Analyzing Accuracy of a Battery Fuel Gauge System

BMS – Applications

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    2. Gauging Accuracy
2. Common Terminology
3. How to Compute Accuracy
4. Test Cases
    1. Common Loads
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    3. Low Temperature
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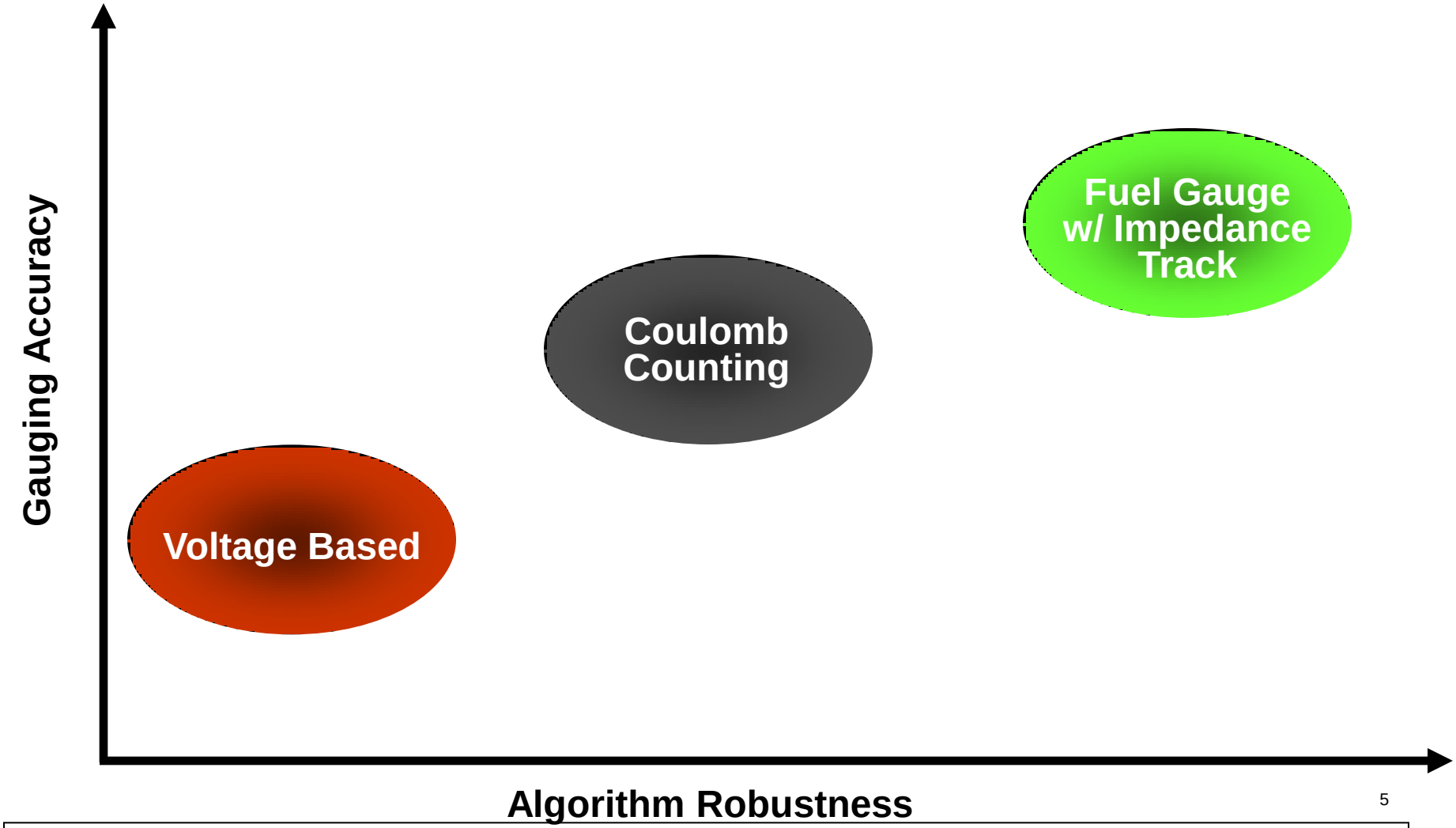
Defining Accuracy

Measurement Accuracy v. Gauging Accuracy

Defining Accuracy

- A fuel gauge algorithm needs to have data from the battery. A gauge gathers data from the battery through various measurements. Gauge measurements include
  - Battery voltage
  - Current flowing into and out of the battery
  - Battery temperature
- Measurement accuracy is dependent upon the gauge's hardware and is independent of gauging accuracy
- Gauging accuracy is dependent upon the robustness of the gauging algorithm and the gauge's measurement accuracy.
  - Poor measurement accuracy can lead to poor gauging accuracy

