

Circuits from the Lab®

Reference Designs

Circuits from the Lab® reference designs are engineered and tested for quick and easy system integration to help solve today's analog, mixed-signal, and RF design challenges. For more information and/or support, visit www.analog.com/CN0565.

Devices Connected/Referenced

AD5940	High Precision, Impedance & Electrochemical Front End
ADG2128	I ² C CMOS 8x12 Analog Switch Array with Dual/Single Supplies
ADuM5020	Low Emission 500 mW Isolated DC-to-DC Converter
ADM7150	800 mA, Ultralow Noise/High PSRR LDO
ADM8829	Switched Capacitor Voltage Inverter
ADuM3151	3.75 kV, 7-Channel, SPIisolator Digital Isolators for SPI (with 2/1 Aux Channel Directionality)
ADuM1250	Hot Swappable Dual I ² C Isolator

Electrical Impedance Tomography Measurement System

EVALUATION AND DESIGN SUPPORT

- ▶ Circuit Evaluation Boards
 - ▶ [CN0565 Circuit Evaluation Board \(EVAL-CN0565-ARDZ\)](#)
- ▶ Design and Integration Files
 - ▶ [Schematics, Layout Files, Bill of Materials, Software](#)

CIRCUIT FUNCTIONS AND BENEFITS

Electrical impedance tomography (EIT) is a type of imaging in which an image is constructed from multiple impedance measurements taken between various points across the surface of a specimen. Compared with other imaging techniques such as X-ray, ultrasound, or computerized axial tomography (CAT) scan, EIT is considerably lower cost, lower power, radiation-free, and easily adapted to portable, wearable, and continuous monitoring applications. While EIT is typically lower resolution than X-ray, ultrasound, or CAT scan, it finds broad application in medical imaging, often augmenting other methods. EIT can be as effective as other imaging methods in certain pulmonary function measurements.

EIT images are constructed by placing an array of electrodes across the surface of a sample. A pair of electrodes is then

excited with a current, and the resulting voltage is measured between a second pair of electrodes. A series of measurements is taken across the sample, with the exact sequence dependent on the imaging technique. From these measurements, a calculation determines the internal impedance profile, from which a two- or three-dimensional (2D or 3D) image is produced.

The circuit shown in [Figure 1](#) is a 24-electrode EIT measurement system for measuring the impedance profiles of various materials. The electrode configuration is arbitrary; excitation can be applied to any two electrodes, and measurements taken across any two electrodes. Excitation frequency is adjustable between 0.015 Hz and 200 kHz, allowing the measurement of frequency-dependent effects.

The design features complete power and signal isolation from the host controller, essential for medical, bioimpedance analysis (BIA), and certain industrial applications. The module uses an Arduino compatible form factor, and the software example is based on the industry-standard industrial input/output (IIO) framework for easy integration into end-user systems.

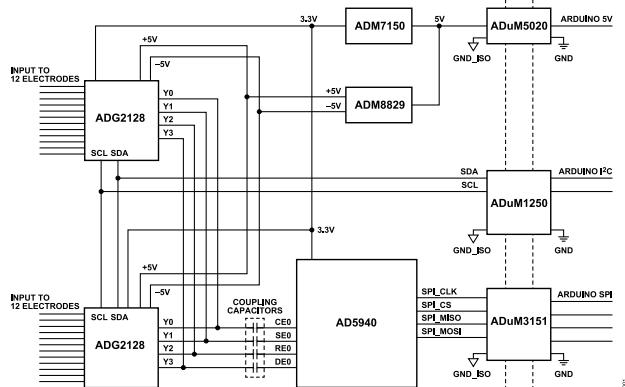


Figure 1. CN0565 Simplified Block Diagram

CIRCUIT DESCRIPTION

ELECTRICAL IMPEDANCE TOMOGRAPHY

In its simplest form, EIT is implemented by placing an array of electrodes across the surface of a sample and exciting pairs of electrodes with a current signal while measuring the voltages induced on other electrodes. From these measurements, a calculation determines the sample's internal impedance profile and uses this input to create a 2D or 3D image.

Figure 2 shows a typical EIT system. An array of 8 electrodes is placed around the test object, and an AC current at a certain frequency is injected into a pair of forcing electrodes (F+ and F-). The resultant voltage between a pair of sense electrodes (S+ and S-) is measured and stored. The sequence continues to the next pair of electrodes until all required inputs to the impedance calculation are collected. The impedance readings are then mapped to an EIT image showing the sample's internal impedance profile.

