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2024 AUSTIN

EMERSON

Advanced Battery Cell Testing Techniques

Felipe Quintana

Principal Systems Engineer

Presenter: Felipe Quintana

Over 10 years of experience developing automated test systems for validation and manufacturing of EV powertrain, with a focus on battery.

As a Principal Systems Engineer at NI Transportation, I am responsible for the design and deployment of industry-driven hardware and software test solutions. Previously, I worked as a manufacturing Engineer for Tesla.

Agenda

- Presenter Introduction
- Cell Testing Challenges and Impact
- Common Cell Quality Testing Techniques
- Common Cell Defects
- Technical Background
  - DCIR
  - ACIR
  - EIS
- The NI Advantage

Cell Testing Challenges and Impact

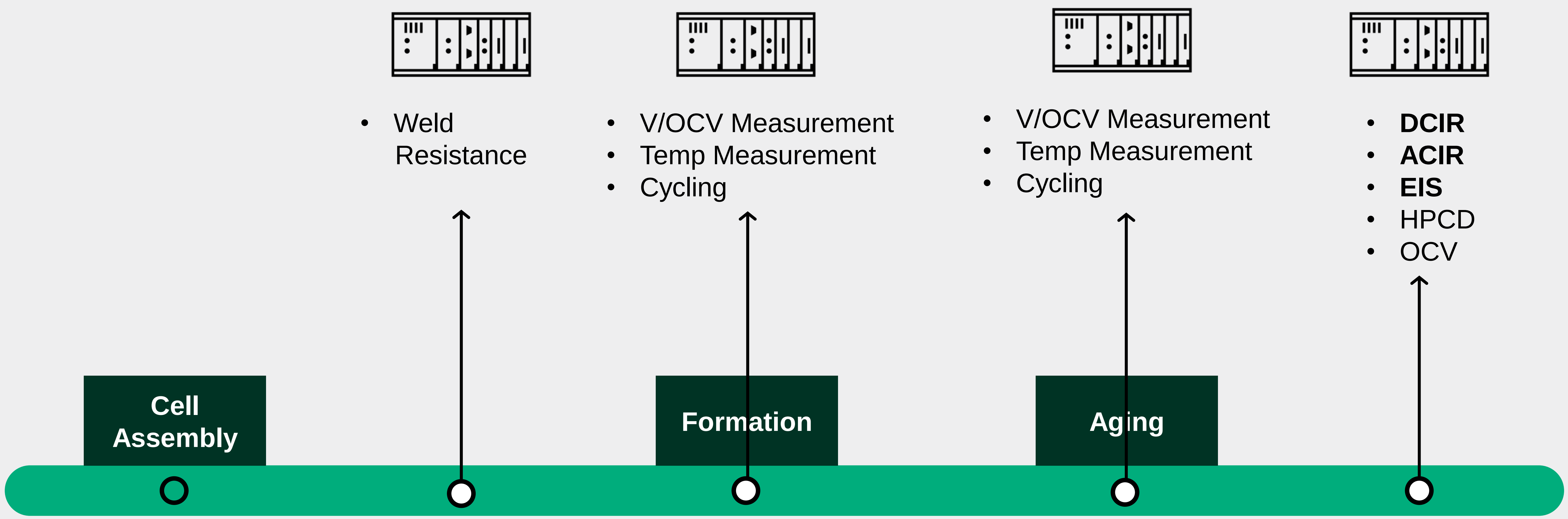
Challenges	Impact
Time and Data	Performance
Standardization	Safety
Limited Techniques	Longevity

Common Cell Quality Testing Techniques

Use-Cases and Considerations

Test	DUT	Description
OCV	Cell, Module or Pack	Performed periodically throughout aging process to evaluate leakage testing over time. Can also be used to ensure balance, though that is increasingly the responsibility of the pack
ACIR	Cell	More comprehensive evaluation of cell quality and formation process that injects current at 1kHz
EIS (<1kHz)	Cell	Measures the impedance of a cell across a spectrum of different frequencies and compares response with a data model to screen for specific failure modes and bin them appropriately
High-Frequency EIS (>1kHz)	Cell	Measures the impedance of a cell across a spectrum of different frequencies and compares response with a data model to screen for specific failure modes and bin them appropriately. Higher frequencies are useful for specific defects and reduce overall test time
High Pressure Current Detection (HPCD)	Pouch Cell	Leakage testing of pouch cells while applying mechanical pressure to the structure of the cell. The physical force is intended to aggravate micro-shorts
Standard Leakage Testing	Cell or Module	Precisely determines the cell voltage before putting the SMU into a steady state voltage mode while measuring the required current
DCIR	Cell, Module or Pack	Application of a current pulse, generally high current, to analyze the internal resistance of the battery reacting to DC pulses

NI Battery Cell Production Test Solutions



○ Test Station with NI/Cell Quality Offering Content

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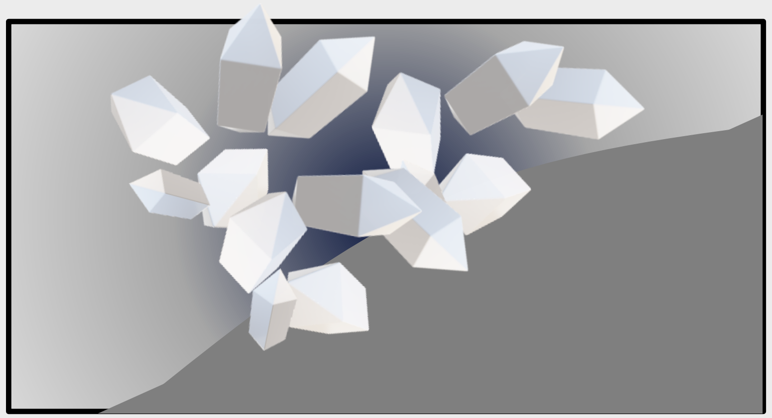
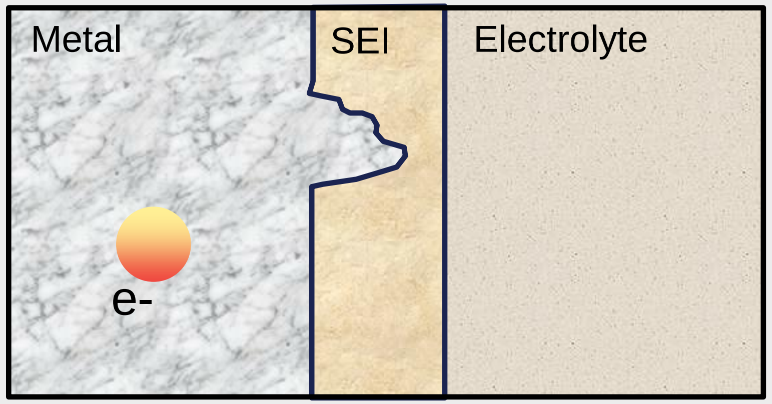
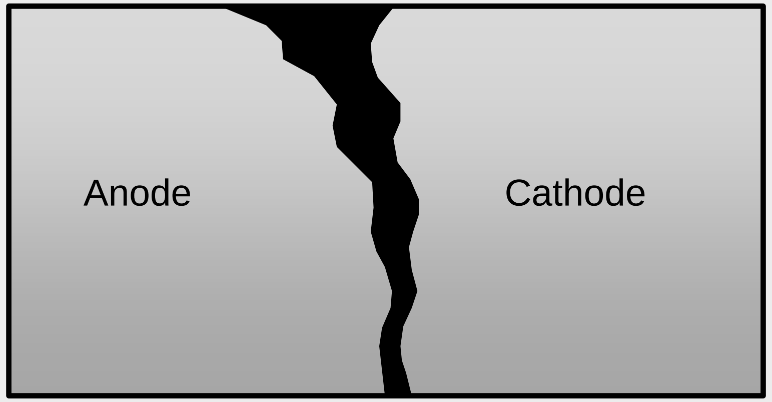
Advanced Measurement Solutions are Required to Catch All Failure Modes



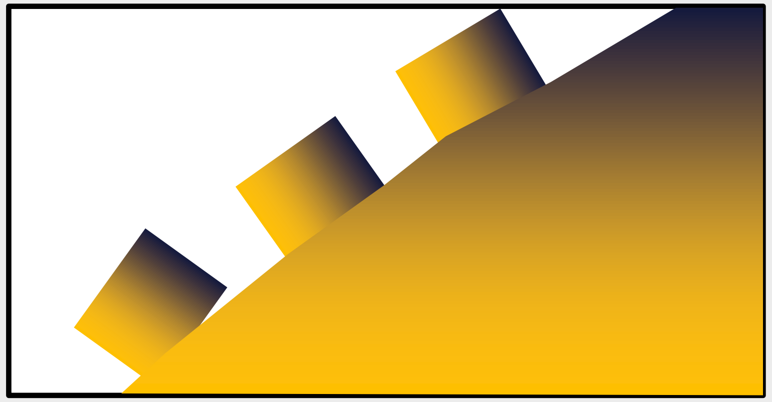
Dendrite Build-up



Un-even SEI Layer



Wrinkled or Folded Separator



Torn or Dislocated Tab Weld

Other Common Defects Include:

Internal Shorts:

1. Torn tab
2. Internal shorting
3. Internal contamination

After Electrolyte is Added:

1. Over/under-lithiation
2. Graphite slurry defect
3. Electrolyte additive mixture defect
4. Improper wetting
5. SEI composition and distribution
6. Cell formation recipe assessment
7. Delamination

Basic OCV/Resistance measurements are not enough to detect all failure modes

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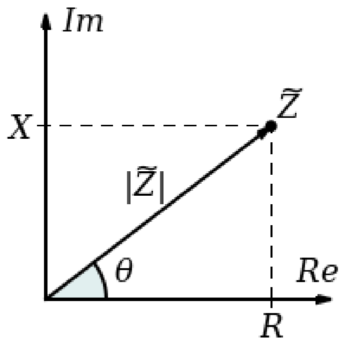
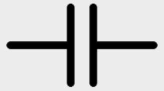
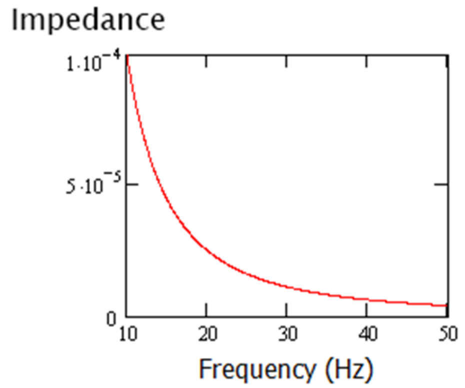
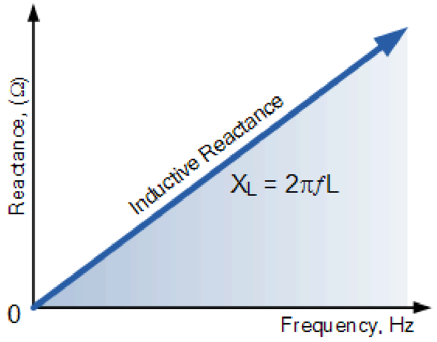
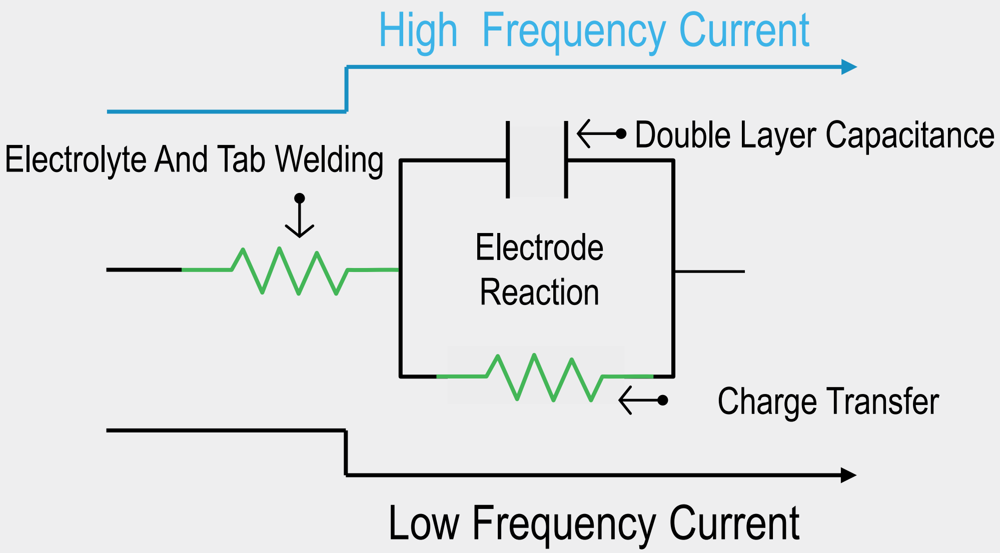
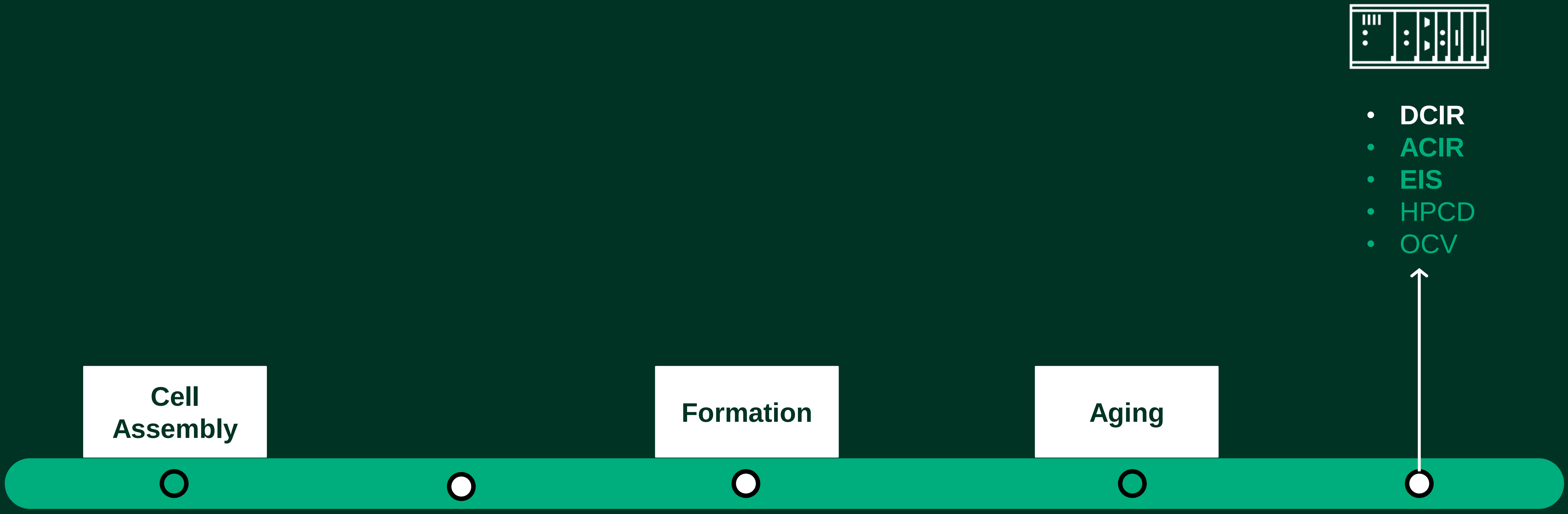
Technical Background | Impedance

DC	AC		
$R = \frac{V}{I}$	$Z = \frac{V}{I}$	$Z = R + jX$	
 $R_C = \infty$	$X_C = -\frac{1}{2\pi f C}$		
 $R_I = 0$	$X_L = 2\pi f L$		

Technical Background | Cell Model

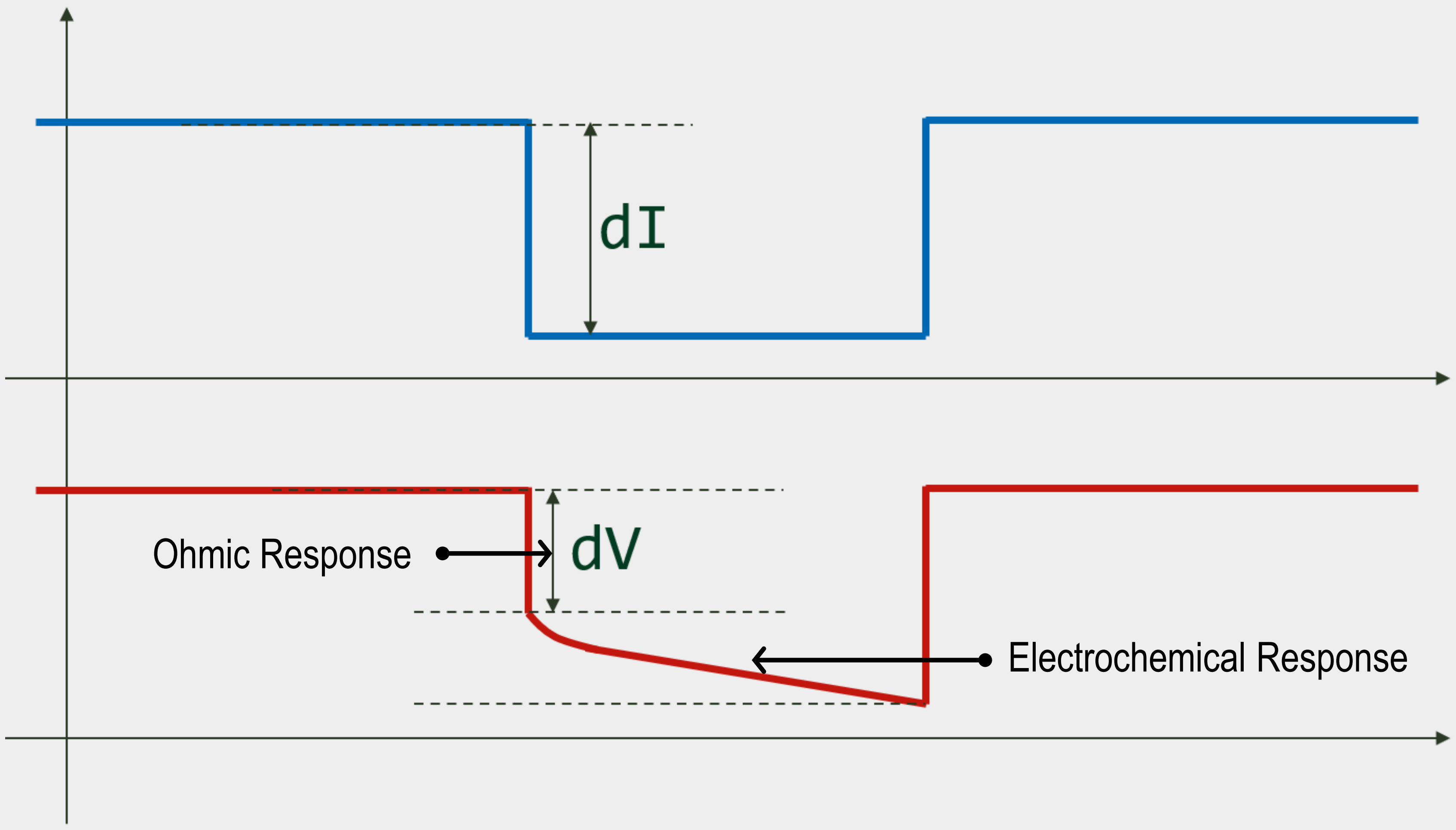


DC Internal Resistance (DC-IR)