Gauging Accuracy



Gauging Accuracy

Cell Voltage Measurement

- Measures cell voltage
- Advantage: Simple
- Not accurate over load conditions

Coulomb Counting

- Measures and integrates current over time
- Affected by cell impedance
- Affected by cell self discharge
- Standby current
- Cell Aging
- Must have *full to empty* learning cycles
- Must develop cell models that will vary with cell maker
- Can count the charge leaving the battery, but won't know remaining charge without complex models
- Models will become less accurate with age

Impedance Track™

- **Directly measures effect of discharge rate, temp, age and other factors by learning cell impedance**
- **No host algorithms or calculations**

Measurement Accuracy

- Voltage
  - Accurate voltage measurements are critical for
    - Initialization of relaxed cell
    - Updates during self-discharge of cell
    - Correction for coulomb counting error
  - TI fuel gauges use a 15 bit ADC to provide accurate voltage measurements
- Current
  - Accurate coulomb counting is critical to
    - Capture low sleep currents
    - Capture short load spikes
    - Capture proper passed charge
  - TI fuel gauges have a dedicated 15 bit integrating ADC (i.e. coulomb counting hardware)
- Temperature
  - Accurate temperature measurements are critical for
    - Proper compensation of resistance
    - Proper compensation of predicted runtime
  - TI fuel gauges provide flexible temperature measurement options
    - External measurements with cell's thermistor or board hotspot
    - Host can write the temperature to the fuel gauge
    - Internal IC temperature measurements

Common Terminology

Common Terminology

- Chemical Capacity (Qmax)
  - Total chemical capacity of the battery, mAh
- Remaining Capacity (RM)
  - Useable capacity of the battery from current state to empty state, mAh
- Full Charge Capacity (FCC)
  - Amount of charge passed from a fully charged state until termination voltage, mAh
- Relative State of Charge (RSOC) : 0% -100%
  - RSOC=RM/FCC
- Depth of Discharge (DOD): 0% - 100%
  - 0% is charged to the brim, 100% is completely empty of energy
  - Does not depend on load or temperature or system characteristics
- Passed Charge (dQ or passedQ)
  - Integration of current with respect to time.

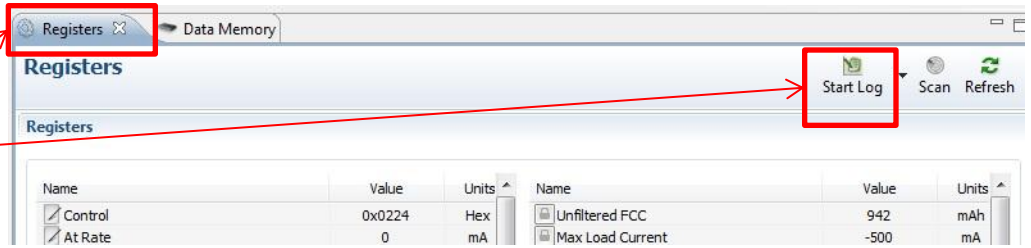
Common Terminology-Cont'd

- Coulomb
  - A unit of electric charge. It is the charge carried by a one ampere current in one second
- Terminate Voltage (EDV)
  - Voltage at which the system can no longer operate; target for 0% SOC
- Reserve Capacity
  - Capacity that is left after reaching 0% SOC

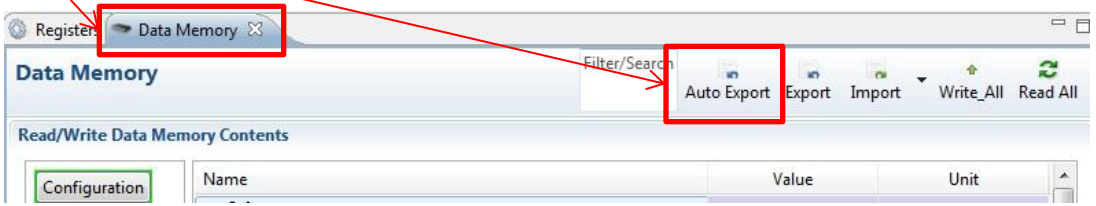
How to Compute Accuracy

Conduct a Test

- Start with a properly configured gauge
  - Ensure gauge has been calibrated
  - For IT gauge, this means a properly created golden image
- Start logging:
  - Log DataRAM registers
    - Open Registers plug-in
    - Click “Start Log”
  - Log interval: 1 to 10 seconds
  - Export Data Memory (optional)
    - Open Data Memory plug-in
    - Click “Auto Export”
- Fully charge at room temp.