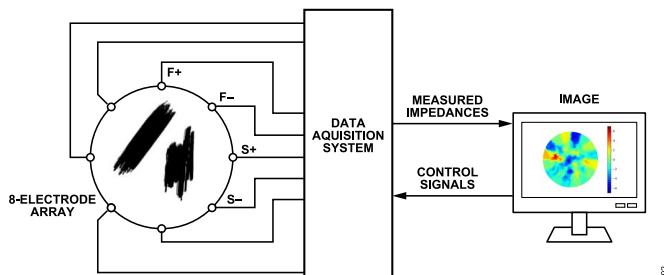


Figure 2. Simplified EIT System with 8 Electrodes

IMPEDANCE MEASUREMENT

Multiple, independent impedance measurements must be taken in order to create a tomographic image. The electrical techniques for measuring DC resistance and AC impedance are well established; conceptually, a circuit element is excited with a current, and the resulting voltage is measured.

In general, impedance measurements can be performed with either two electrodes or four electrodes, shown in **Figure 3**.

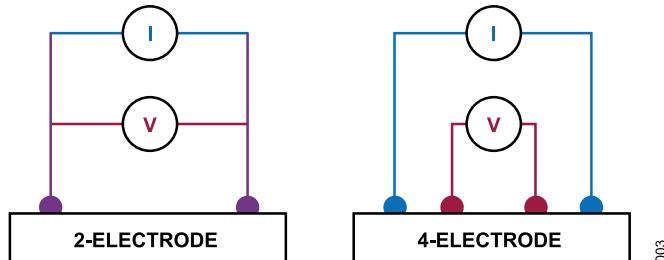


Figure 3. Impedance Measurement Techniques

Bioimpedance measurements have additional considerations; medical devices must conform to the IEC 60601 standard, which limits the amount of DC and AC voltage that can be applied to the human body. Furthermore, electrodes have their own impedance that can vary considerably from unit to unit, contact to a sample, and over time.

2-Wire Impedance Measurement

The simplest form of impedance measurement uses two connections to the unknown sample, shown in **Figure 4**.

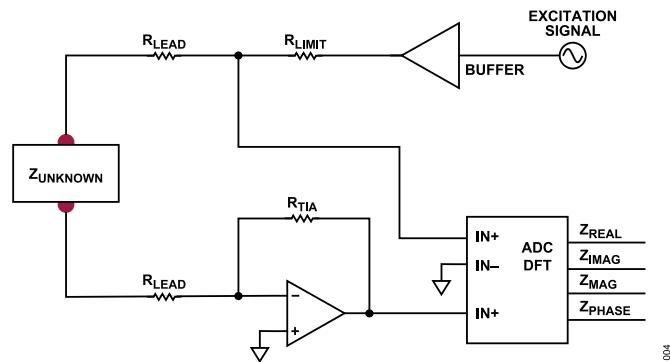


Figure 4. 2-Wire Impedance Measurement

A voltage excitation signal is applied across the unknown impedance ($Z_{UNKNOWN}$) in series with a current limiting resistor (R_{LIMIT}). The voltage across the electrodes ($V_{UNKNOWN}$) is measured, which does not include the drop across the limiting resistor. At the same time, current flow through the unknown impedance ($I_{UNKNOWN}$) is converted to a voltage by a transimpedance amplifier (TIA).

In practice, the 2-wire method is not practical for impedance measurements in medical applications. While the impedances in these applications are typically high enough that the lead resistance is insignificant, the electrode impedance appears in series with the measured impedance. Also in tomography applications, multiple sense measurements at other locations on the sample may be required for a given pair of force electrodes.

4-Wire Impedance Measurement

Figure 5 shows how the 4-wire impedance measurement technique overcomes the electrode impedance problem by using separate force and sensing electrodes. Any voltage drop across the force electrodes drops out of the calculation, similar to the drop across R_{LIMIT} . The IN+ and IN- sense inputs are high-impedance, so drop across the sense electrodes and their corresponding R_{LEAD} is negligible.