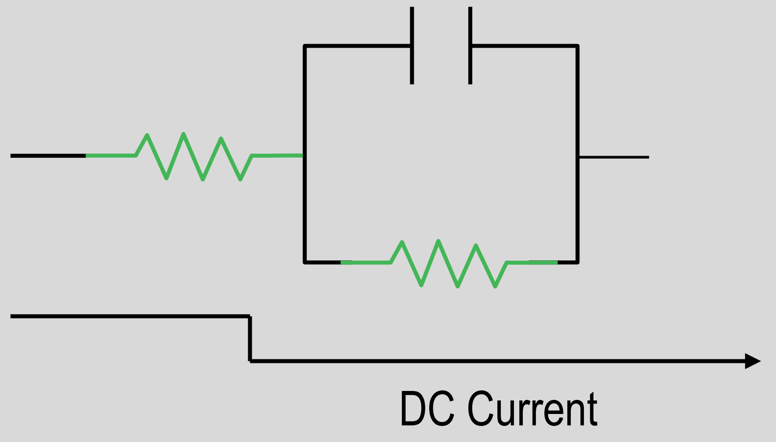


Test Station with NI/Cell Quality Offering Content

Test Process | DC Internal Resistance (DC-IR)

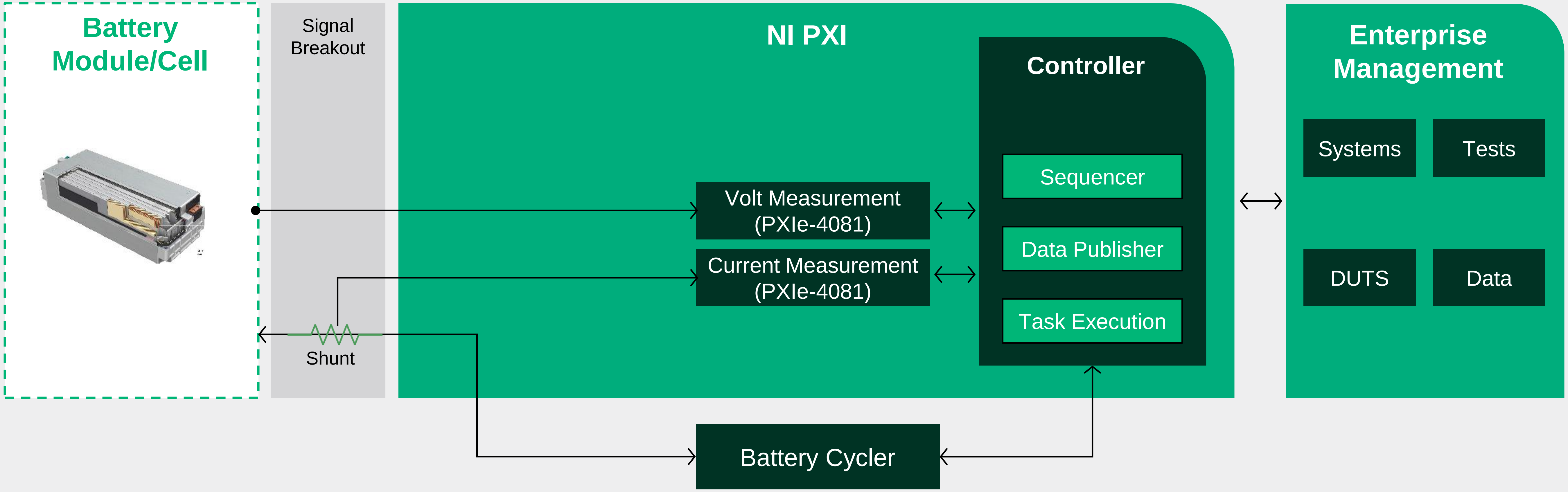


$$DCR = \frac{V_1 - V_2}{I_2 - I_1}$$

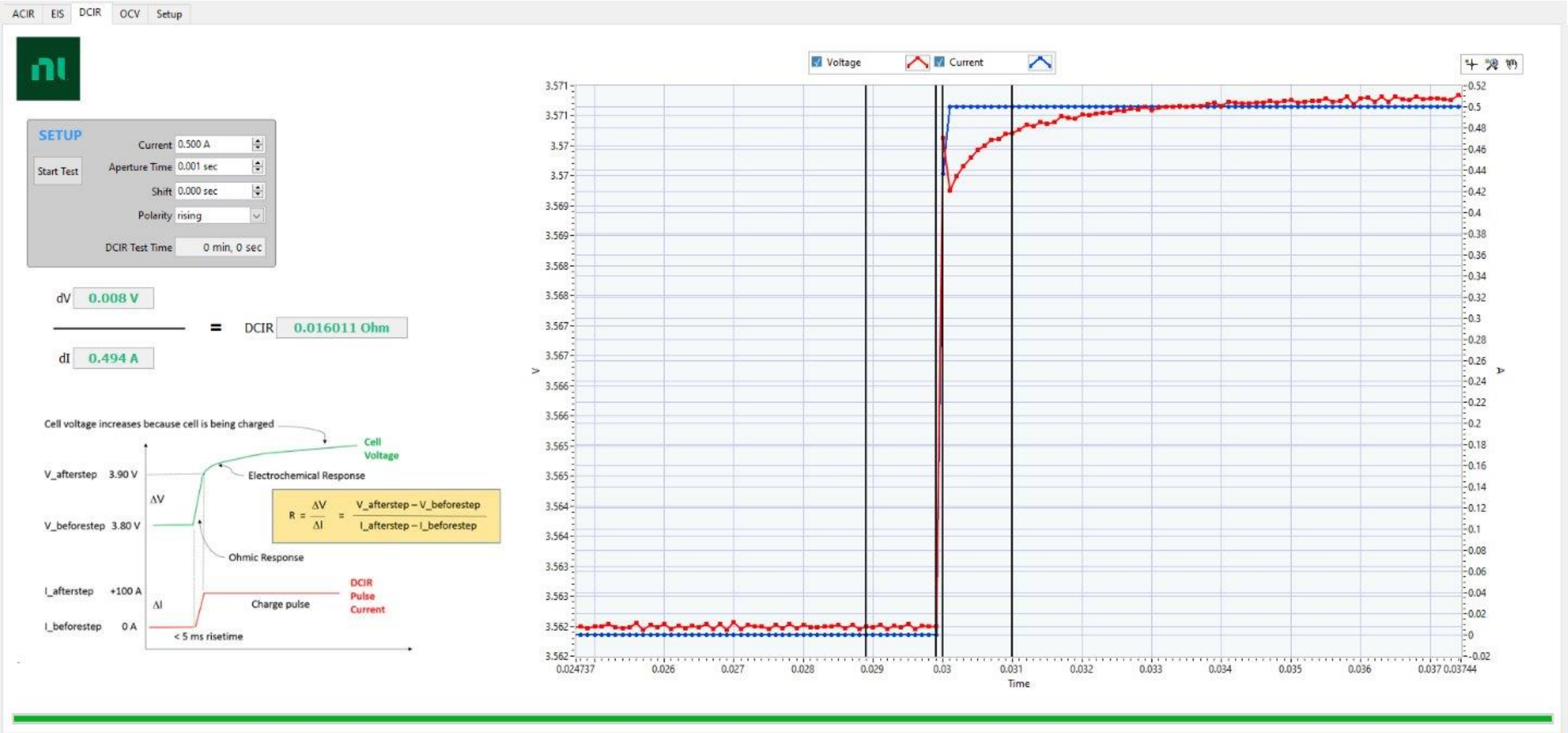


The NI Solution

DC INTERNAL RESISTANCE (DC-IR)



NI Cell Quality Software DC-IR Example



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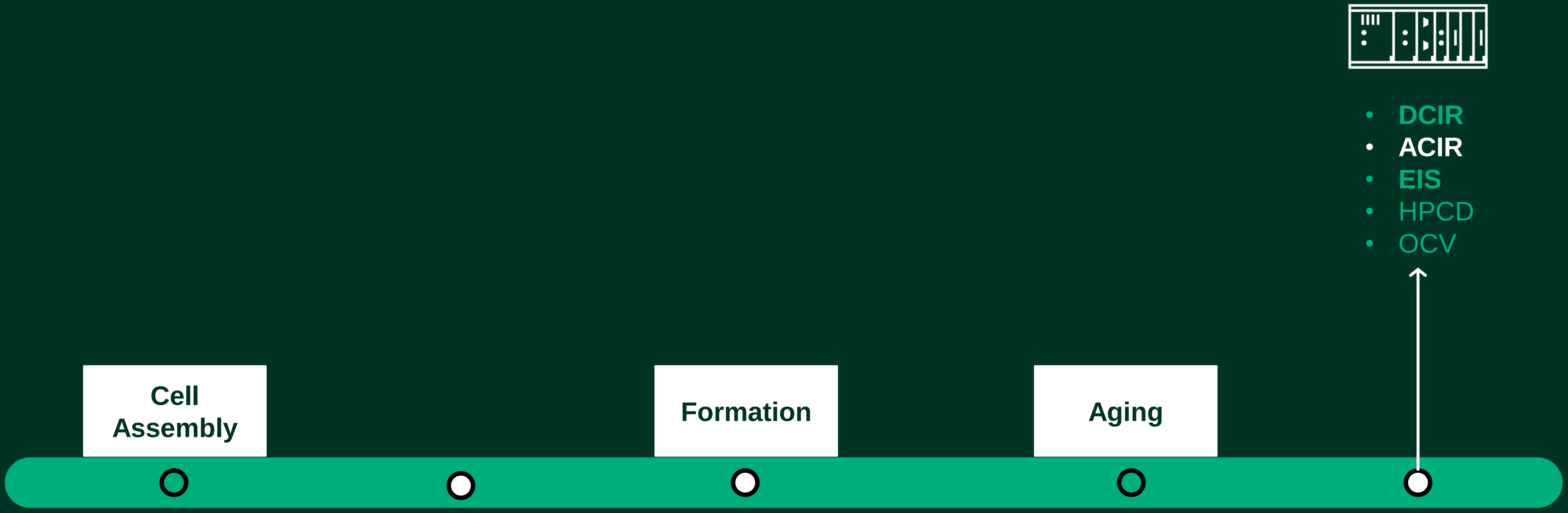
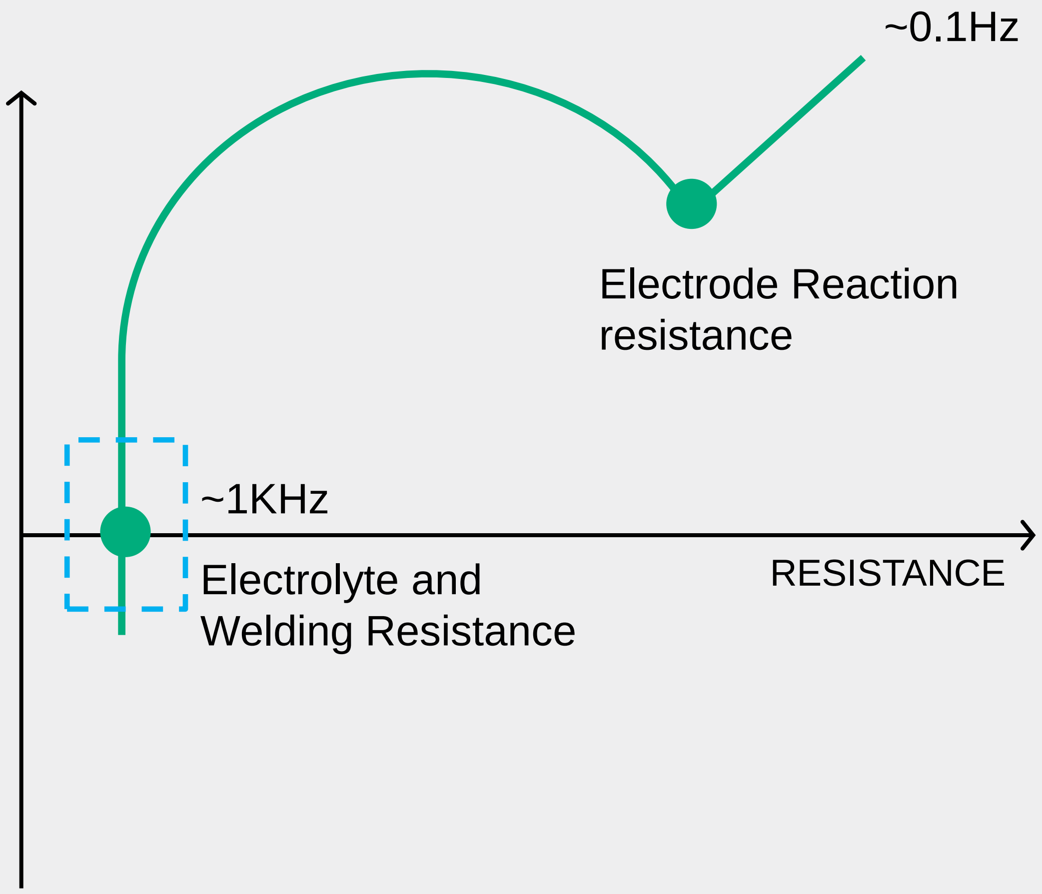
AC Internal Resistance (AC-IR)

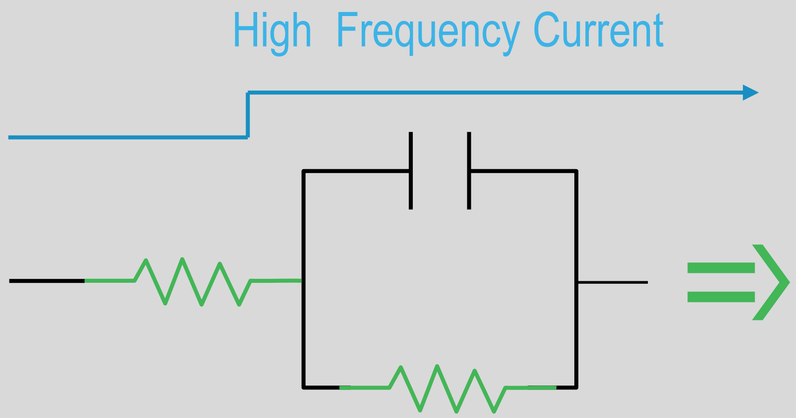


Test Station with NI/Cell Quality Offering Content

Test Process | AC Internal Impedance (AC-IR)