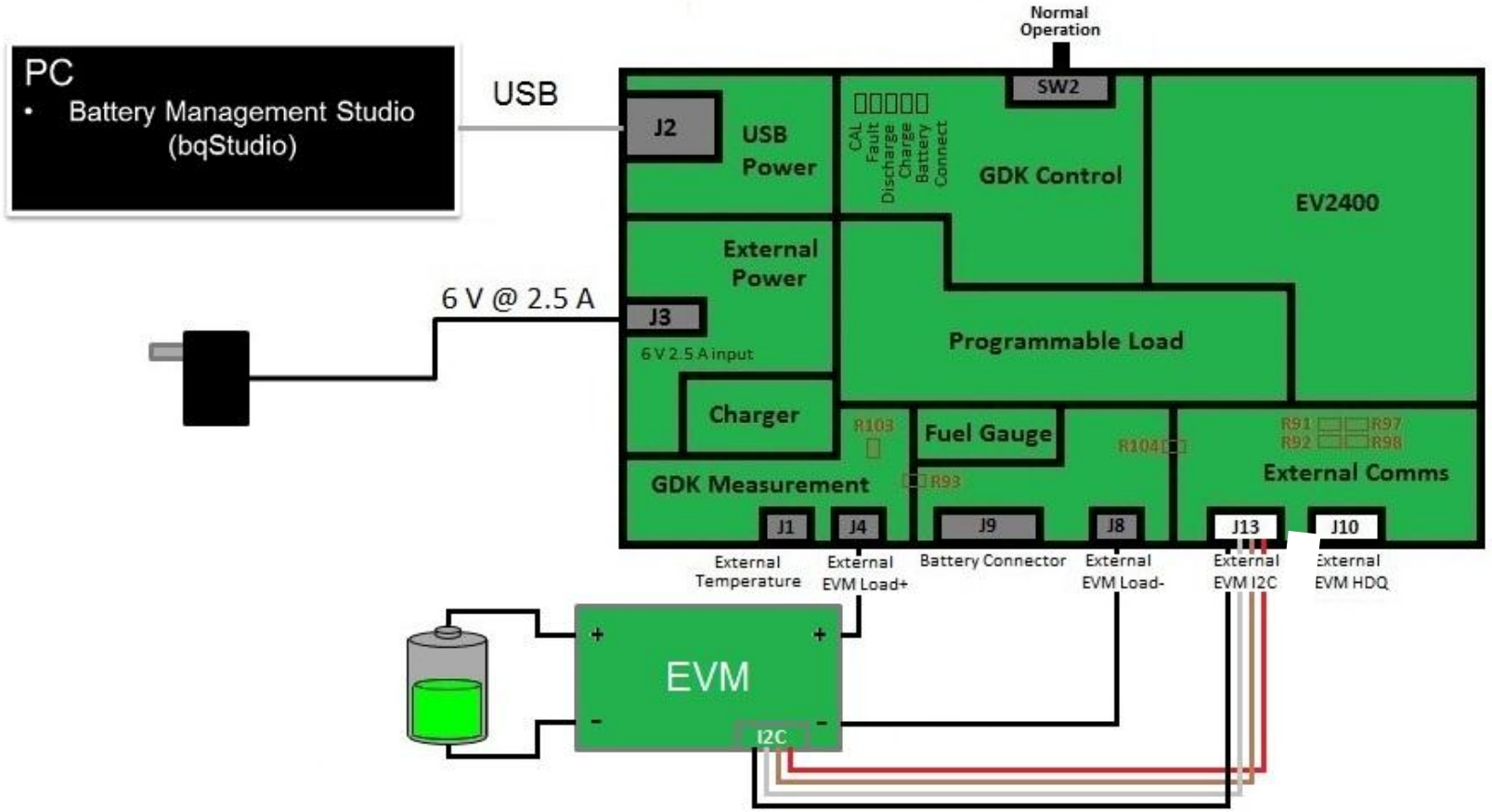
**Logging interval set in Window -> Preferences -> Registers



**Export interval set in Window -> Preferences -> Data Memory

- Discharge to terminate voltage using desired load.