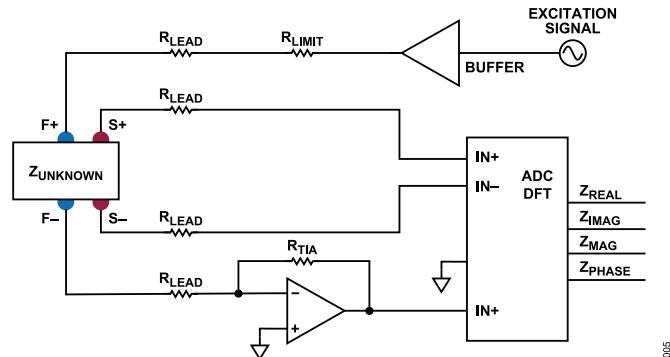


Figure 5. 4-Wire Impedance Measurement

ANALOG FRONT END

The core of the **CN0565** is the **AD5940** high precision, impedance, and electrochemical front end. [Table 1](#) shows the two operation modes of AD5940's digital-to-analog converter (DAC).

Table 1. AD5940 DAC Operation

	Low Bandwidth Operation	High Bandwidth Operation
DAC	low power, dual-output DAC	high-speed DAC
Operation	generates the bias voltage for the low power transimpedance amplifier and the bias voltage for the potentiostat amplifier	generates a high frequency, AC excitation signal for high-speed transimpedance amplifier designed to convert high bandwidth current signals
Excitation Frequency Range	< 200 Hz	> 200 Hz
Application Examples	electrodermal activity measurements	body impedance measurements, battery impedance measurements

The AD5940 includes a flexible switch matrix that can select the electrodes, high speed DAC excitation amplifier, and the high speed TIA inverting input, as well as an external calibration resistor.

[Figure 6](#) shows the AD5940 configured for a 4-wire impedance measurements, including 0.47 μ F DC-blocking capacitors.

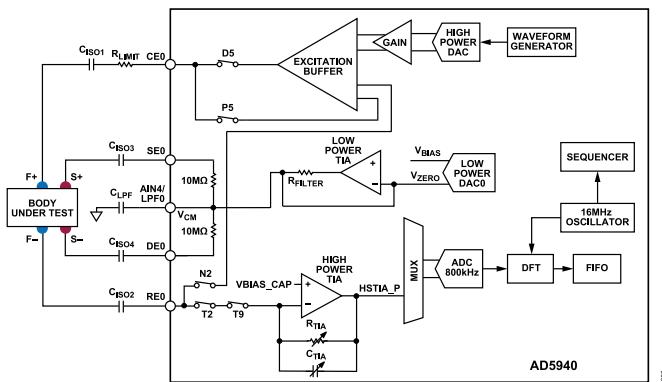


Figure 6. Impedance Signal Path

Excitation Signal

The CN0565 includes a high speed DAC and waveform generator to provide a precision AC voltage source. A digital waveform generator produces a sine wave, square wave, or trapezoid pattern which is routed to the 12-bit, high speed DAC and excitation amplifier, which then drives the electrodes. The impedance under test is connected between the counter electrode pin (CE0) and reference electrode input pin (RE0). An internal differential sense configuration inside the AD5940 guarantees the accuracy of the voltage source by connecting CE0 and RE0 back into the excitation buffer. The excitation signal amplitude and frequency are programmable up to ± 607 mV and 200 kHz, respectively.

Current Limit

The CN0565 includes a current limit resistor, which limits the amount of AC current that enters the sample. To conform to IEC 60601 standards for medical applications, the maximum allowable AC current is 500 μ A at 50 kHz and 600 μ A at 60 kHz. When calculating the R_{LIMIT} resistor value, the maximum output voltage from the AD5940 is 1.2 Vp-p (0.4243 V_{RMS}). Set the maximum allowable AC current to 80% of maximum, or 400 μ A_{RMS}. Calculate the current limit using [Equation 1](#):

$$R_{LIMIT} = \frac{0.4243 \text{ V rms}}{400 \mu\text{A rms}} \quad (1)$$

As such, a 1 k Ω R_{LIMIT} is selected and is connected to the CE0 pin on the AD5940. The 0.47 μ F C_{ISOx} has an impedance of 6.8 Ω at 50 kHz and is ignored in this calculation.

Isolation Capacitors

The IEC 60601 standards set 10 μ A as the maximum DC current allowed to enter the human body. The DC current of the CN0565 is guaranteed to be zero due to the addition of isolation capacitors. A value of 0.47 μ F is selected for the isolation capacitors because 0.47 μ F is a sufficiently large capacitance that is also available in small packages suitable for wearable electronics. See the EDA section of [AN-1557 application note](#) for details on capacitor size calculations.