Cole-Cole Plot

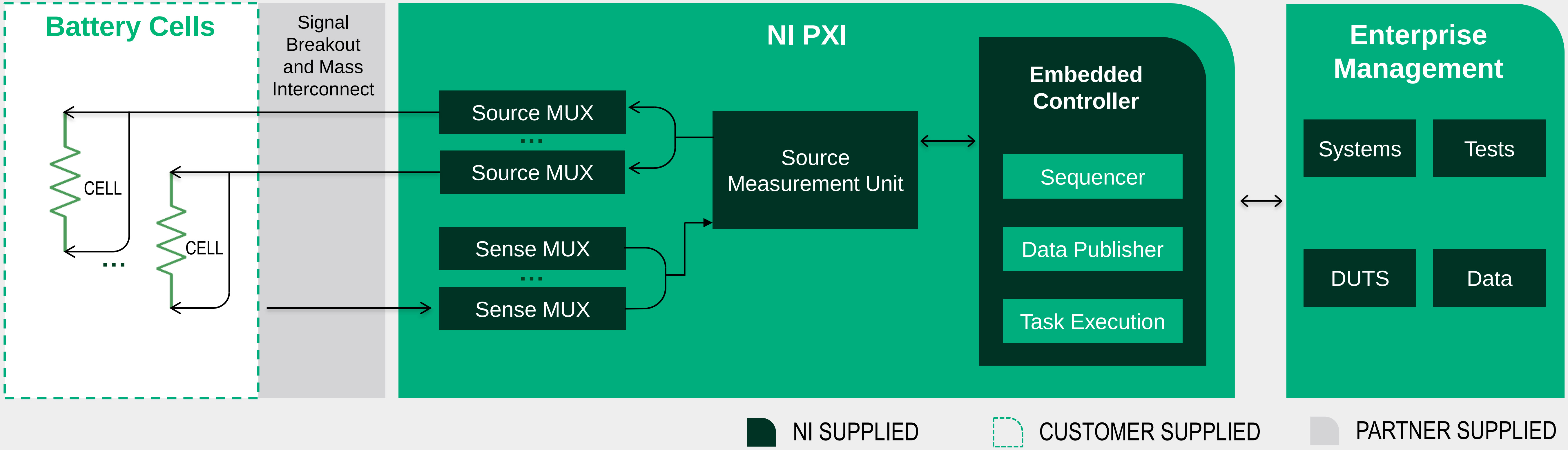




The NI Solution

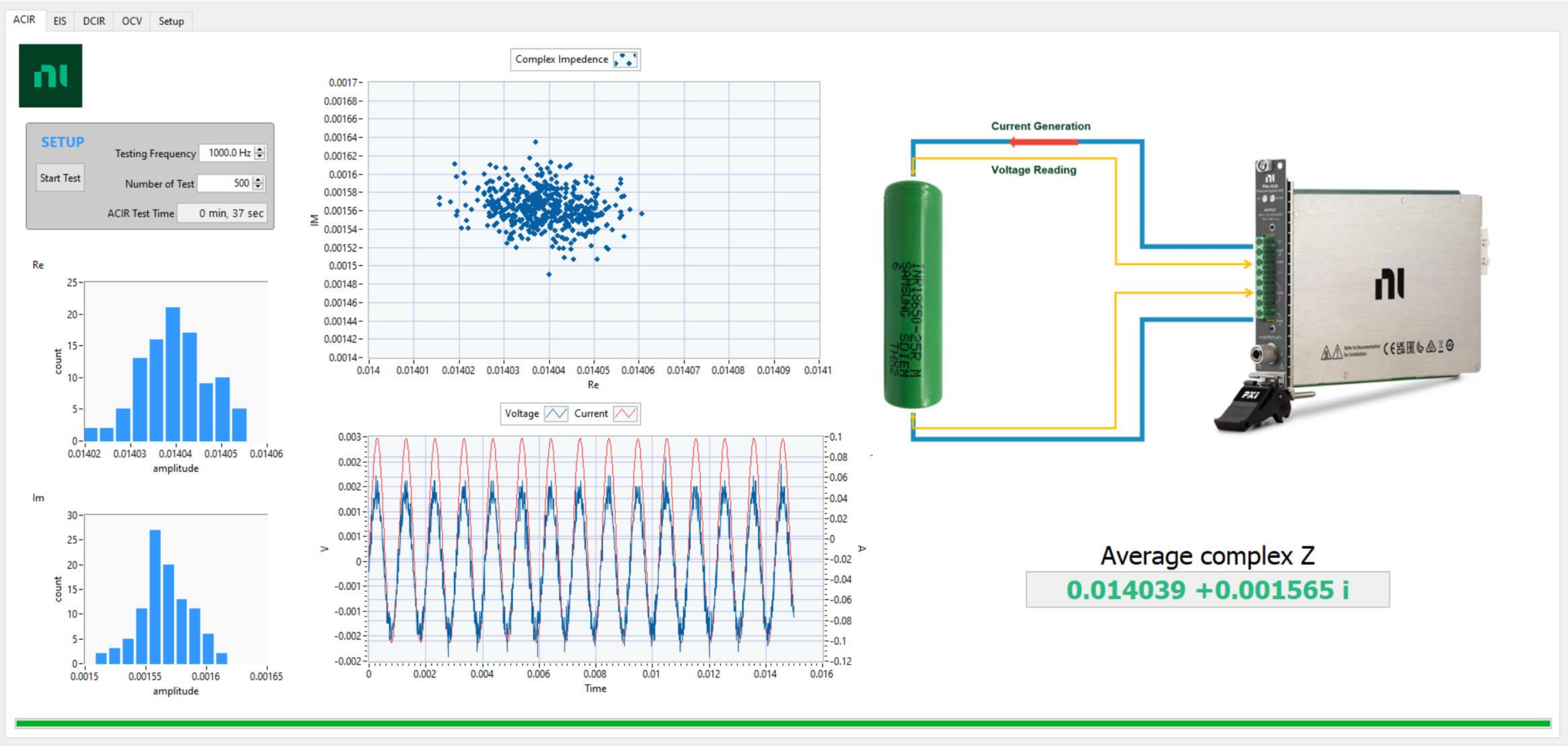
SPECIFICATIONS	
Current	100mA - 2A
Frequency	1kHz
Repeatability	1μΩ
Cycle Time	10 cells/second
Channels	Up to 480 in 3U chassis*

AC INTERNAL RESISTANCE (AC-IR)

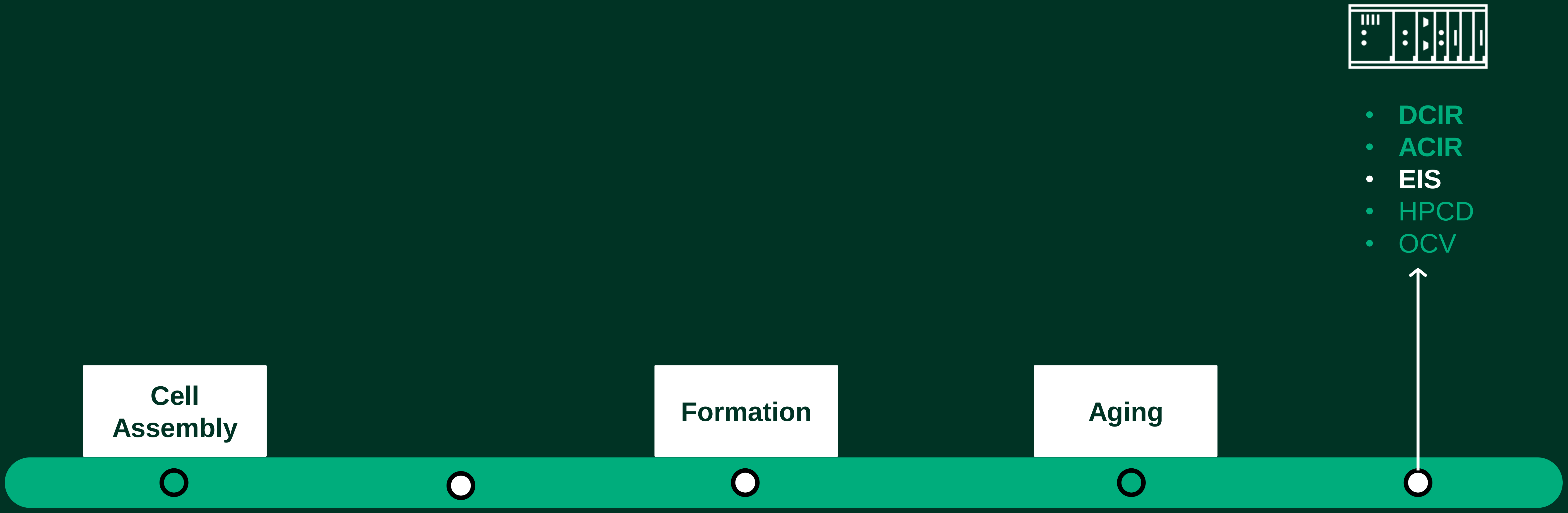


*CAN BE SCALED BASED ON APPLICATION REQUIREMENTS

NI Cell Quality Software AC-IR Example

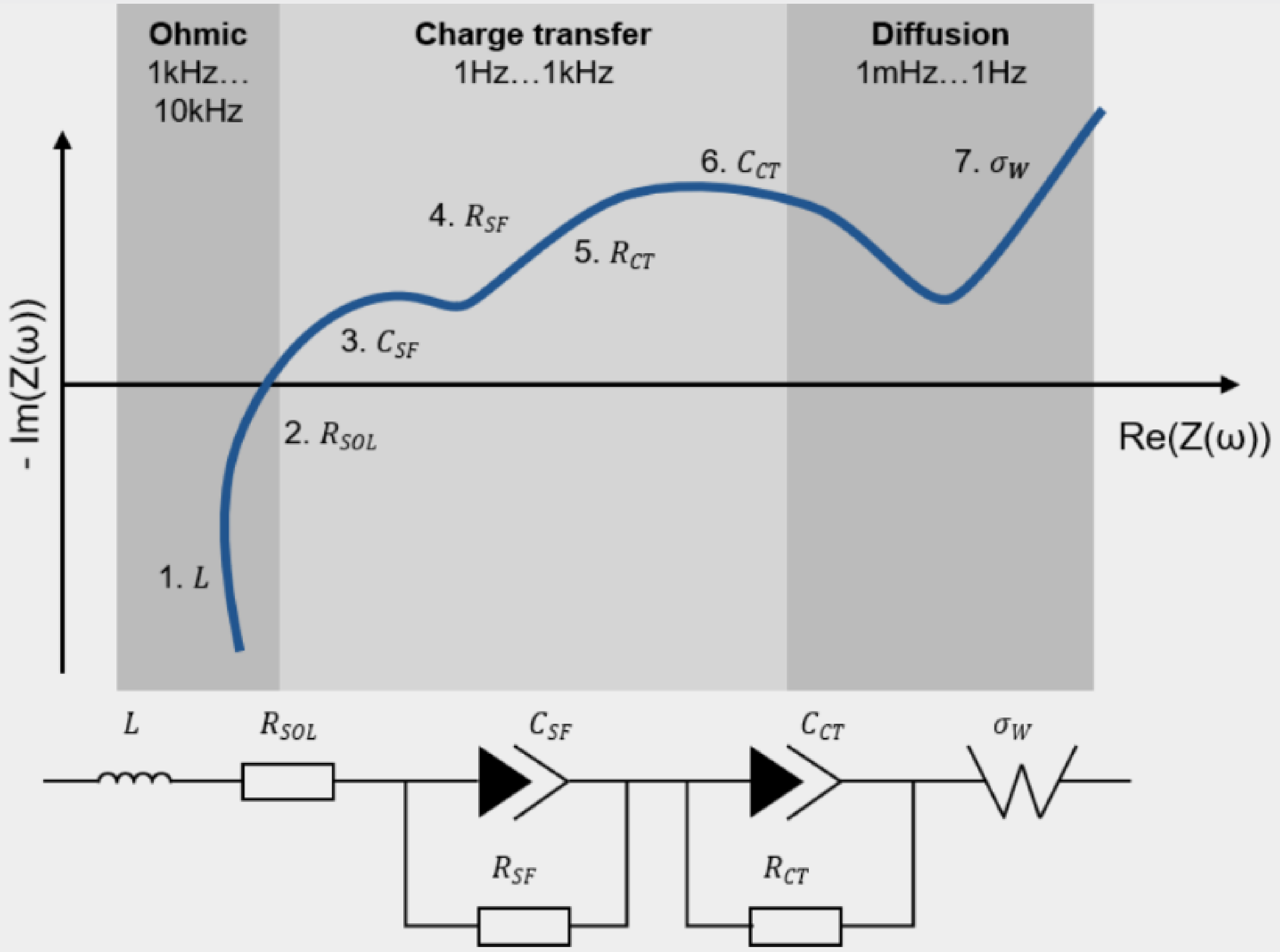


Electrochemical Impedance Spectroscopy (EIS)

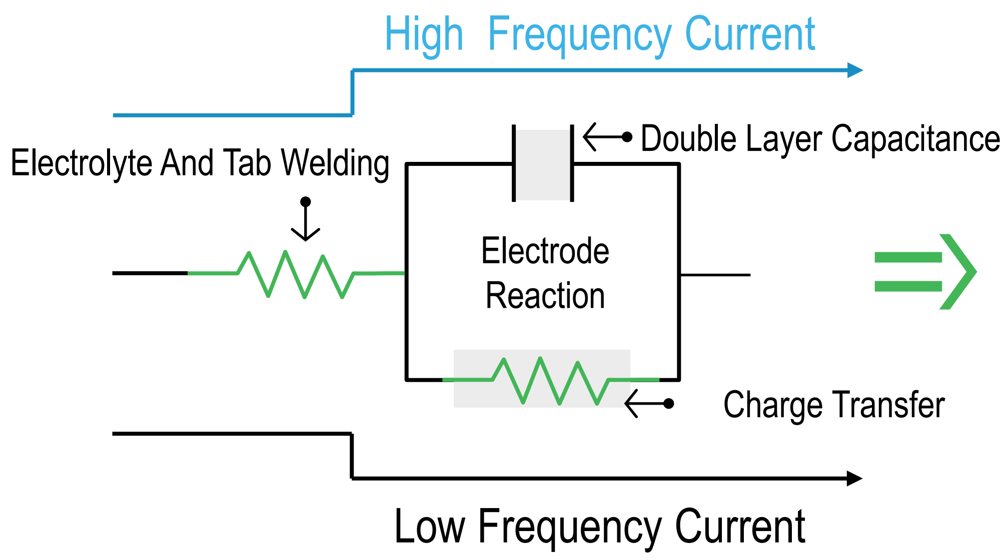


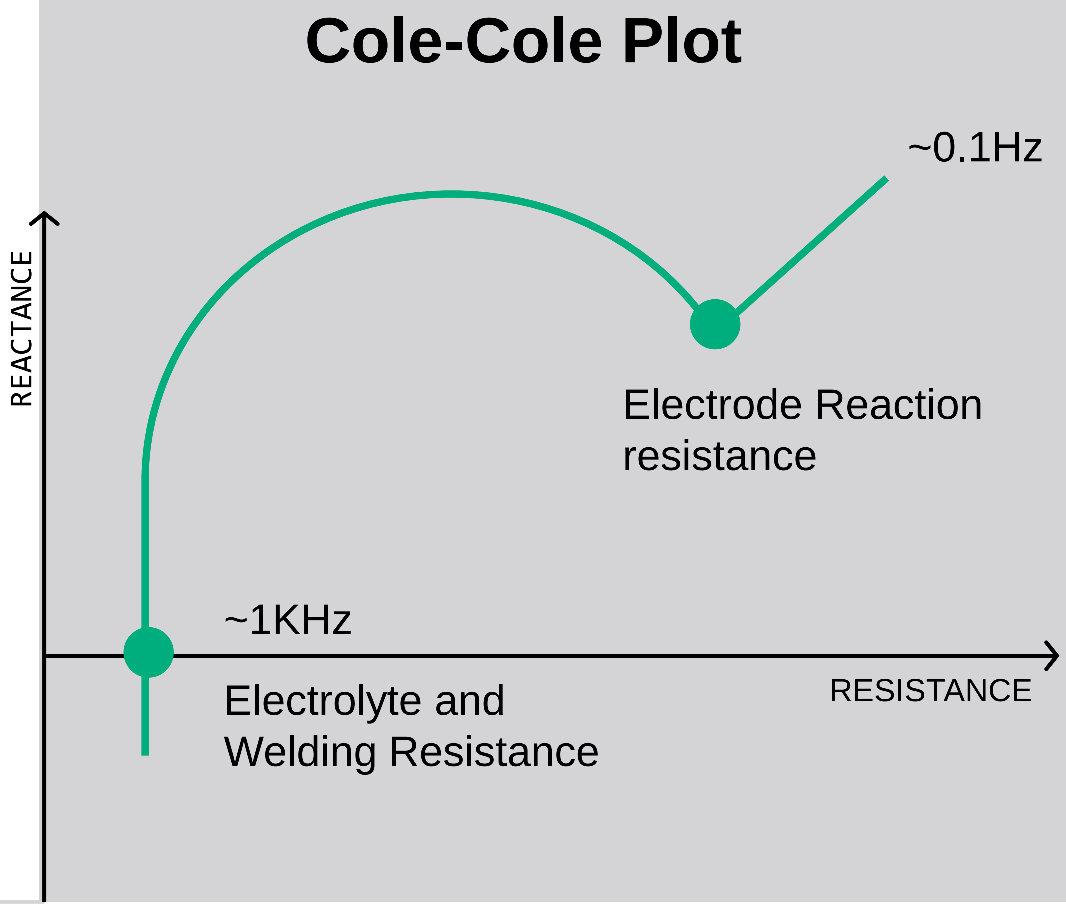
Test Station with NI/Cell Quality Offering Content