Testing Made Easy with the Gauge Development Kit



Simple inspection

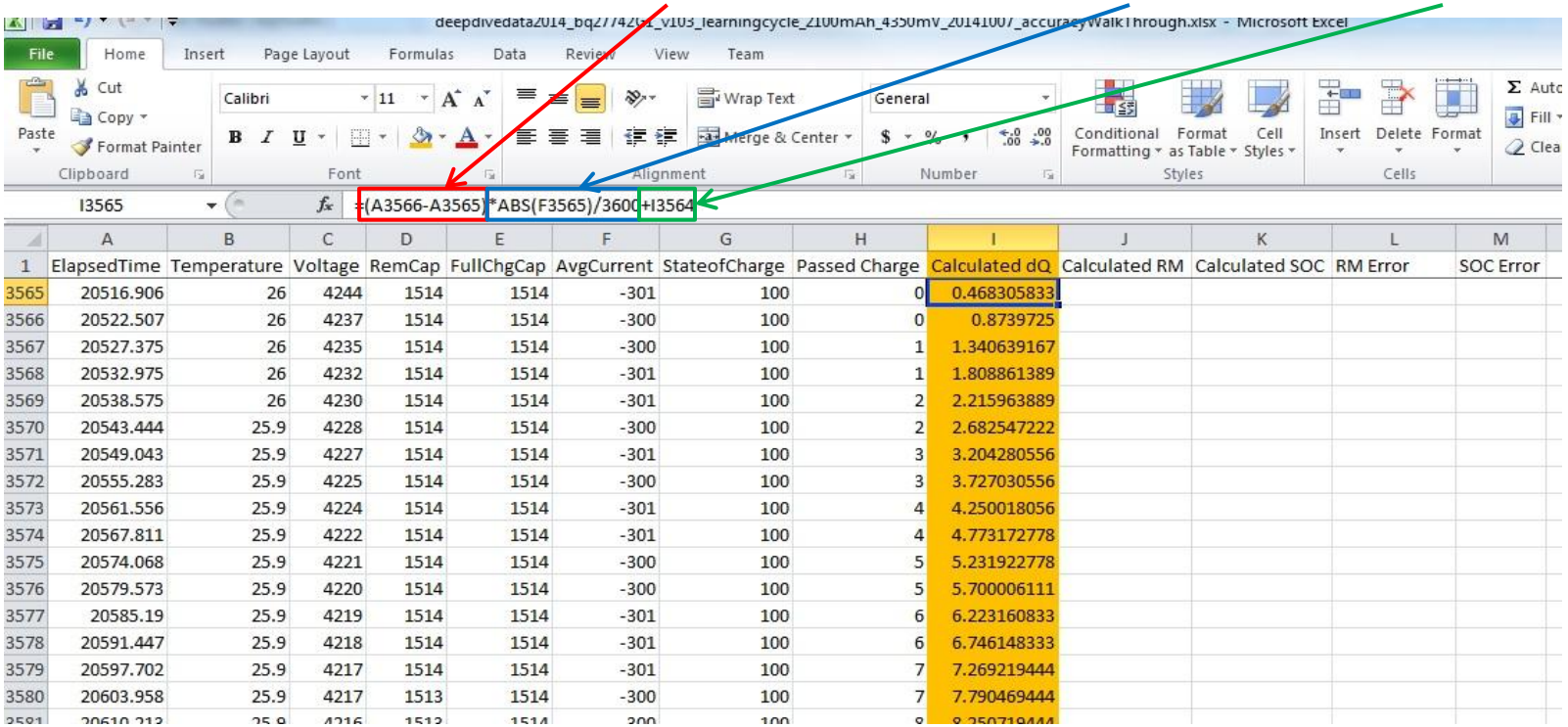
- Log gauge data every 1-10 seconds
- Import to spreadsheet and plot voltage, SOC, current, etc.
- Inspect
  - Does it report 0% at or near your true terminate voltage?
    - If not, by how much capacity and/or run-time was it off?
  - Does it look smooth or have large jumps?
- Very subjective and difficult to gauge relative error magnitude

Steps for Computing Accuracy

1. Start with gauge log
2. Calculate a new column: Calculated dQ = rolling sum of current_reading*time_since_last_log_point
   - Start from full condition and go to empty condition (EDV)
3. Calculate FCC_true = Integrated capacity from fully charged state down to termination voltage
   - Simple integration: capacity = constant current * total discharge time from full to terminate voltage
   - More accurate integration: calculate each log point Current*Tdelta and keep a rolling sum.
4. Calculate a new column: Calculated_RM = FCC_true – calculated_dQ
   - True remaining capacity at any point (mAh)
5. Calculate a new column: Calculated_SOC = Calculated_RM / FCC_true * 100
   - True relative state of charge (%)
6. Calculate a new column: SOC_error = (Calculated_SOC – SOC_gauge)
   - SOC_gauge is “State of Charge” in IT gauge log files
7. Plot voltage, RSOC_true, RSOC_gauge, RSOC_error
8. Summarize in table showing
   1. % error at the point when termination voltage is reached
   2. Max % error