While the AD5940 excitation frequency can be programmed as low as 0.015 Hz, at low frequencies the impedance of the isolation capacitor is high enough to attenuate the excitation current. This reduces the signal-to-noise ratio (SNR) of the impedance measurement, resulting in noisy readings. [Figure 7](#) shows the impedance of two 0.47 μ F in series vs. excitation frequency and can be used to estimate the lowest practical frequency that can be used for a given sample impedance. For example, using a guideline that the drop across the isolation capacitor should be less than or equal to the drop across the sample, an excitation frequency of 150 Hz will be suitable for impedances as low as 4515 Ω .

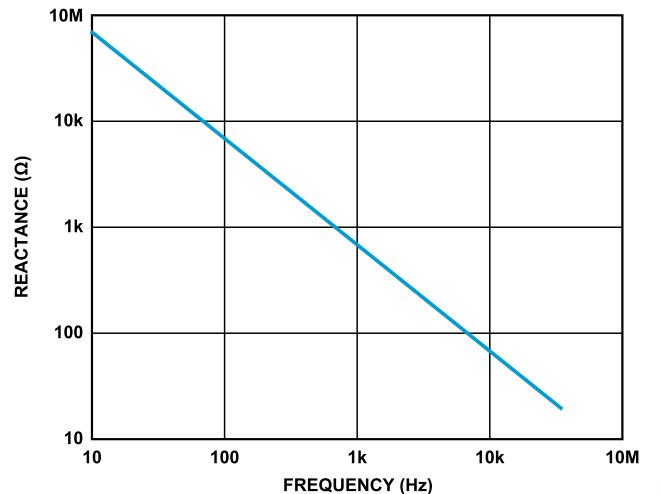


Figure 7. Isolation Capacitor Reactance

High Speed TIA Gain Resistor and ADC Input Range

To achieve an accurate, low-noise impedance measurement, the voltage and current measurements should exercise a large fraction of the analog-to-digital converters (ADC) input range. The sense lead voltages are measured directly, and the ADC input range of 900 mV peak accommodates the 600 mV peak DAC output voltage. Note that an infinite impedance (open circuit) would result in the full DAC voltage at the ADC input. The current measurement is scaled by the transimpedance amplifier's R_{TIA} , which can be set to one of ten values between 50 Ω and 160.1 k Ω .

With the excitation set to maximum (600 mV), the value of the minimum impedance can be calculated using [Equation 2](#):

$$Z_{MIN} = R_{TIA} \times 2/3 \quad (2)$$

where:

Z_{MIN} is the minimum impedance in the force path.

R_{TIA} is the gain resistor value of the transimpedance amplifier.

Note that the impedance includes the lead resistance, isolation capacitors, and R_{LIMIT} , as all of these reduce the magnitude of the excitation current.

The LTspice simulation shown in [Figure 8](#) is a conceptual model of the AD5940, isolation capacitors, switch resistance, and can be used to estimate an optimal excitation amplitude and R_{TIA} value for any application. [Figure 9](#) shows the TIA output voltage for a given resistor value and excitation frequency.

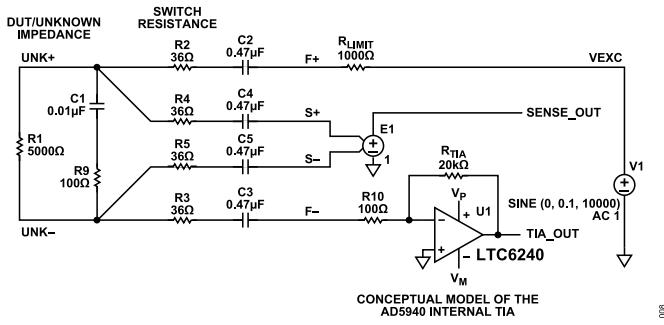


Figure 8. Conceptual Model of the CN0565 Signal Chain

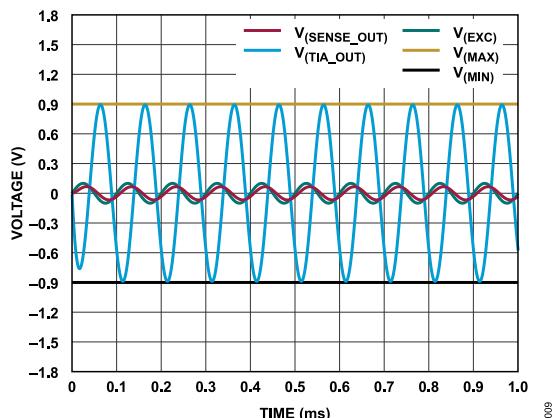


Figure 9. Validating TIA Output Range

Crosspoint Switch

The CN0565 includes two **ADG2128** 8x12 analog crosspoint switches, which allow force and sense electrodes to be assigned arbitrarily. The switch resistances are less than 35 Ω , and has a typical capacitance of 18.5 pF. The switches are powered from a ± 5 V bipolar supply, allowing a ± 5 V common-mode range of the electrodes with respect to isolated circuit ground.