Test Data Map to Cell Model



Test Process | EIS

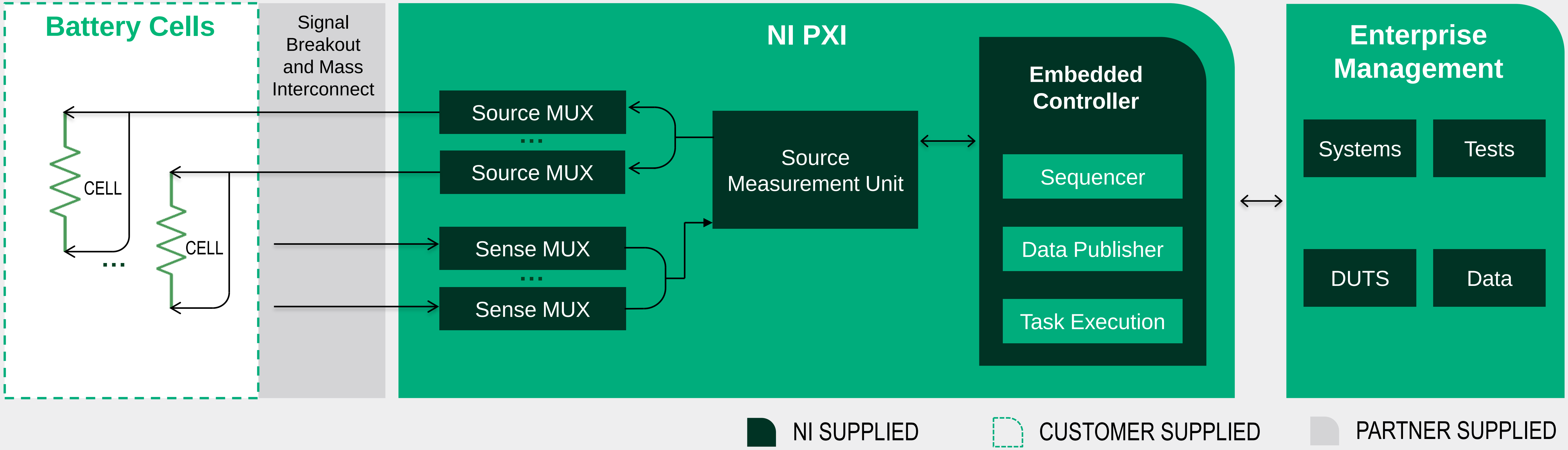




The NI Solution

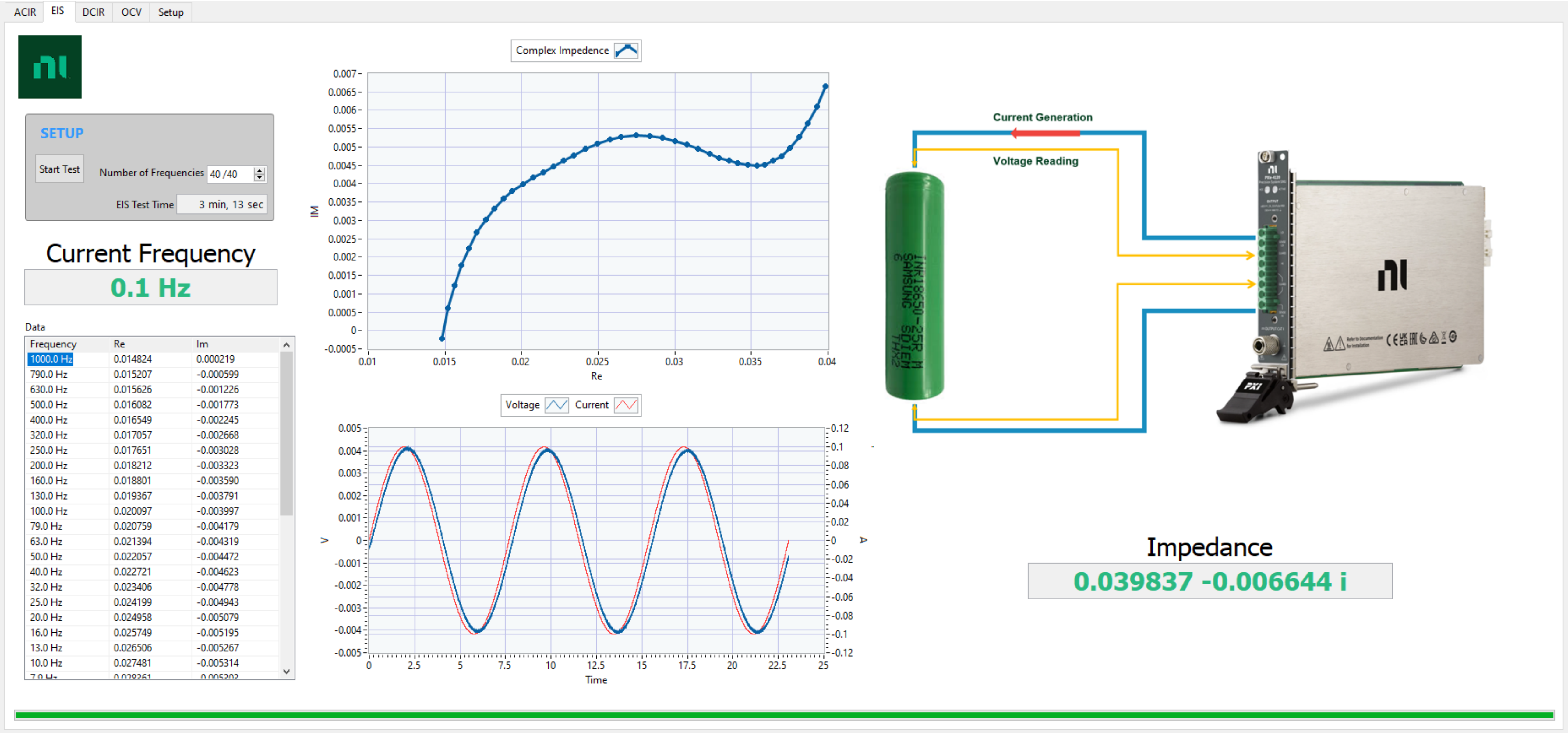
SPECIFICATIONS	
Current	100mA - 2A
Frequency	0.1Hz – 2MHz
Repeatability	1μΩ
Channels	Up to 480 in 3U chassis*

ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY (EIS)



*CAN BE SCALED BASED ON APPLICATION REQUIREMENTS

NI Cell Quality Software EIS Example



Why NI

PXI Solution for Cell Quality and Inspection

Flexibility

Modular, Programmable Hardware

Future-proof systems with reconfigurable hardware that can support various measurements and test techniques

Measurement IP

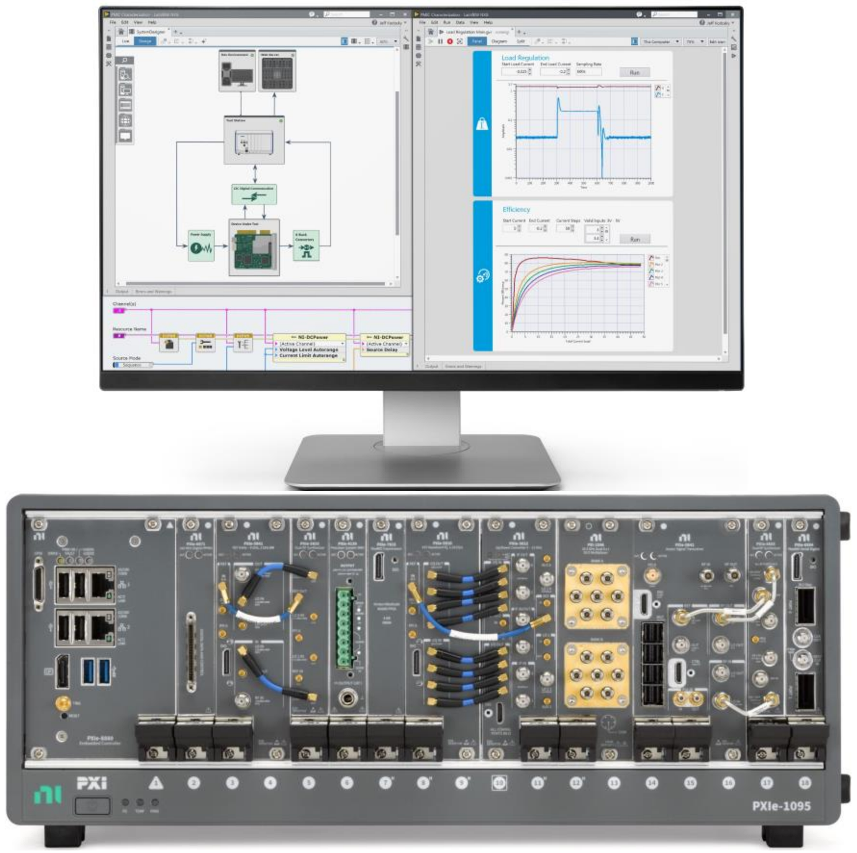
Out-of-the-box Solution

Pre-built IP for advanced battery test techniques, including OCV, ACIR, EIS, HPCD and others

Production Ready

Rugged and Reduced Footprint

Integrate multiple instruments and channel expansion into a single chassis



Software

Systems and Data Management

Integrates with solutions for managing system configuration, remote monitoring, and data aggregation and analysis

Measurement Quality

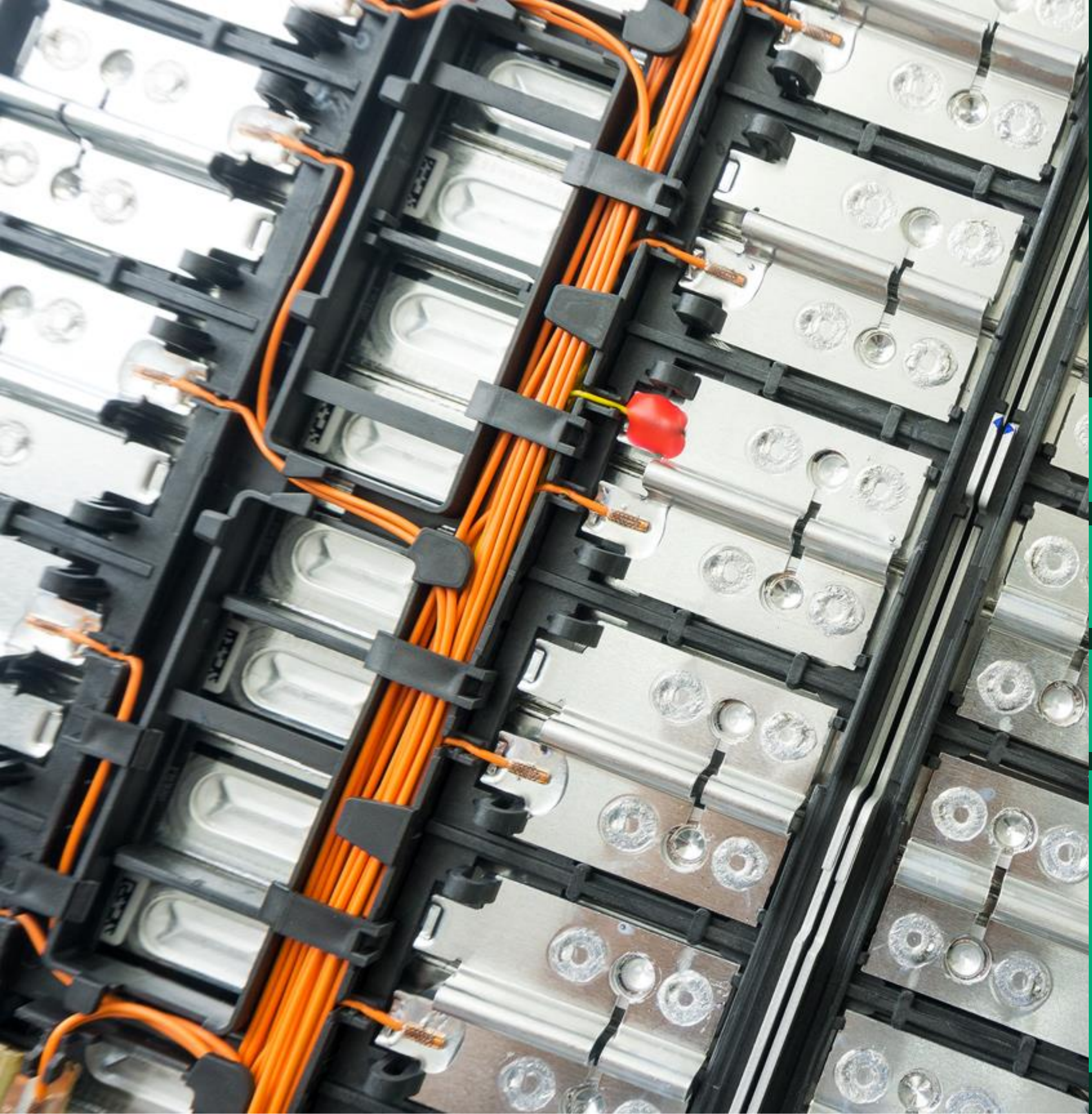
Accuracy and Repeatability

Industry-leader in repeatable and accurate measurements with a wide portfolio enables the right mix of cost and performance

Timing and Synchronization

PXI Chassis

PCI Express Gen 3 throughput up to 24 GB/s, sub nanosecond latency, P2P streaming, integrated triggering



Benefits

Battery Cell Testing

- Cycle Times
- Repeatability
- Performance
- Scalability
- Footprint
- Channel Count

PXI Based Cell Quality Analysis Provides Scalability and Flexibility

Vendor defined functionalities

Open software based solution that enables to integrate customer IP

Traditional Method
Utilize vendor defined analysis methods without access to intermediate data
→difficult to understand battery attributes that require customized analysis

Software-Defined
Cell quality analysis functions provided by NI could be customized by customers.
Can combine data from multiple modules for flexible cell quality analysis
Smaller Footprint

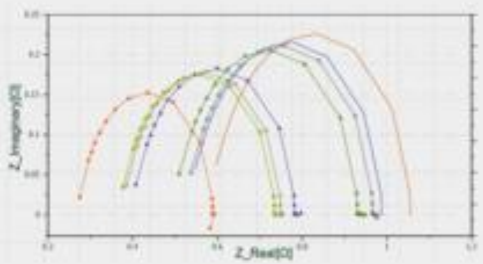
Sample Configuration:

PXIe-4139: ACIR, EIS, Weld Integrity
Optional **PXIe-4190**: high frequency EIS

PXIe-2525 & PXI-2530B: Testing multiple Cells

PXIe-4081: OCV

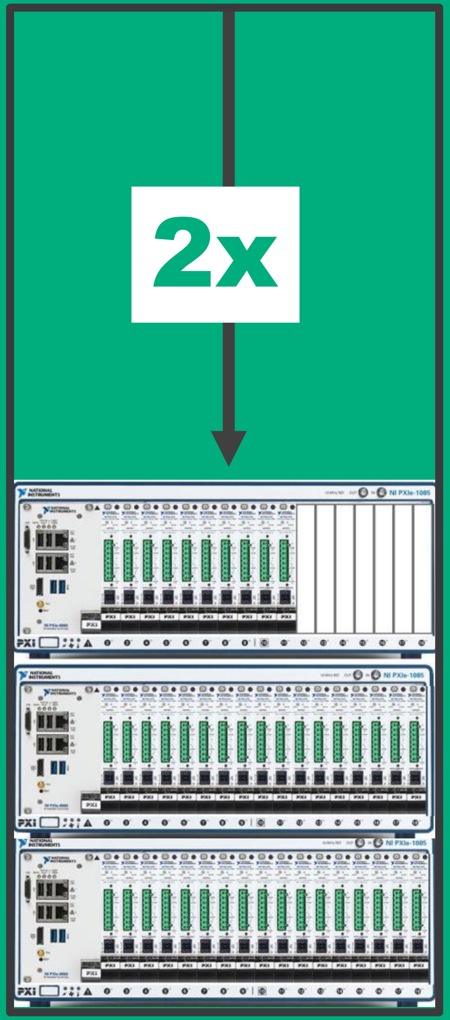
ACIR・EIS



Cole-Cole Plots

What Does 44 SMU Channels Look Like?