Steps for Computing Accuracy

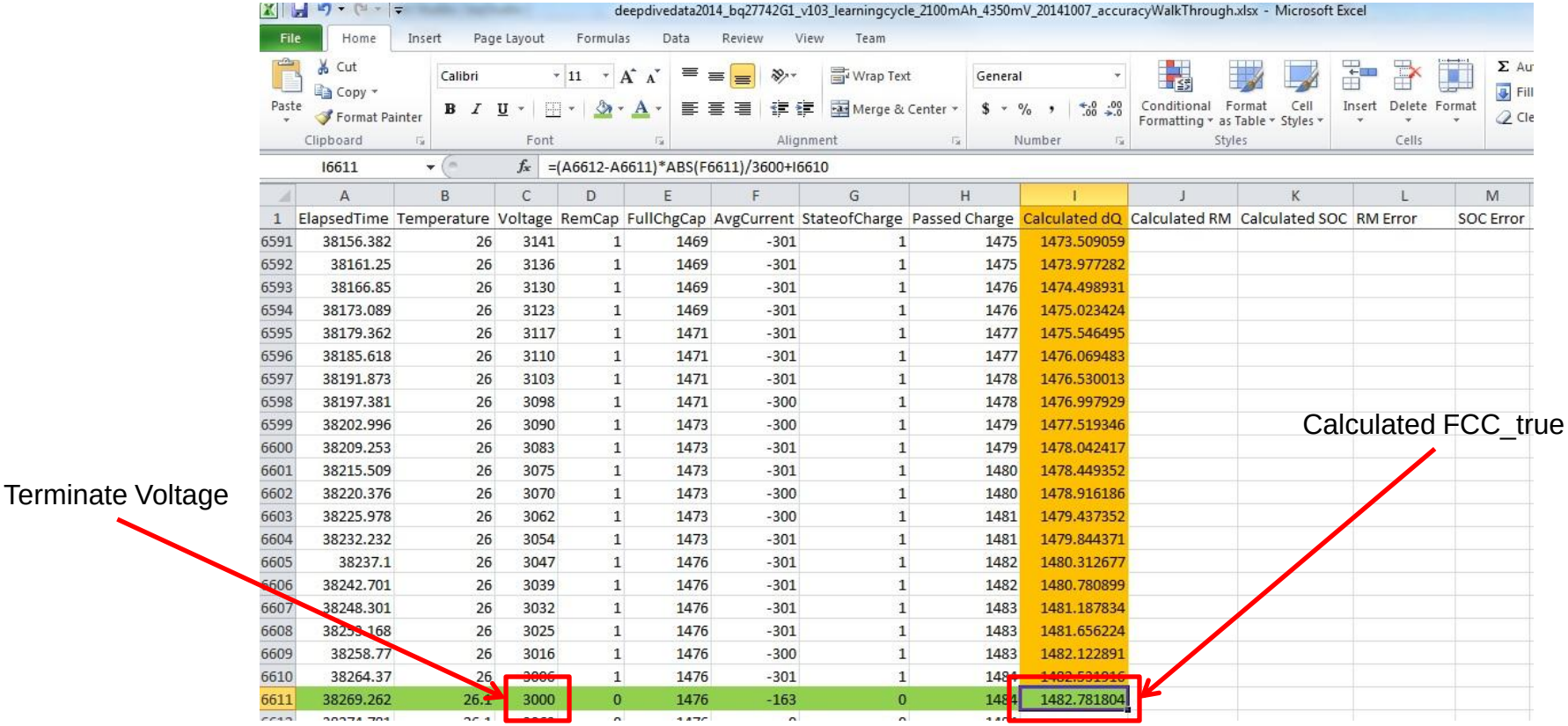
- Start with Gauge log
- Create new column for calculated passed charge (dQ)
  - Calculated_dQ = rolling sum of current_reading * time_since_last_log_point
    - Start from full and calculate until empty (or discharge stops)
    - Excel formula: $(ElapsedTime_{N+1} – ElapsedTime_N)*|AvgCurrent_N| /3600+ Calculated\_dQ_{N-1}$