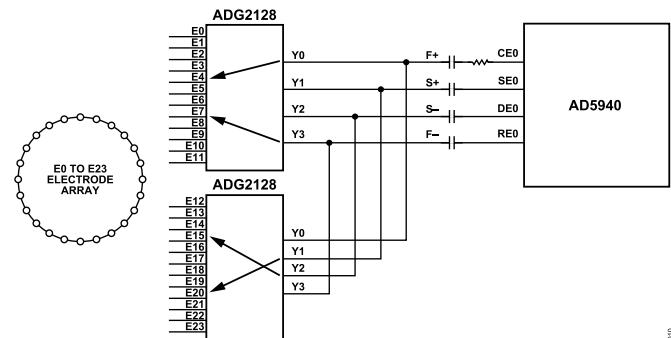


Figure 10. Crosspoint Switch Functional Block Diagram

As shown in [Figure 10](#), the four Y input/output of the two ADG2128 switches are routed to the four analog pins of the AD5940. The first 12 electrode connections (E0 to E11) are connected to the input/output nodes of the first ADG2128, and the second set of 12 electrodes are connected to input/output nodes of the second ADG2128.

INPUT MEASUREMENT

The AD5940 uses a high speed, high precision TIA to convert the current from the electrode into a voltage measured by the ADC at a speed of 800 kSPS. The TIA is internally biased to 1.1 V, centering the output in the ADC's full scale range.

A discrete Fourier transform (DFT) is performed on the ADC data for the current and voltage values, and is configurable up to 16,384 points. The magnitude and phase of the voltage and current are then calculated from the real and imaginary outputs of the DFT in [Equation 3](#) and [Equation 4](#), respectively. The AD5940 then calculates the real and imaginary parts and the unknown impedance is derived using [Equation 5](#):

$$|V_{MAG}| = \sqrt{r_v^2 + i_v^2} \quad (3)$$

$$|I_{MAG}| = \sqrt{r_i^2 + i_i^2} \quad (4)$$

$$|Z_{UNKNOWN}| = \frac{|V_{MAG}|}{|I_{MAG}|} \times R_{TIA} \quad (5)$$

where:

$Z_{UNKNOWN}$ is the unknown impedance of the specimen under test.

V_{MAG} is the magnitude of the voltage across the $Z_{UNKNOWN}$.

I_{MAG} is the magnitude of the current through the $Z_{UNKNOWN}$.

r_v and i_v are the real and imaginary components from the voltage DFT measurements.

r_i and i_j are the real and imaginary components from the current DFT measurements.

R_{TIA} is the value of the high speed TIA gain resistor in Ω .

POWER ARCHITECTURE

Figure 11 shows the complete power tree of the CN0565. The host platform board provides 5 V to the **ADuM5020** isolated DC-to-DC converter, producing an isolated 5 V, 500 mW output voltage. The isolated 5 V output is used as input to the whole section of the circuit responsible for the actual impedance measurement and processing.

The isolated 5 V is fed into the **ADM7150** low dropout linear regulator, producing a regulated 3.3 V with 120 mA output. The 3.3 V is used to power the AD5940 as well as provide the digital power supply to the ADG2128 crosspoint switches.

The isolated 5 V rail is also used as input to the **AD8829** voltage inverter, which produces a dual supply, ± 5 V for the two ADG2128 analog crosspoint switches.