Box SMUs



NI 1-ch SMUs

Comparable Power & Specs (Up to 200V, 3A, 40W)

2x Space Savings

Faster Execution

Integration

Low Volume Production/Validation

Test System (DMC-provided)

- **Test Rack**
  - Instruments
  - Controller
  - Software
- **Cell Interface**
  - Fixturing
  - Probes
  - Cabling

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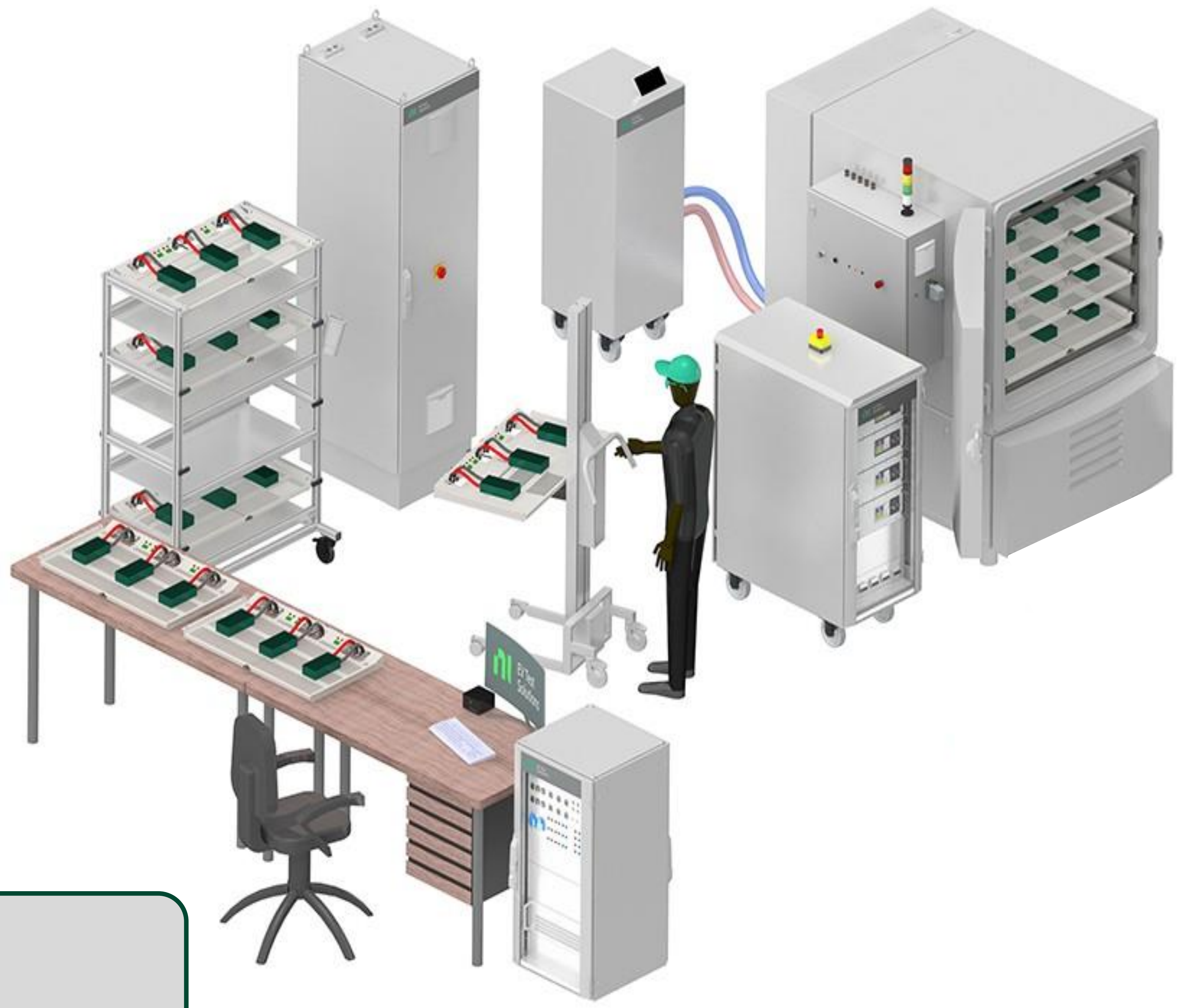
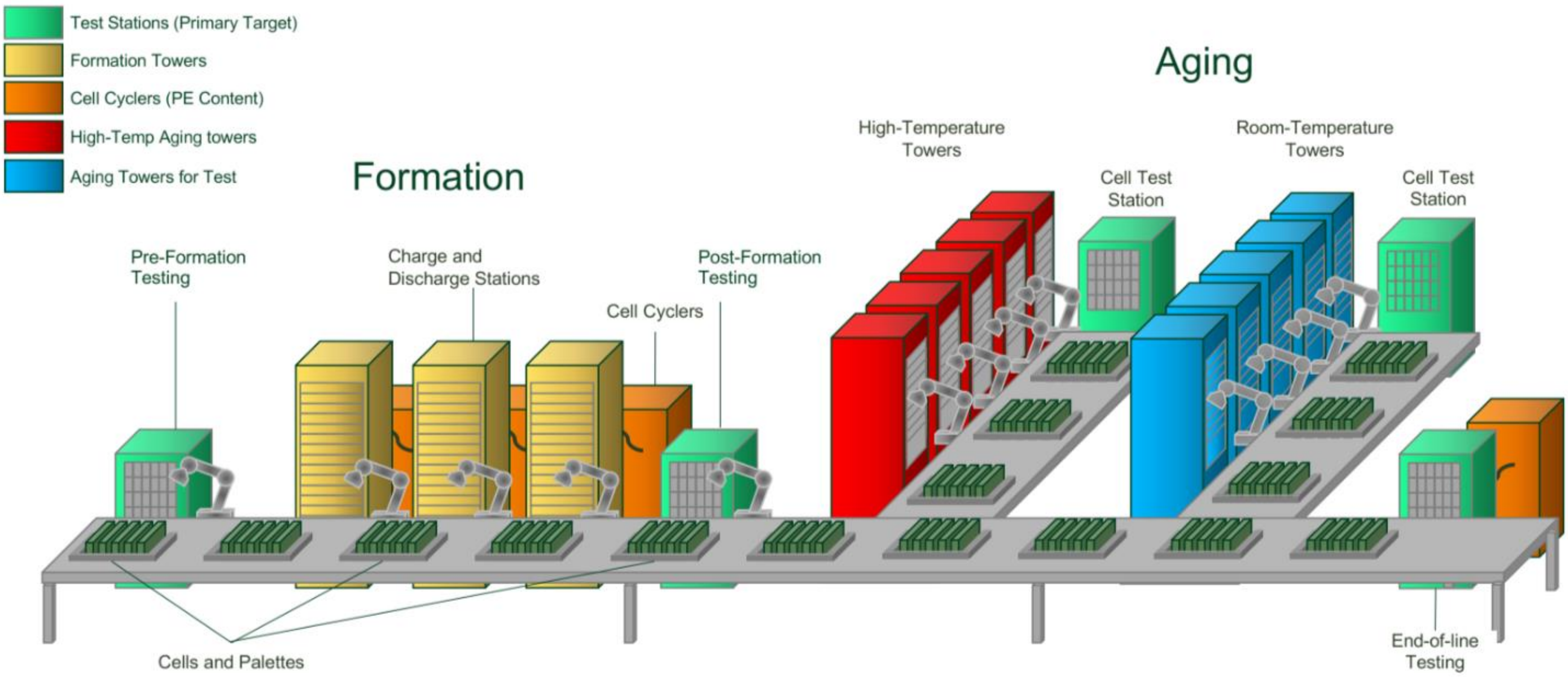
Facility

- Network
- AC Power
- Floor Space



Medium/High Volume Production



Medium/High Volume Production

Test Cell (DMC-provided)

- **Test Rack**
  - Instruments
  - Test Controller + Software
  - PLC + Controls
- **Cell Interface**
  - Fixturing
  - Automated Probes
  - Mechanical Actuation

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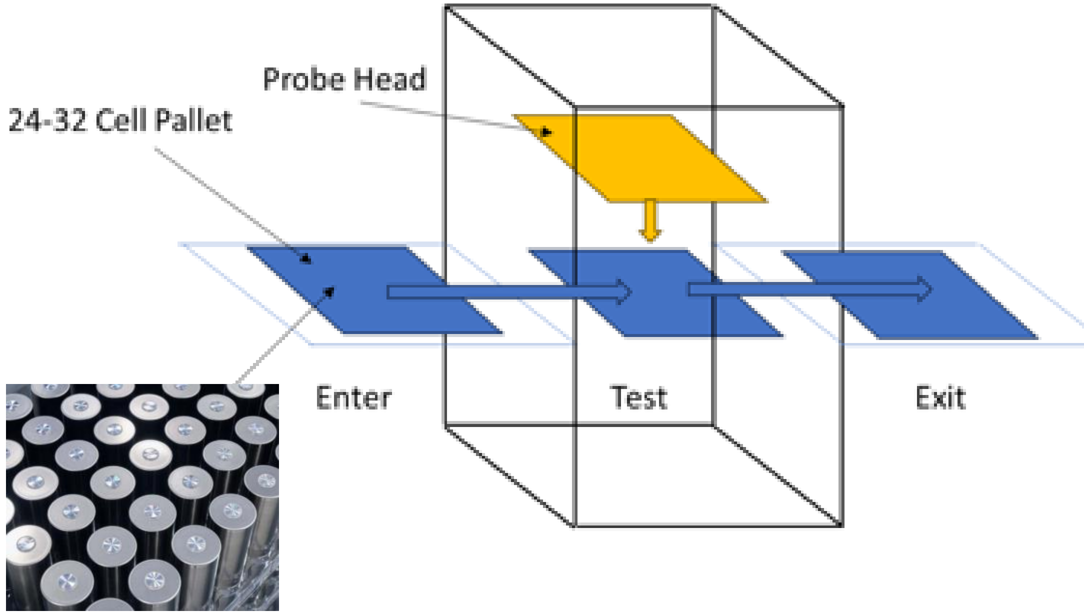
Facility / Production Line Infrastructure

- Network
- AC Power
- Floor Space
- MES
- Material Handling



DMC Service Areas Overview

TEST & MEASUREMENT AUTOMATION

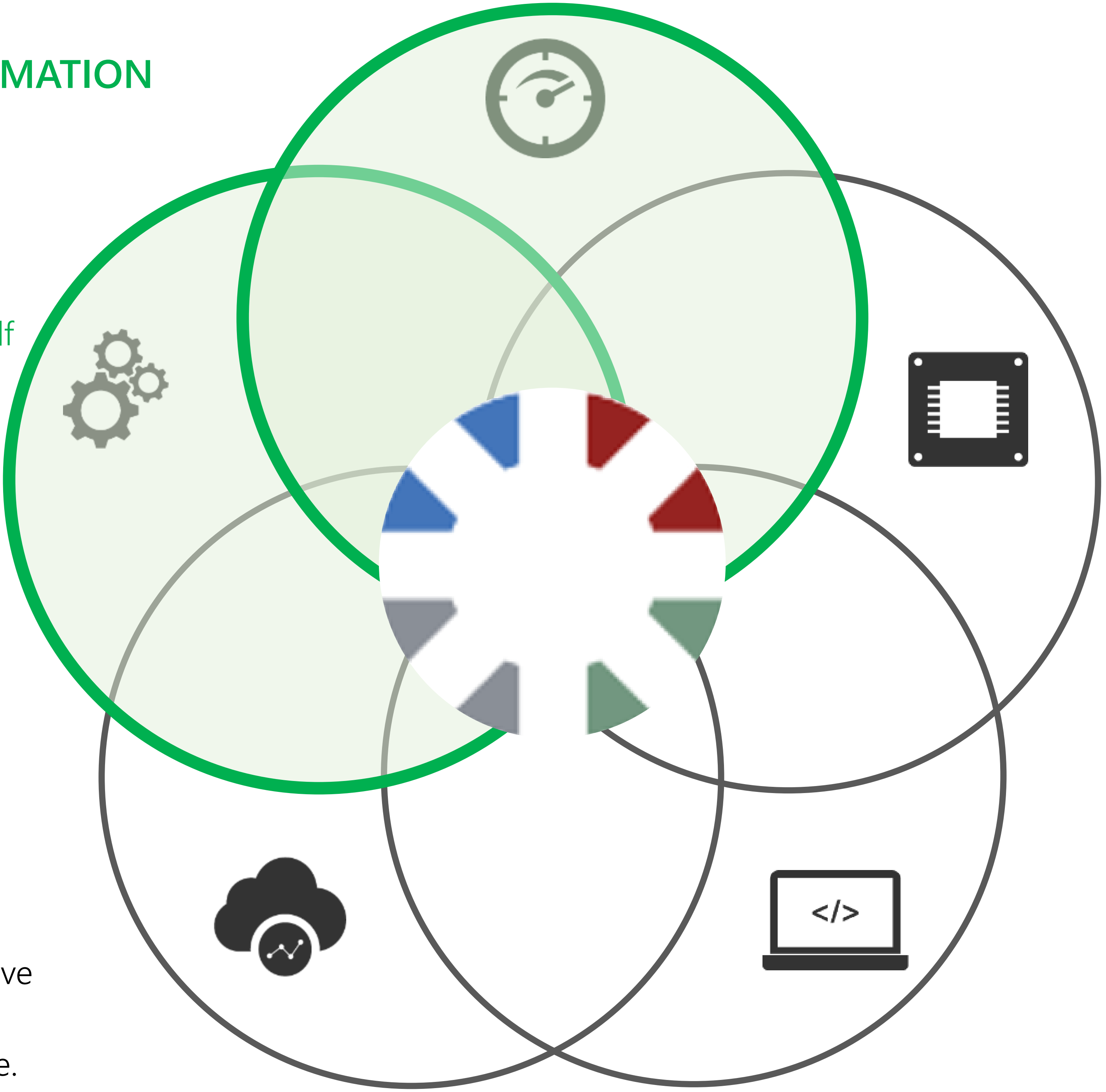
DMC develops software and turnkey systems for automated testing across R&D, validation, production, and field environments using LabVIEW and Python programming and off-the-shelf and custom hardware.

MANUFACTURING AUTOMATION & INTELLIGENCE

DMC programs the systems that keep factory floors running, including PLC, HMI, SCADA, Servos, Robotics and more.

DIGITAL WORKPLACE SOLUTIONS

DMC offers hands-on expertise to organizations that want to take advantage of technologies that improve productivity, communication, and collaboration in their digital workplace.



EMBEDDED DEVELOPMENT & EMBEDDED PROGRAMMING

DMC can help you with your product development needs. Our services include developing intelligent hardware systems from circuit design and custom PC boards to complex embedded systems.

APPLICATION DEVELOPMENT

DMC develops applications that connect to your systems applying intelligent algorithms and structured code including PC apps, web apps, mobile apps, and database driven systems.

DMC Overview

Established in 1996, DMC serves customers worldwide from offices in Chicago, Austin, Boston, Cincinnati, Dallas, Denver, Detroit, Houston, Nashville, New York, Raleigh, San Diego, Seattle, St. Louis, and Washington, D.C.

280+

employees & growing

DMC Certifications and Services

Center of Excellence

Silver Partner
SYSTEMLINK

Silver Partner
SYSTEM INTEGRATION

DEVELOPER
DEVELOPER
INSTRUCTOR
ARCHITECT
ARCHITECT
LabVIEW CHAMPION

- Battery test consulting
- ATE design/development
- Manufacturing integration

csia CERTIFIED

CERTIFIED BY SCB ISO 9001

Device Under Test	R&D / Validation (Functional, HIL, Lifecycle)	Production (EOL)	Warranty / Remanufacturing / Maintenance / Diagnostics
Battery Packs	NI BTS Solution	DMC BPT Solution	DMC BPT Solution
Battery Modules	NI BTS Solution	DMC BPT Solution	DMC BPT Solution
Battery Cells	DMC Validation Test Platform + NI Cell Quality IP	DMC Validation Test Platform + NI Cell Quality IP	DMC Validation Test Platform + NI Cell Quality IP
Battery Management Systems (BMS)	DMC BMS Test Platform	DMC BMS Test Platform	DMC BMS Test Platform

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NI CONNECT

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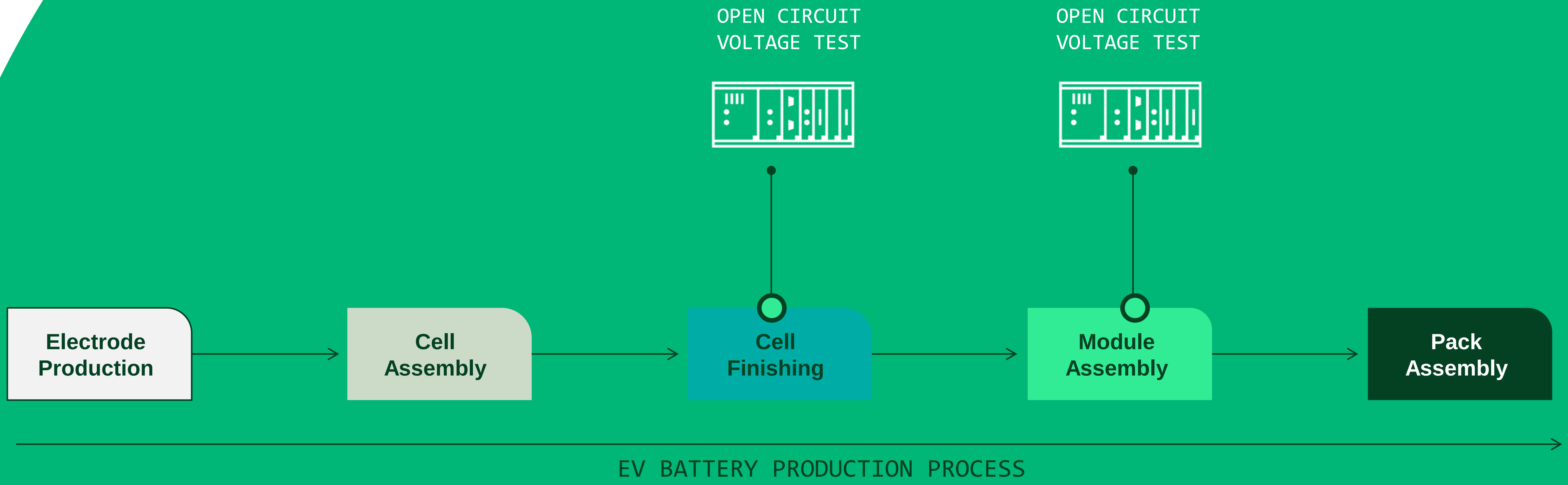
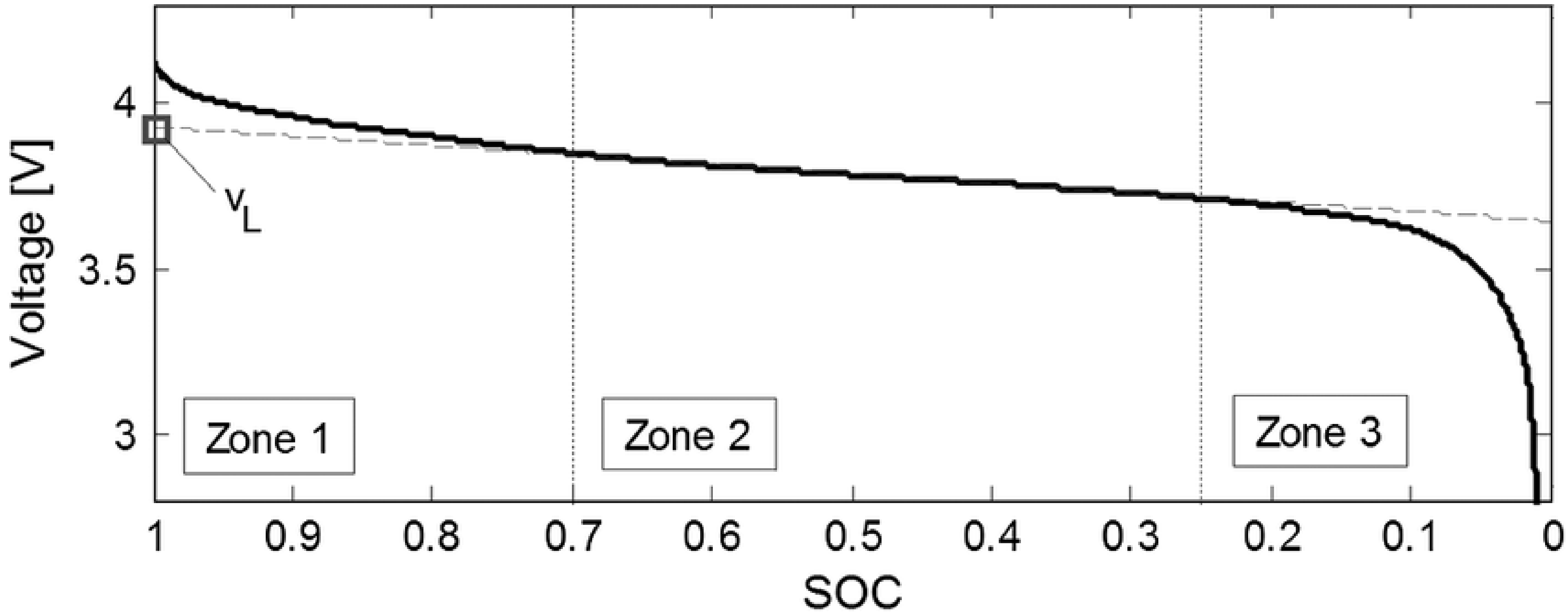
- Partner network that can help with the implementation of the solutions. DMC is one of our partners that has been involved in the battery space for over a decade, We have done a lot of work with DMC in the battery cell ,module and pack.