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	ElapsedTime	Temperature	Voltage	RemCap	FullChgCap	AvgCurrent	StateofCharge	Passed Charge	Calculated dQ	Calculated RM	Calculated SOC	RM Error	SOC Error
3565	20516.906	26	4244	1514	1514	-301	100	0	0.468305833				
3566	20522.507	26	4237	1514	1514	-300	100	0	0.8739725				
3567	20527.375	26	4235	1514	1514	-300	100	1	1.340639167				
3568	20532.975	26	4232	1514	1514	-301	100	1	1.808861389				
3569	20538.575	26	4230	1514	1514	-301	100	2	2.215963889				
3570	20543.444	25.9	4228	1514	1514	-300	100	2	2.682547222				
3571	20549.043	25.9	4227	1514	1514	-301	100	3	3.204280556				
3572	20555.283	25.9	4225	1514	1514	-300	100	3	3.727030556				
3573	20561.556	25.9	4224	1514	1514	-301	100	4	4.250018056				
3574	20567.811	25.9	4222	1514	1514	-301	100	4	4.773172778				
3575	20574.068	25.9	4221	1514	1514	-300	100	5	5.231922778				
3576	20579.573	25.9	4220	1514	1514	-300	100	5	5.700006111				
3577	20585.19	25.9	4219	1514	1514	-301	100	6	6.223160833				
3578	20591.447	25.9	4218	1514	1514	-301	100	6	6.746148333				
3579	20597.702	25.9	4217	1514	1514	-301	100	7	7.269219444				
3580	20603.958	25.9	4217	1513	1514	-300	100	7	7.790469444				

Steps for Computing Accuracy

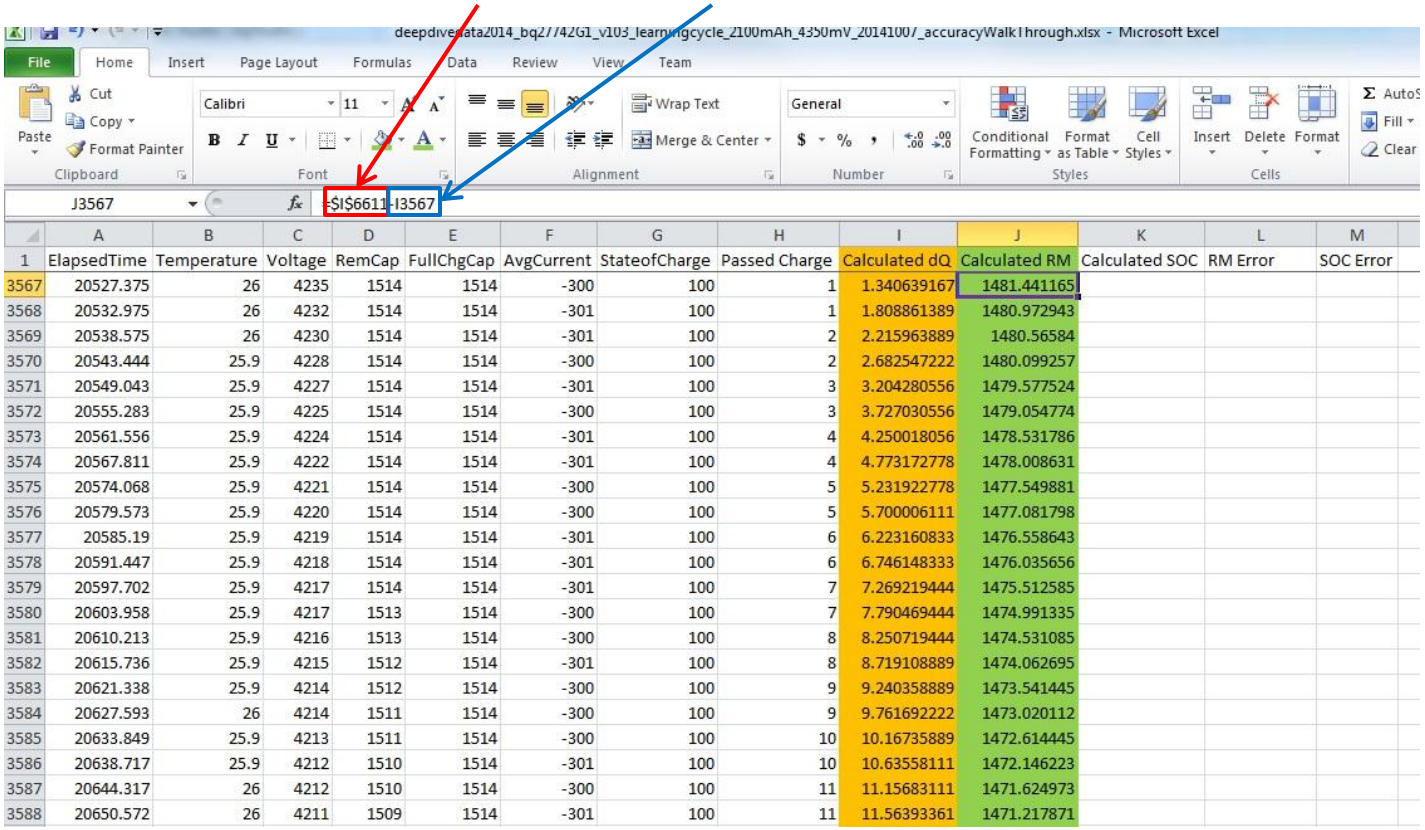
- Calculate FCC_true = Integrated capacity from fully charged state down to termination voltage