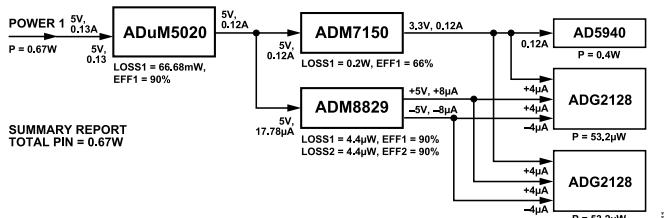


Figure 11. CN0565 Power Tree

ISOLATION

The entire measurement circuit is galvanically isolated via the ADuM5020 DC-to-DC converter, **ADuM1250** I²C isolator, and **ADuM3151** 7-channel digital isolator for serial peripheral interface (SPI) with aux channels. No explicit stitching capacitance is included, for a total isolated capacitance of 18 pF between grounds.

The minimum creepage on the CN0565 is 20 mils due to layout constraints, providing a basic isolation of 150 V. When designing a board to meet a specific regulatory standard, refer to the standard for creepage requirements, and refer to the [Safety and Regulation for Digital Isolation](#) for agency certifications.

SYSTEM PERFORMANCE

The fidelity of a tomography image is dependent on several factors including the accuracy of electrode placement, the imaging mode, and fundamentally, the accuracy of the impedance measurements themselves. The 20% typical R_{TIA} tolerance directly affects the measurement and must be calibrated. An external calibration resistor between RCAL0 and RCAL1 pins provides an accurate reference. During calibration, a software routine sets the multiplexer to connect RCAL between the excitation buffer and TIA input, and an excitation signal is applied. Calibration values are measured, calculated, and stored, removing the R_{TIA} error from subsequent impedance measurements.

Figure 12 and Figure 13 show the post-calibration measurement error for various resistances and capacitances at a typical excitation frequency of 20 kHz.



Figure 12. Resistance Measurement Accuracy

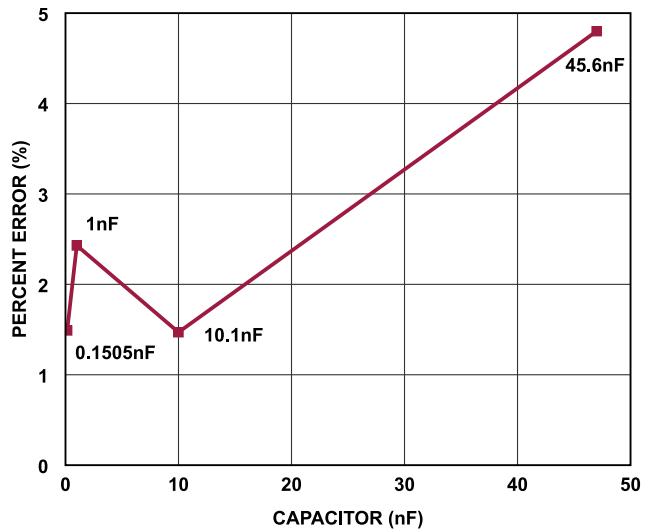


Figure 13. Capacitance Measurement Accuracy

IMAGE RECONSTRUCTION ALGORITHMS

From the collected data, the image of the electric impedance distribution may be constructed by use of certain reconstruction algorithms. In EIT, the conductivity distribution of the unknown object is estimated from boundary voltages induced by different current patterns with the aid of various image reconstruction algorithms. The CN0565 example software can perform three image reconstruction algorithms: back-projection (BP), Jacobian calculations (JAC), and Graz consensus reconstruction EIT (GREIT).

With back-projection, reconstructed images can be simply understood as a superposition of boundary measurements. JAC algorithm preserves sharp edges, while GREIT uses training data to generate images with more uniform amplitude response.

Figure 14 shows a sample EIT image using different reconstruction techniques.

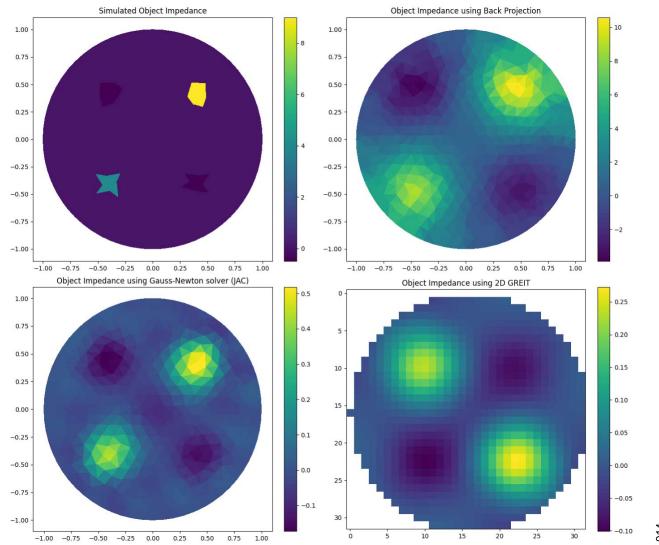


Figure 14. Image View Based on Different Reconstruction Algorithms

Sensing Area

The CN0565 supports up to 24 electrodes and various impedance measurement methods are supported. Figure 15 shows the neighboring method, whereby the current is applied through neighboring electrodes and the voltage is measured successively from all other adjacent electrode pairs. Lines of equipotential are shown, and the measured impedance is a weighted average of the red shaded area.