No-Defect Type	Specific Defect	OCV	ACIR	EIS (<1kHz)	EIS (>1kHz)	HPCD (pouch only)	Leakage Test	Weld Test
Internal shorts	Torn tab	Maybe	Maybe	Maybe	Yes		Maybe	No
	Torn separator	Maybe	Maybe	Maybe	Yes		Maybe	No
	Folded separator	No	Maybe	Maybe	Yes		Maybe	No
	Dendrites	Maybe	Maybe	Maybe	Yes		Maybe	No
	Internal shorting	Yes	Maybe	Maybe	Yes		Maybe	No
	Internal contamination	No	Maybe	Maybe	Yes		Maybe	No
Welds	Bad tab weld	Maybe	Maybe	Maybe	Yes		No	Yes
	Bad fuse weld	Maybe	Maybe	Maybe	Yes		No	Yes
After Electrolyte is added	Over/under-lithiation	No	Maybe	Yes	Yes		No	No
	Graphite slurry defect	No	Maybe	Yes	Yes		No	No
	Electrolyte additive mixture defect	No	Maybe	Yes	Yes		No	No
	Improper wetting	No	Maybe	Yes	Yes		No	No
	SEI composition and distribution	No	Maybe	Yes	Yes		No	No
	Cell formation recipe assessment	No	Maybe	Yes	Yes		No	No

BACKUP and REFERENCE SLIDES FROM THIS POINT ONWARDS

Open Circuit Voltage (OCV)

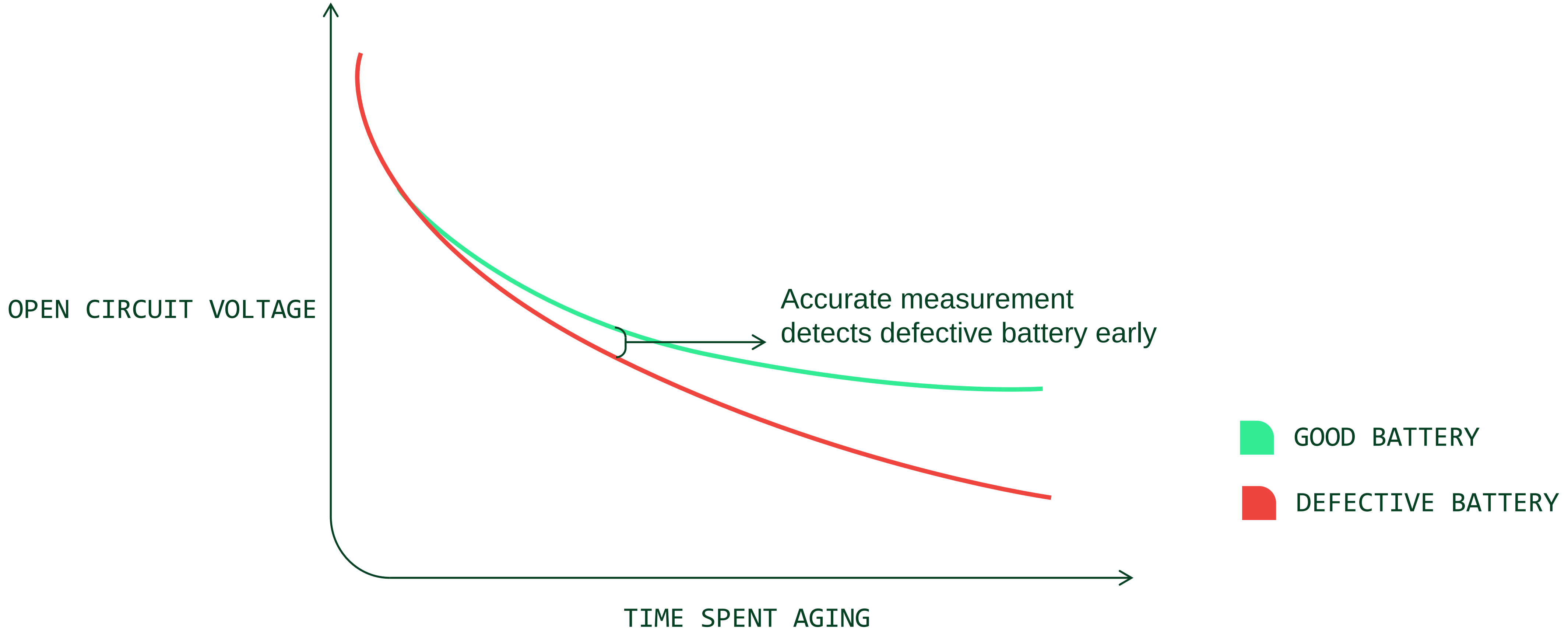




Voltage [V]
4
3.5
3
v_L
Zone 1
Zone 2
Zone 3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
SOC

Test Challenge

Detect micro-shorts that occur during cell aging process by monitoring OCV variation



Defective battery OCV changes gradually with time, accurate measurements are essential to early fault detection

REQUIREMENTS

Low Voltage

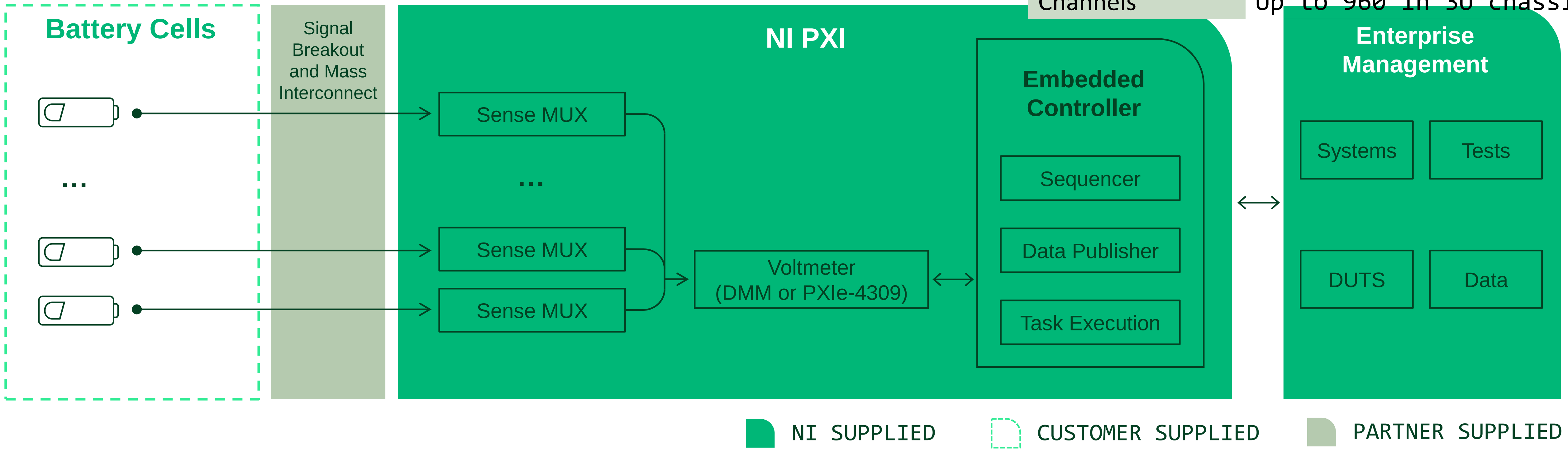
High Repeatability

Fast Cycle Times

The Solution

OPEN CIRCUIT VOLTAGE (OCV)

SPECIFICATIONS	
Voltage	Up to 1000V
Resolution	18-28 bits (sample rate dependent)
Repeatability	Up to 500nV
Cycle Time	Up to 10 cells/second
Channels	Up to 960 in 3U chassis*



BENEFITS

- Cycle Times
- Repeatability
- Scalability
- Footprint

*can be scaled based on application requirements

Screen grab of OCV Demo

ACIR | EIS | DCIR | OCV | Setup

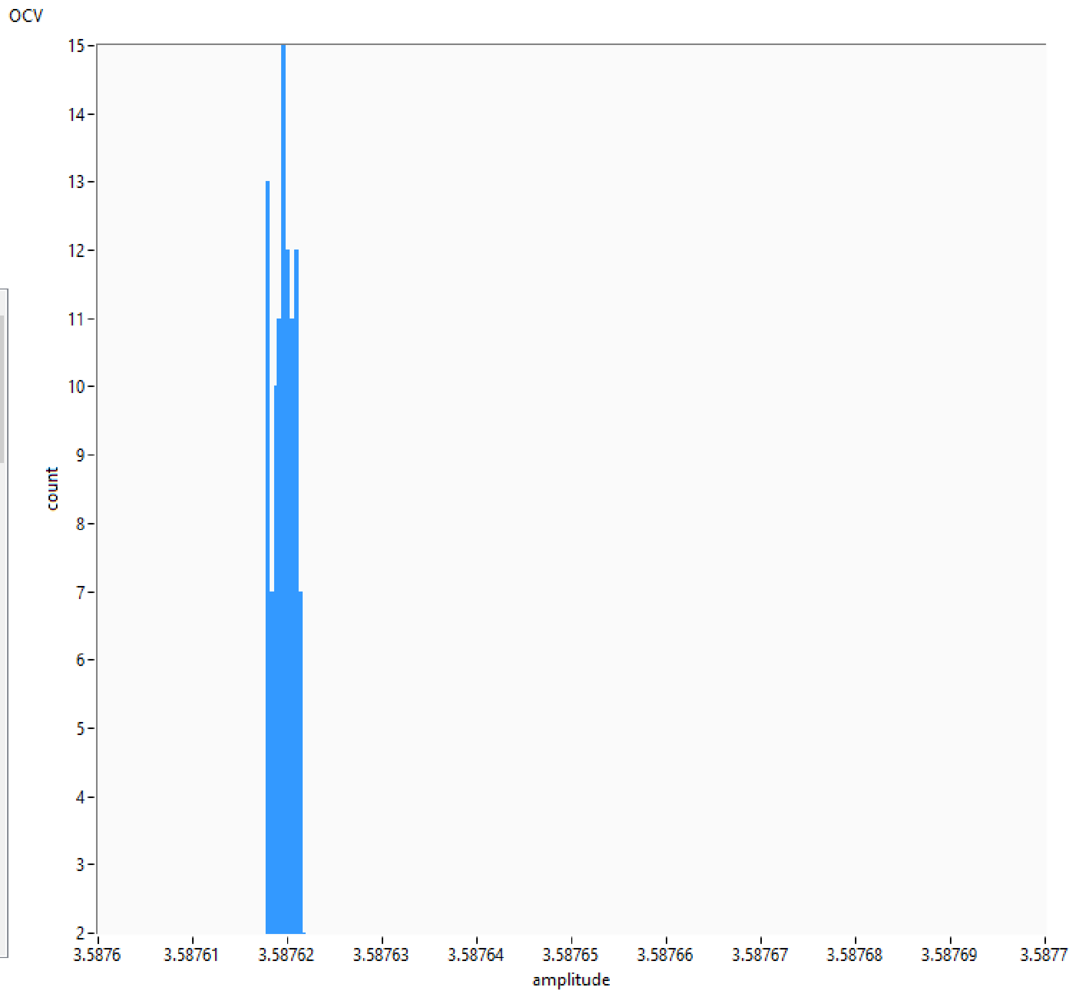
SETUP

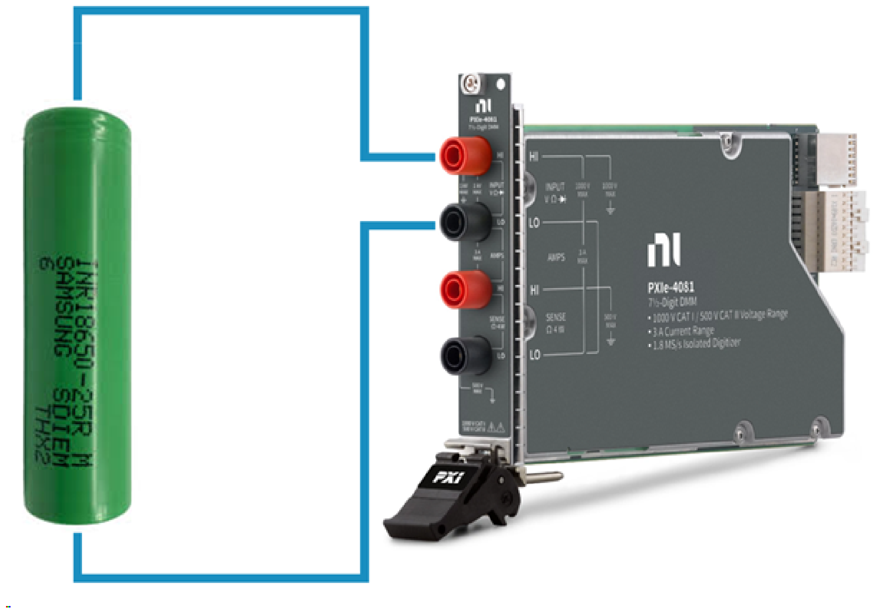
Start Test Number of reading 100

OCV Test Time 1 min, 54 sec

Data

Reading	OCV	STD
test: 0	3.587618 V	0.000 uV
test: 1	3.587618 V	0.103 uV
test: 2	3.587618 V	0.206 uV
test: 3	3.587618 V	0.231 uV
test: 4	3.587618 V	0.199 uV
test: 5	3.587619 V	0.323 uV
test: 6	3.587618 V	0.299 uV
test: 7	3.587618 V	0.280 uV
test: 8	3.587618 V	0.287 uV
test: 9	3.587618 V	0.292 uV
test: 10	3.587618 V	0.278 uV
test: 11	3.587618 V	0.275 uV
test: 12	3.587618 V	0.265 uV
test: 13	3.587618 V	0.263 uV
test: 14	3.587618 V	0.246 uV
test: 15	3.587619 V	0.280 uV
test: 16	3.587618 V	0.277 uV
test: 17	3.587618 V	0.275 uV
test: 18	3.587618 V	0.262 uV
test: 19	3.587618 V	0.250 uV
test: 20	3.587618 V	0.244 uV
test: 21	3.587619 V	0.269 uV
test: 22	3.587619 V	0.330 uV
test: 23	3.587619 V	0.344 uV
test: 24	3.587619 V	0.350 uV