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	ElapsedTime	Temperature	Voltage	RemCap	FullChgCap	AvgCurrent	StateofCharge	Passed Charge	Calculated dQ	Calculated RM	Calculated SOC	RM Error	SOC Error
6591	38156.382	26	3141	1	1469	-301	1	1475	1473.509059				
6592	38161.25	26	3136	1	1469	-301	1	1475	1473.977282				
6593	38166.85	26	3130	1	1469	-301	1	1476	1474.498931				
6594	38173.089	26	3123	1	1469	-301	1	1476	1475.023424				
6595	38179.362	26	3117	1	1471	-301	1	1477	1475.546495				
6596	38185.618	26	3110	1	1471	-301	1	1477	1476.069483				
6597	38191.873	26	3103	1	1471	-301	1	1478	1476.530013				
6598	38197.381	26	3098	1	1471	-300	1	1478	1476.997929				
6599	38202.996	26	3090	1	1473	-300	1	1479	1477.519346				
6600	38209.253	26	3083	1	1473	-301	1	1479	1478.042417				
6601	38215.509	26	3075	1	1473	-301	1	1480	1478.449352				
6602	38220.376	26	3070	1	1473	-300	1	1480	1478.916186				
6603	38225.978	26	3062	1	1473	-300	1	1481	1479.437352				
6604	38232.232	26	3054	1	1473	-301	1	1481	1479.844371				
6605	38237.1	26	3047	1	1476	-301	1	1482	1480.312677				
6606	38242.701	26	3039	1	1476	-301	1	1482	1480.780899				
6607	38248.301	26	3032	1	1476	-301	1	1483	1481.187834				
6608	38253.168	26	3025	1	1476	-301	1	1483	1481.656224				
6609	38258.77	26	3016	1	1476	-300	1	1483	1482.122891				
6610	38264.37	26	3006	1	1476	-301	1	1484	1482.531916				
6611	38269.262	26.1	3000	0	1476	-163	0	1484	1482.781804				

