Plots.



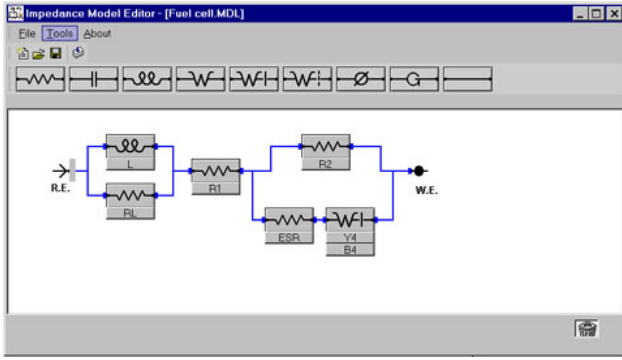
Impedance Spectra as a Function of Current. These data were acquired on Cell 2 of a 19 cell PEM stack using a Dynaload RBL488 100-120-800 Load. The AC modulation was 0.5 Amps. The voltage leads of the FC350 can sample a single cell, a group of cells, or the entire stack.

Tabs are available to quickly display the Experimental Setup and Experimental Notes. Notes can be entered during setup for a detailed description of your sample. The Hardware Settings tab contains detailed information on the FC350 during the EIS experiment.

Modeling the EIS Results

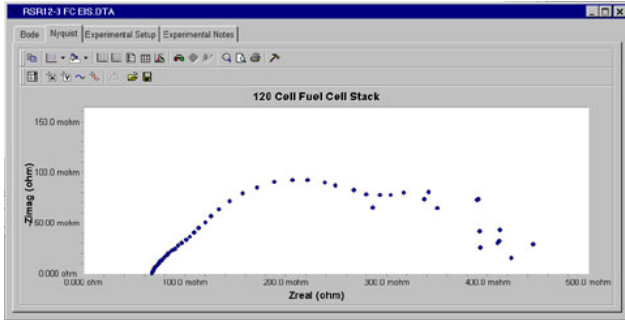
The Echem Analyst includes a complete modeling package for interpretation of the results. Use the six pre-configured models or build and build your own model using the graphical Model Editor. The following elements are included in the Echem Analyst:

- | | |
|------------------------|-----------------|
| Resistor | Capacitor |
| Constant Phase Element | Inductor |
| Infinite Warburg | Bounded Warburg |
| Porous Bounded Warburg | Gerischer |



The FC350 Model Editor employs an easy-to-use click-and-drag mechanism to build an equivalent circuit. Build it once and save it.

The equivalent circuit is fit to the data using either a Simplex or the Marquardt-Levenberg algorithm. The Echem Analyst overlays the fit onto the data and generates a goodness-of-fit coefficient that approximates the relative error. If you wish, you can model a portion of the EIS curve and undesirable data points can be excluded from the fit. The data with the fit can be saved in the Echem Analyst.



EIS of a 120 Cell PEM Fuel Cell Stack. Current for this experiment is 60 Amps and the voltage is 85-95 Volts. The AC current is 0.5 Amps. This data was acquired with a Dynaload WCL488 400-100-12000 Electronic Load.

If you prefer, you can use other EIS modeling programs. The data format of the FC350 is tab-delimited ASCII text, so it can be easily imported into other EIS data analysis software such as Equivalent Circuit, Zview 2, or ZsimpWin.

Applications Assistance

If you're new to EIS, we can provide some suggestions. Pay a visit to www.gamry.com, go to the App Note section, and take a look at "The EIS Primer". There's an excellent list of references at the end of the Application Note. For specific questions, call us at our factory or your local Gamry sales office.

System Information

The FC350 Fuel Cell Monitor requires an Electronic Load to conduct experiments on high-current fuel cells. Gamry recommends Electronic Loads from TDI Dynaload. They have good bandwidth, multiple current ranges, and they work well on single cells, which often exhibit a very low voltage. We have also configured systems to work with Loads from Agilent and Kikasui. Contact us for details.

For battery testing, we have configured systems using power supplies from Kepeco and Basytec.

Microsoft Windows 2000™ or XP™ is required for operation of the FC350. Gamry recommends a computer with a 700 MHz processor or higher with 256 MB of RAM or higher.

Gamry Instruments can supply complete FC350 systems in a desktop or portable computer and including an Electronic Load. Custom computer configurations, software, training, and installation are available by special order. Contact the factory or your local Gamry Distributor for further details on these systems.