Mean OCV

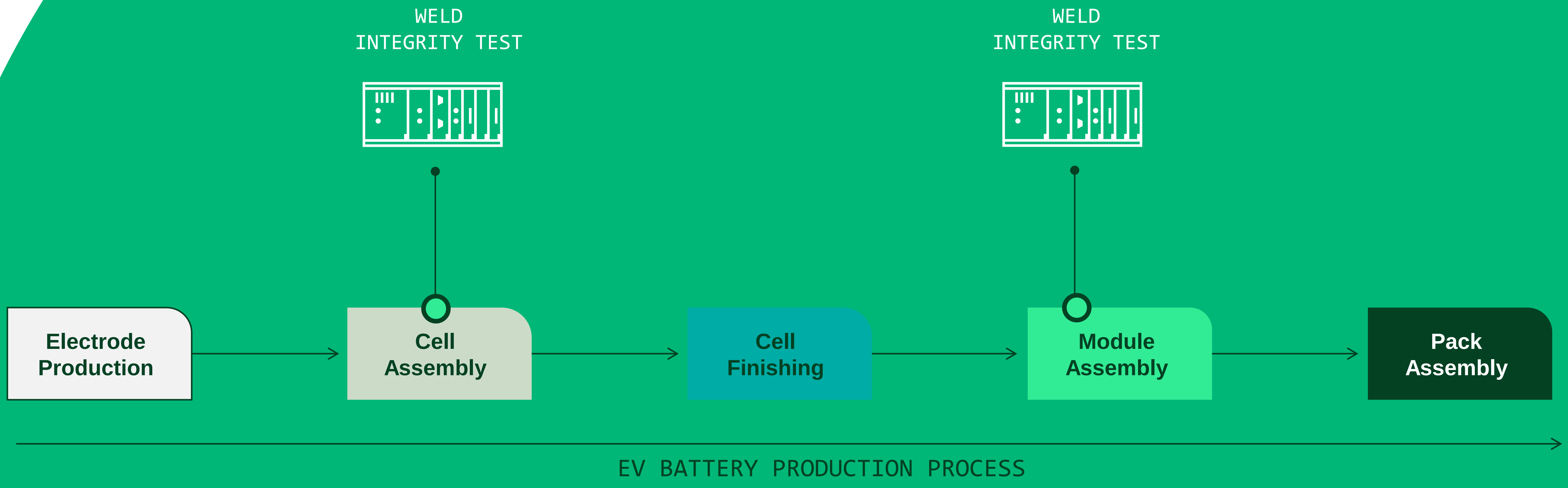
3.587620 V

Standard Deviation

1.089 uV

ni.com

Laser Weld Integrity Test



Test Challenge

Confirm weld seam quality by measuring resistance

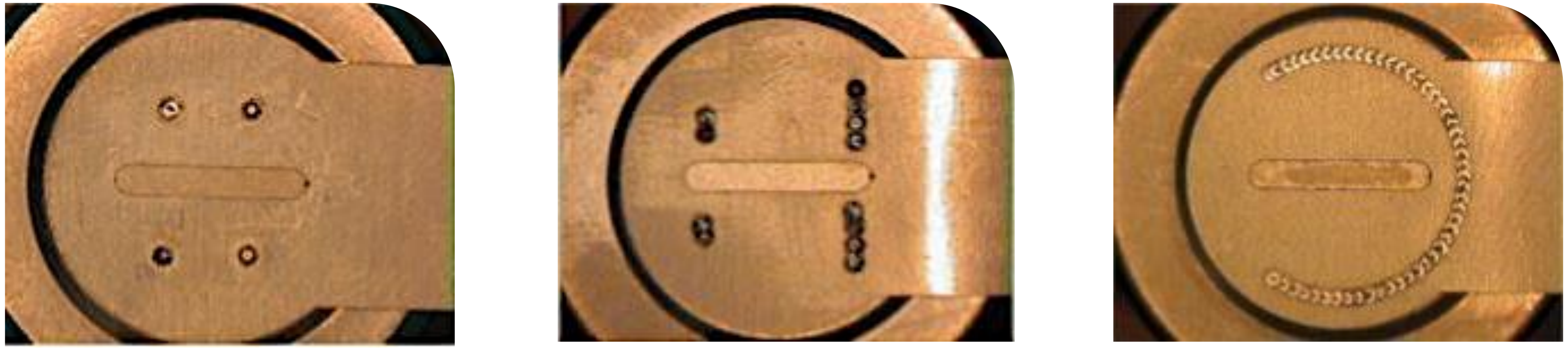


IMAGE SOURCE:
Manufacturing Tomorrow: New Laser Sources Improve Battery Performance by Enabling dissimilar Metal Joining

REQUIREMENTS

μΩ Resistance

nΩ Repeatability

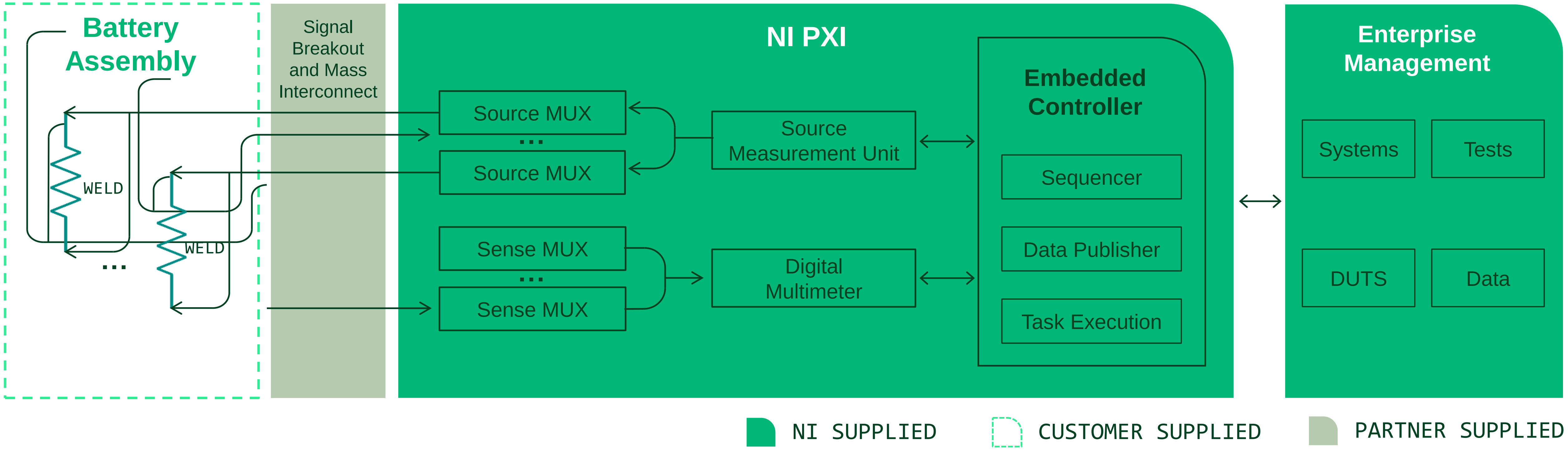
High Speed

Precise Control

The Solution

LASER WELD INTEGRITY

SPECIFICATIONS	
Current	100mA - 2A
Range	1µΩ - 10µΩ
Cycle Time	20 - 100 welds/second
Channels	Up to 350 in 3U chassis*
Isolation	150V



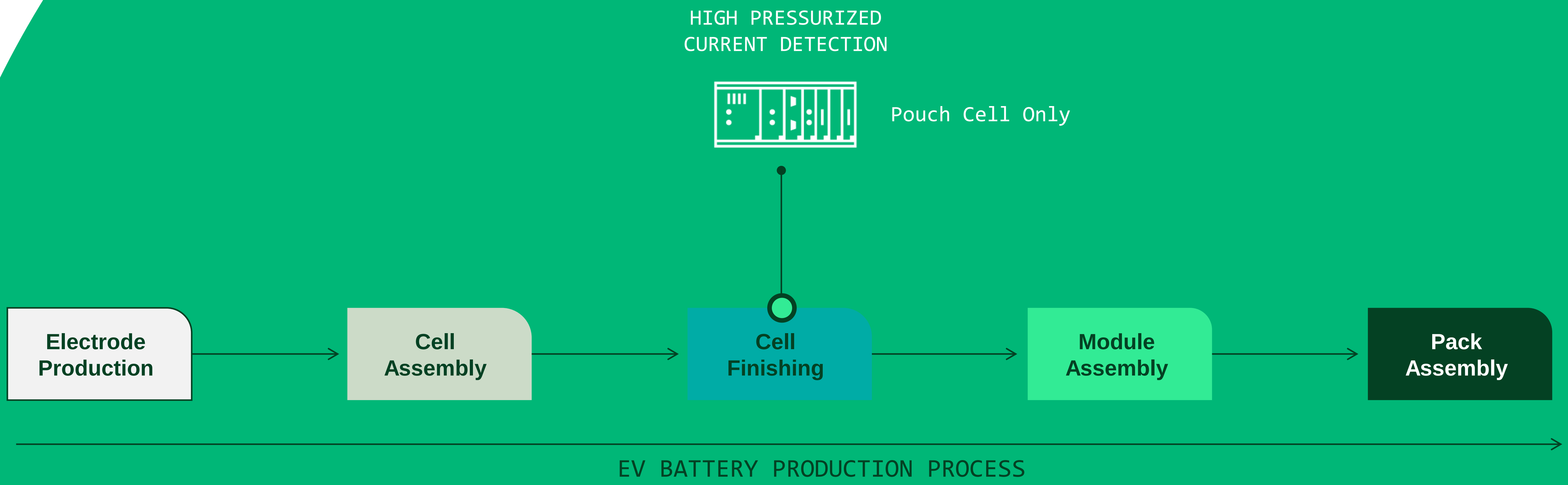
BENEFITS

Cycle Times | Repeatability | Scalability | Footprint

*can be scaled based on application requirements

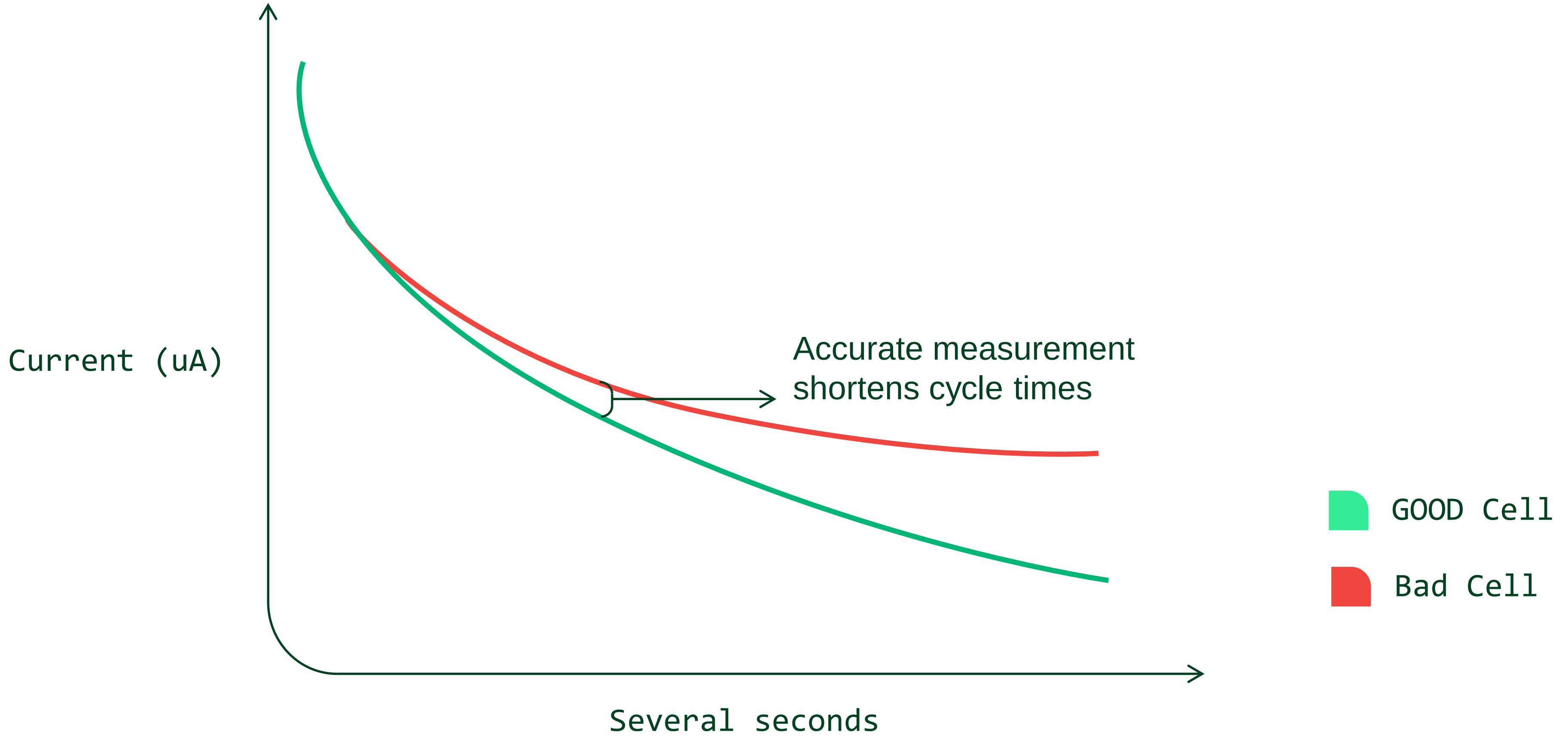
Screen grab of Laser Weld Integretiy Demo

High Pressurized Current Detection (HPCD)



Test Challenge

Detect bad cells after applying high pressure by monitoring current variation in a short time



Defective battery current changes in few seconds, accurate measurements are essential to shorten cycle times

REQUIREMENTS

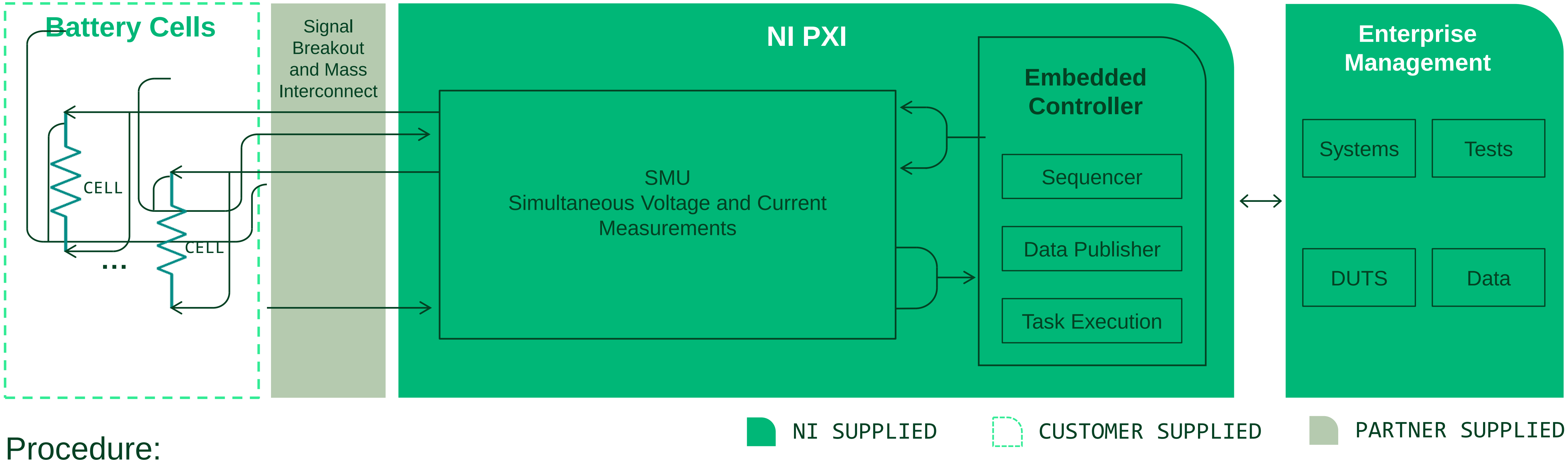
Current Accuracy

High Repeatability

Fast Cycle Times – few minutes to few seconds

The Solution

High Pressurized Current Detection (HPCD)



Procedure:

- Measure OCV in Constant Current Mode
- Change Pin State to Constant Voltage Mode by setting the voltage to OCV + few uV
- Measure and Monitor Current on a cell for few seconds
- Judge Pass and Fail

BENEFITS

Cycle Times	Repeatability	Scalability	Footprint

Vision for Serving the Battery Test Workflow

We combine best-in-class measurement hardware, power electronics, software, and advanced data modelling techniques to deliver disruptive test solutions that significantly reduce the cost of test and enable auto manufacturers to accelerate their transition to electric vehicles.