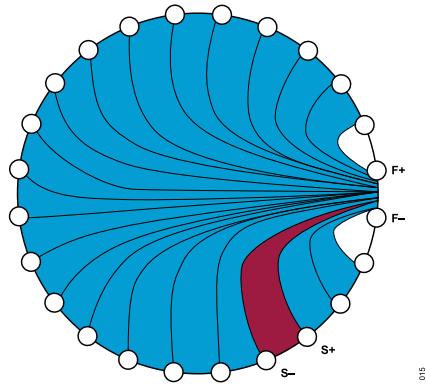


Figure 15. Working Area of the Adjacent Current Excitation Mode

COMMON VARIATIONS

As the number of electrodes vary depending on the application, variations in array sizes and number of switches are possible using different crosspoint switches. For applications requiring only 8 electrodes, the [ADG2188](#) crosspoint switch is an alternative to the ADG2128. This switch offers eight columns and eight rows in the switch array, providing a total of 64 switch channels. For applications using 10 electrodes, the [ADG2108](#) crosspoint switch can be used. This part has an array size of 8 × 10, providing a total of 80 switch channels.

CIRCUIT EVALUATION AND TEST

This section describes the setup and procedure for evaluating the EVAL-CN0565-ARDZ. For complete information on the circuit evaluation setup, refer to the [CN0565 User Guide](#).

EQUIPMENT NEEDED

- EVAL-CN0565-ARDZ circuit evaluation board
- [EVAL-ADICUP3029 development platform](#)
- Host PC (Windows)
- Micro-USB cable

SETUP AND TEST

1. Connect the EVAL-CN0565-ARDZ to the EVAL-ADICUP3029 via the Arduino headers.
2. Connect the impedance test board to the main EVAL-CN0565-ARDZ board via the 30-pin, 100-mil headers.
3. Power the boards by connecting the micro-USB cable into P10 on the EVAL-ADICUP3029 and then plug the other end of the cable to the host PC, as shown in Figure 16.
 - a. The DS2 in the EVAL-CN0565-ARDZ must turn green to indicate power.

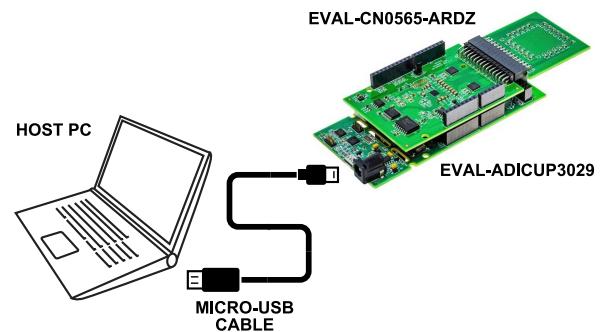


Figure 16. Complete EIT System

4. Install Python and the pyadi-ii0 library which includes CN0565 hardware support and example scripts.
 - a. Ensure the version of Python is supported in pyadi-ii0.
5. Load the CN0565 firmware to the EVAL-ADICUP3029 by copying the pre-built .hex file directly into the DAPLink drive.
 - a. Ensure that the DAPLink is visible in the file explorer to indicate a proper connection between boards.
 - b. Drag and drop the CN0565.hex file to the DAPLink. The DAPLink will automatically disconnect and connect again, indicating a successful upload.
6. Open a command terminal and navigate to the working directory where the example script is saved by entering:

```
cd <folder address>
```