RESEARCH and DEVELOPMENT | VALIDATION | PRODUCTION

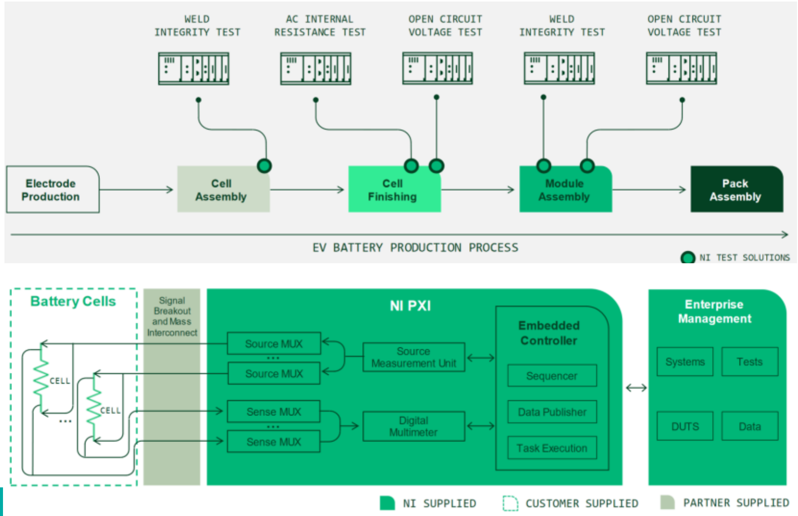
SW/HW Development → Virtual Test → Prototyping → Component Characterization → Durability → System Integration → Road Test → Process Tests → End of Line Test

Open and Flexible Solution Stack

Research and Validation Labs

- Data Analytics
- Data & Systems Management
- Test Software (Control/Sequencing)
- Control System (Comms, Measurements, Safety)
- Power Electronics
- Lab/Line Infrastructure
- Connectivity and Fixturing
- Commissioning, Operation, Maintenance

Production Test Stations



Connected workflow

Increase Productivity | *Deepen System Insight* | *Lower Total Cost of Test*

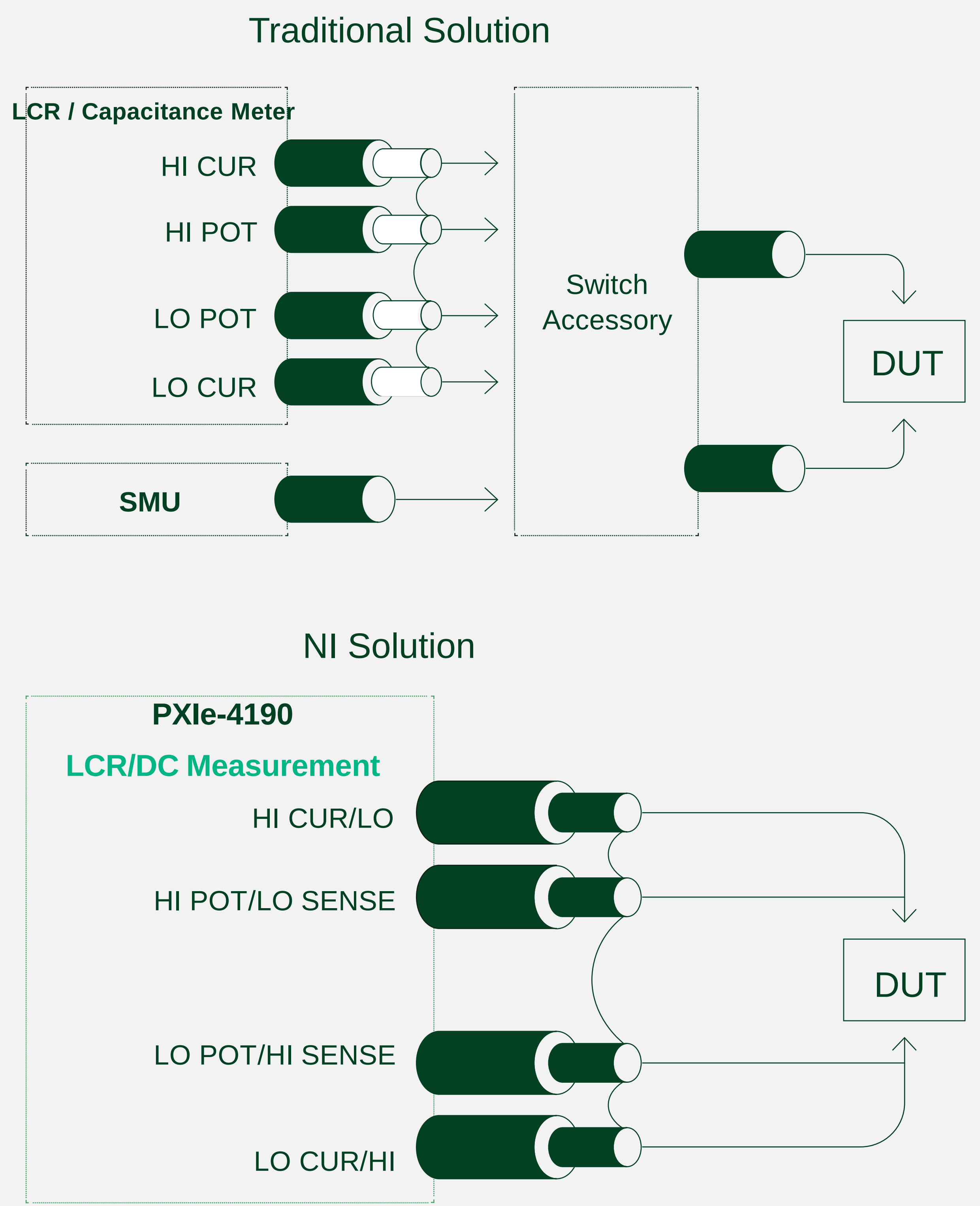
NI Cell Quality | PXI Bundles

Pre-Configured Systems

<table>
<tr><th>MEASUREMENT CAPABILITES</th><th>Part Number: 866575-10B</th><th>Part Number: 866575-11B</th><th>Part Number: 866575-18B</th></tr>
<tr><td>Open Circuit Voltage (OCV)</td><td colspan="3">PXIe- 4081 DMM (1000V, 7 ½ DIGIT)</td></tr>
<tr><td>AC Internal Resistance (AC-IR)</td><td colspan="3" rowspan="2">PXIe-4139 SMU (60V, 1A)</td></tr>
<tr><td>Electrochemical Impedance Spectroscopy (EIS) – Low Frequency</td></tr>
<tr><td>Electrochemical Impedance Spectroscopy (EIS) – High Frequency</td><td>N/A</td><td>N/A</td><td>PXIe-4190 (2MHz, 40V)</td></tr>
<tr><td>Switching and Multiplexing</td><td>N/A</td><td colspan="2">PXIe-2525 MUX (2 WIRE 64 CH SWITCH), PXIe-2530B MATRIX (2 WIRE 4X16 SWITCH)</td></tr>
<tr><td>Temperature Measurement</td><td colspan="3">PXIe-4353 (32 CHANNEL, THERMOCOUPLE INPUT MODULE)</td></tr>
</table>

* Power cables needed for the systems are not included within the configurations and need to be another line item on the quote.

A Better Solution for Battery Test



NI SMUs combine the functionality of **impedance and DC** instrumentation types into a **single form factor-** the first instrument of its class.

Power **simpler measurement systems** with high channel density and no connection changes

PXIe-4139 for AC-IR and EIS

- EIS Frequency: .1Hz – 1kHz
- Max current source: 3A

PXIe-4190 for High Frequency EIS

- EIS Frequency: 40 Hz – 2 MHz
- Max current source: 70mA

NI OCV Solution is 3.5x More Accurate than Hioki 4560

The greater accuracy of the NI solution enables a higher-fidelity assessment of leakage current in a form factor that combines OCV and ACIR.

OCV Specifications

NI PXIe-4081: +/-55.4uV of uncertainty

(assumes +/- 5C temperature range)

Hioki 4560: +/-197uV (.0035%, +/- 5%)

Key Points

- The 4081 has a self-calibration procedure that monitors the temperature drift of the onboard ADCs
- The NI uncertainty assumes a 2-year calibration window
- The Hioki uncertainty assumes a 1-year calibration window
- Hioki does not support a full calibration procedure
- NI uncertainty improves in a tighter temperature range
- Hioki requires an external temperature sensor to achieve specified accuracy, whereas the NI solution is internal
- Hioki has higher-accuracy OCV solution, but this will require a separate box in order to have both OCV and ACIR

Detailed Differentiators

1. Our instrumentation supports a broader range of frequencies for EIS, which enables analysis at different parts of the spectrum correlated with specific failure modes (specific spectrum is cell specific). Note that the addition of the 4190 enables ~2MHz, which is useful for specific defects
2. Our SMUs enable customization of the current range, which can be used to ensure the appropriate current is sourced to accommodate custom switch routing and production fixturing
3. The PXI form-factor enables a high density of measurements in a single chassis (ACIR, OCV, HPCD, Leakage, EIS, and more..)
4. The PXI form-factor also enables a mix of simultaneous and multiplexed inputs, which lets the customer balance cost and performance for their ideal throughout. For example, combine a bunch of 4147s for high density of simultaneous channels, or combine them with 2525s for even higher density at a lower price point per channel
5. Our software provides an API that enables extensive customization at the API, data and presentation layers
6. Our calibration procedure enables very precise measurements to be performed with custom fixturing and signal routing
7. Our time per measurement is generally faster thanks to the high-performance nature of PXI (of course, depends on specific measurement and setup, but referring mainly to ACIR)
8. Our accuracy and resolution are best-in-class. This is hard to benchmark because every EIS/ACIR measurement changes the SoC of the cell slightly, but initial testing has shown a smaller standard deviation than a Hioki box
9. Our solution is better suited for large cells with capacity over 140Ah (some of the competitors will struggle with larger sizes – we need to better quantify and assess this)

Batteries are a Limiting Factor

Expensive and time-consuming to produce

Significant variability in manufacturing process

Defects are difficult to detect

Directly impacts vehicle performance and safety

Significant impact on overall margin and profitability

Undergoing constant changes and improvements

Sensitive to supply-chain challenges

Need for strict control over transportation and handling

Requires significant investment into new equipment and personnel re-training

Field failures can have significant impact on brand and consumer sentiment

Battery Production Challenges

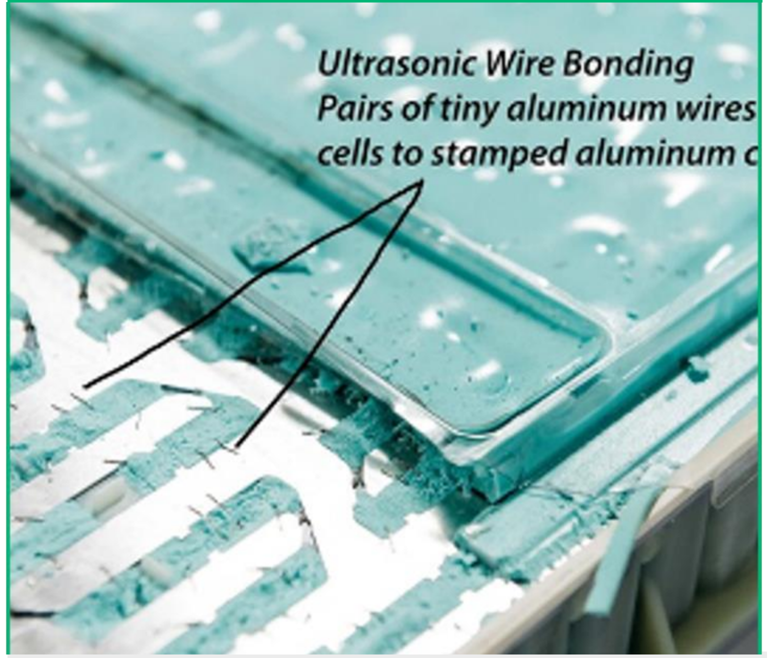
Cell Production

New cells are charged precisely to coat the electrolyte before a lengthy aging and testing process

Challenge:
Achieving massive scale while improving profitability and maximizing quality

Weeks

Module and Pack Assembly



Cells are composed into a sub-assembly structure and ultimately combined with electronics to produce a final pack

Challenge:
Ensuring the quality and consistency of incoming components and assembly processes to minimize rework

Minutes - Days

Service and Remanufacturing

Batteries are evaluated to determine if they are still operating correctly and evaluated for second-life applications

Challenge:
Accurately characterizing the quality and utility of modules and cells to maximize their longevity

Days

Overview of Cell Manufacturing Challenges

Cell Production

New cells are charged precisely to coat the electrolyte before a lengthy aging and testing process

Challenge:
Achieving massive scale while improving profitability and maximizing quality

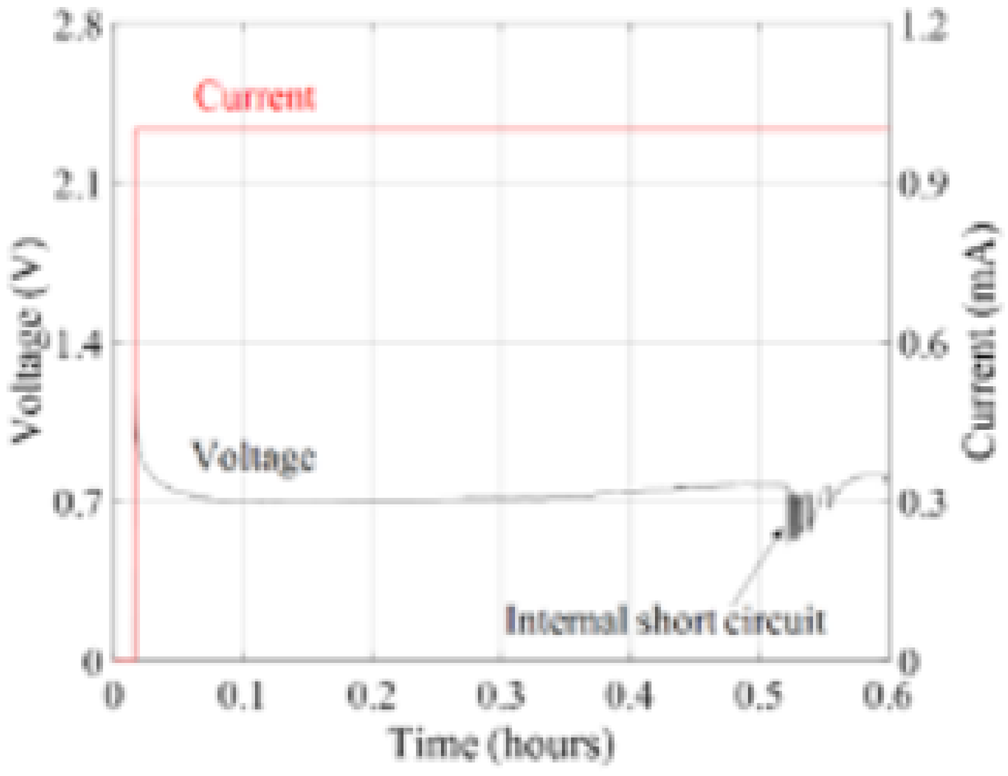
Weeks

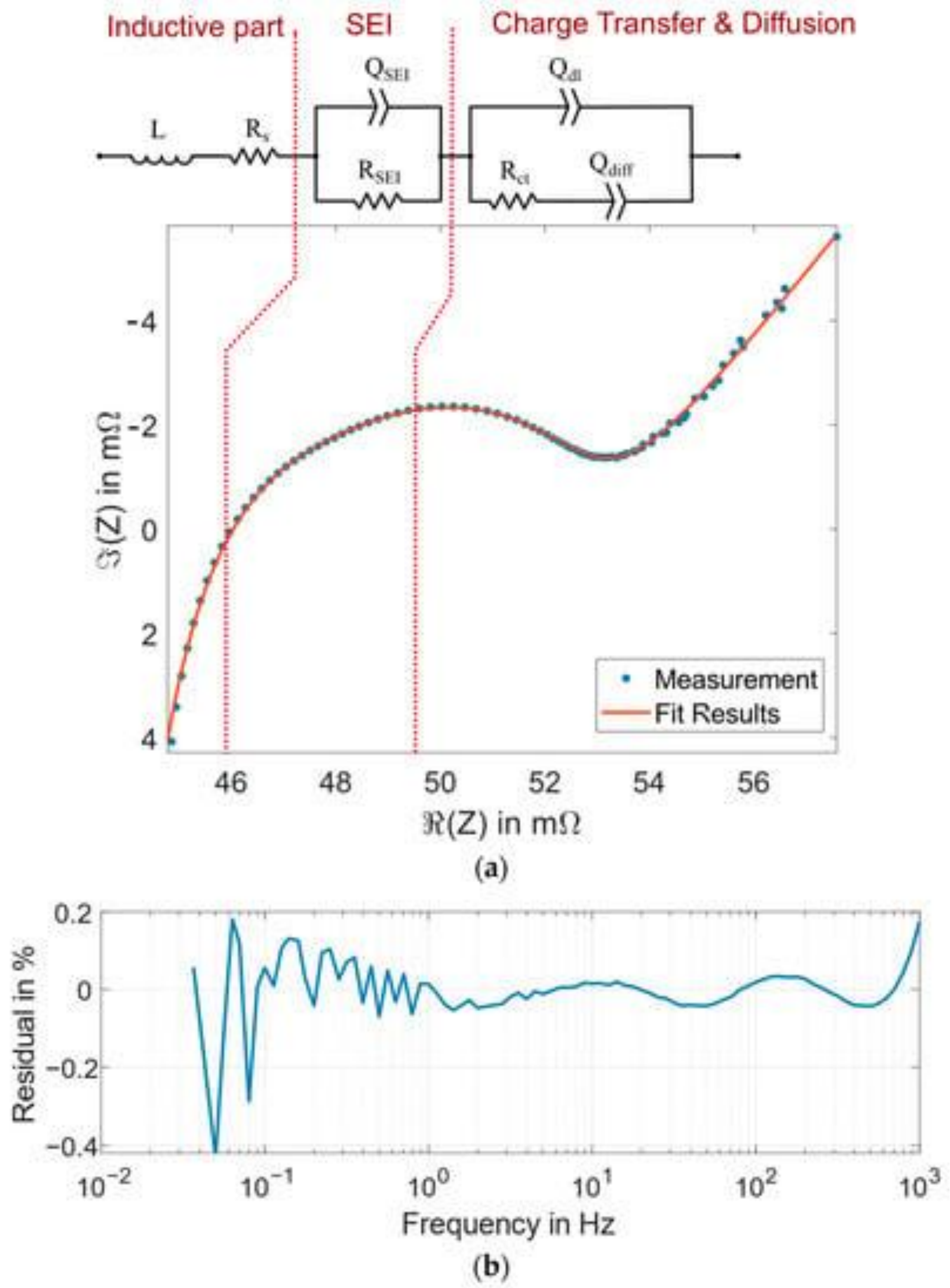
Volume of cell production is one of the largest bottlenecks limiting the market's ability to achieve ambitious EV production targets for a combination of the following reasons:

1. The time required to produce a new cell is significant (8 – 12 days), which necessitates achieving a massive operational scale
2. Yields of cells are limited due to high variability in the manufacturing processes
3. Defects during the manufacturing process can be difficult to detect and they present significant risk to product performance and safety
4. Every interaction with cells increases the risk of introducing subtle defects or damage, thereby introducing the need for additional time-consuming test activities
5. Ongoing improvements to cell formulation and form-factor may lead to more regular changes to the production process
6. The complexity associated with servicing large and cumbersome power electronics

Achieving massive scale while maximizing profitably will require new approaches to manufacturing and test that increase throughout while also ensuring the products are exhaustively tested and that any defects can be rapidly isolated
and corrected

Measurement to defect correlation





EMERSON

NI CONNECT

2024 AUSTIN