7. Execute the script by typing the following command into the terminal window.

```
python cn0565_prod_tst.py
```

The script will measure the impedance test board values and the output should look similar to [Figure 17](#).

```
Electrode 10 - Electrode 11
R1_C36_C38 - R2_C29_C36
Rectangular: (9637.5166015625+104.93243408203125j)
Polar: Magnitude:9638.087832195512 Phase(degrees): 0.623806764501389 or 360.6238067645014
Real Impedance: 9637.5166015625
Imaginary Impedance: 104.93243408203125
-----
Electrode 10 - Electrode 11 - PASSED!
-----
Electrode 12 - Electrode 13
R1_C29_C33 - R3_C33_C37
Rectangular: (6659.58447265625-31920.708984375j)
Polar: Magnitude:32608.000972362643 Phase(degrees): -78.21547818240118 or 281.78452181759883
Real Impedance: 6659.58447265625
Imaginary Impedance: -31920.708984375
-----
Electrode 12 - Electrode 13 - PASSED!
-----
Electrode 14 - Electrode 15
R5_C37_C39 - R7_C39_C41
Rectangular: (266.857666015625-7550.5146484375j)
Polar: Magnitude:7555.228948892322 Phase(degrees): -87.97583910912591 or 272.0241608908741
Real Impedance: 266.857666015625
Imaginary Impedance: -7550.5146484375
-----
Electrode 14 - Electrode 15 - PASSED!
-----
BOARD STATUS: PASSED
```

017

Figure 17. CN0565 Example Script

For detailed instructions on how to run the impedance measurement for a single pair, electrode tomography and for the graphical user interface (GUI) demo by using a phantom or a petri dish, see the CN0565 User Guide.

LEARN MORE

[CN0565 Design Support Package](#)

[EVAL-ADICUP3029 User Guide](#)

[AN-1557. "Implementing the AD5940 and AD8233 in a Full Bioelectric System." Analog Devices.](#)

[CN-0510. "Electrochemical Impedance Spectroscopy \(EIS\) for Batteries." Analog Devices.](#)

[Bera, Tushar Kanti. "Bioelectrical Impedance Methods for Noninvasive Health Monitoring: A Review." 2014.](#)

[Broeders, Jan-Hein. "Jack of All Trades in Impedance Measurement." Analog Devices.](#)

[GitHub. "OpenEIT: Python-based Dashboard for Real-time Electrical Impedance Tomography Including Image Reconstruction Using Back Projection, Graz Consensus and Gauss Newton methods."](#)

[Holder, David and Adler, Andy. "Electrical Impedance Tomography Methods, History and Applications." 2022.](#)

[IEEE. "Electrical Impedance Tomography for Biomedical Applications: Circuits and Systems Review." 2021.](#)

[Liu, Benyuan, et al. "pyEIT: A Python-based Framework for Electrical Impedance Tomography." 17th International Conference on Electrical Impedance Tomography, 2016.](#)

[Madden, Maria, Andrews, Penny, and Habashi, Nader. "Comparison of Chest Radiograph to Electrical Impedance Tomography." *Respiratory Care*, 2018.](#)

[Malmivuo, Jaako. "Bioelectromagnetism: Principles and Applications of Bioelectric and Biomagnetism Fields." Oxford University Press, 1995.](#)

[Safety and Regulatory Certification for Digital Isolation. Analog Devices.](#)

DATA SHEETS AND EVALUATION BOARDS

[AD5940 Data Sheet](#)

[AD5940 Evaluation Board](#)

[ADG2128 Data Sheet](#)

[ADG2128 Evaluation Board](#)

[ADuM5020 Data Sheet](#)

[ADuM5020 Evaluation Board](#)

[ADM7150 Data Sheet](#)

[ADM7150 Evaluation Board](#)

[ADM8829 Data Sheet](#)

[ADuM3151 Data Sheet](#)

[ADuM3151 Evaluation Board](#)

REVISION HISTORY**08/2023—Revision 0: Initial Version****ESD Caution**

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

(Continued from first page) Circuits from the Lab circuits are intended only for use with Analog Devices products and are the intellectual property of Analog Devices or its licensors. While you may use the Circuits from the Lab circuits in the design of your product, no other license is granted by implication or otherwise under any patents or other intellectual property by application or use of the Circuits from the Lab circuits. Information furnished by Analog Devices is believed to be accurate and reliable. However, Circuits from the Lab circuits are supplied "as is" and without warranties of any kind, express, implied, or statutory including, but not limited to, any implied warranty of merchantability, noninfringement or fitness for a particular purpose and no responsibility is assumed by Analog Devices for their use, nor for any infringements of patents or other rights of third parties that may result from their use. Analog Devices reserves the right to change any Circuits from the Lab circuits at any time without notice but is under no obligation to do so.