Steps for Computing Accuracy

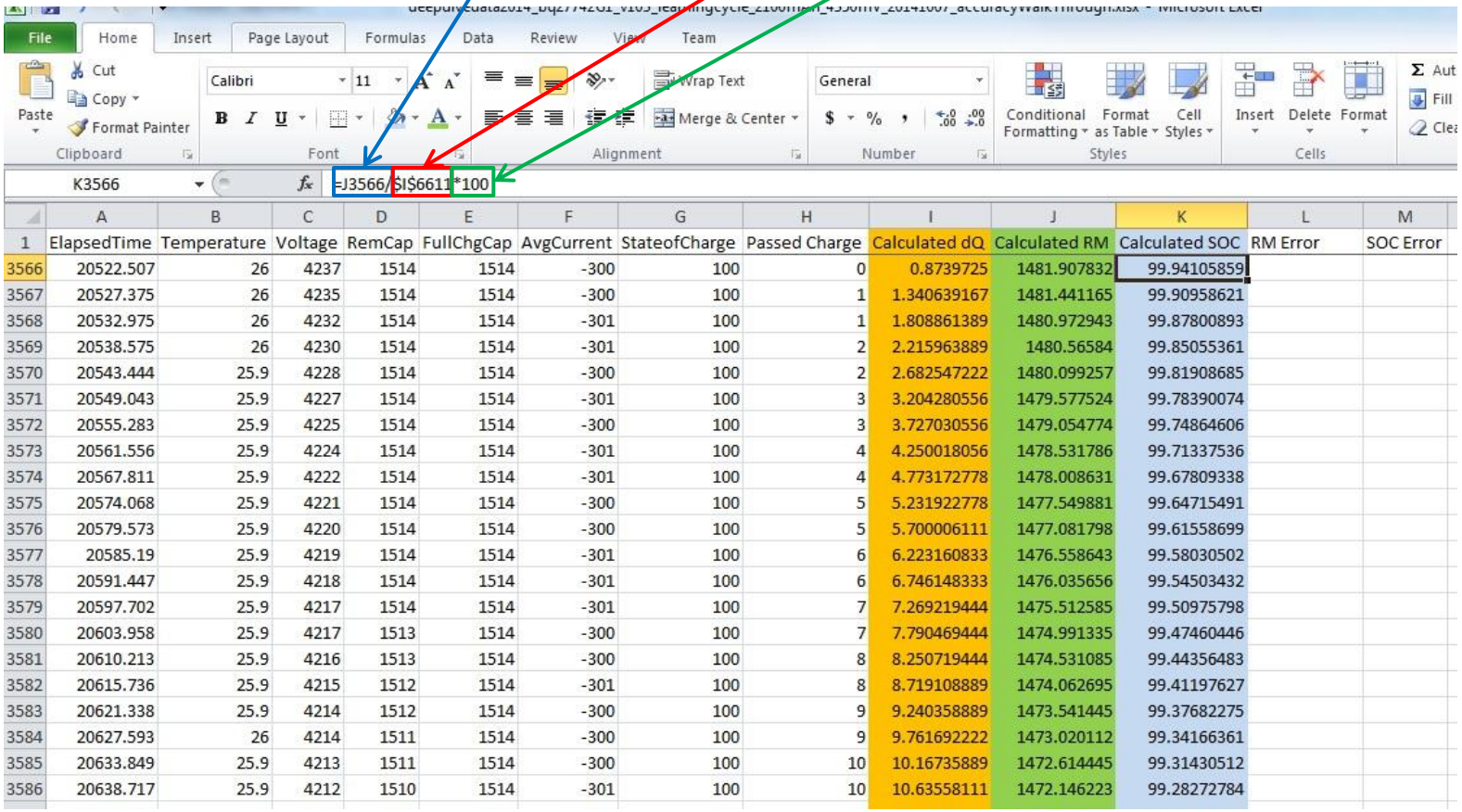
- Calculate a new column: Calculated_RM = FCC_true – Calculated_dQ
  - True remaining capacity at any point (mAh)
    - Excel formula: $FCC_true – Calculated_dQ_N$



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	ElapsedTime	Temperature	Voltage	RemCap	FullChgCap	AvgCurrent	StateofCharge	Passed Charge	Calculated dQ	Calculated RM	Calculated SOC	RM Error	SOC Error
3567	20527.375	26	4235	1514	1514	-300	100	1	1.340639167	1481.441165			
3568	20532.975	26	4232	1514	1514	-301	100	1	1.808861389	1480.972943			
3569	20538.575	26	4230	1514	1514	-301	100	2	2.215963889	1480.56584			
3570	20543.444	25.9	4228	1514	1514	-300	100	2	2.682547222	1480.099257			
3571	20549.043	25.9	4227	1514	1514	-301	100	3	3.204280556	1479.577524			
3572	20555.283	25.9	4225	1514	1514	-300	100	3	3.727030556	1479.054774			
3573	20561.556	25.9	4224	1514	1514	-301	100	4	4.250018056	1478.531786			
3574	20567.811	25.9	4222	1514	1514	-301	100	4	4.773172778	1478.008631			
3575	20574.068	25.9	4221	1514	1514	-300	100	5	5.231922778	1477.549881			
3576	20579.573	25.9	4220	1514	1514	-300	100	5	5.700006111	1477.081798			
3577	20585.19	25.9	4219	1514	1514	-301	100	6	6.223160833	1476.558643			
3578	20591.447	25.9	4218	1514	1514	-301	100	6	6.746148333	1476.035656			
3579	20597.702	25.9	4217	1514	1514	-301	100	7	7.269219444	1475.512585			
3580	20603.958	25.9	4217	1513	1514	-300	100	7	7.790469444	1474.991335			
3581	20610.213	25.9	4216	1513	1514	-300	100	8	8.250719444	1474.531085			
3582	20615.736	25.9	4215	1512	1514	-301	100	8	8.719108889	1474.062695			
3583	20621.338	25.9	4214	1512	1514	-300	100	9	9.240358889	1473.541445			
3584	20627.593	26	4214	1511	1514	-300	100	9	9.761692222	1473.020112			
3585	20633.849	25.9	4213	1511	1514	-300	100	10	10.16735889	1472.614445			
3586	20638.717	25.9	4212	1510	1514	-301	100	10	10.63558111	1472.146223			
3587	20644.317	26	4212	1510	1514	-300	100	11	11.15683111	1471.624973			
3588	20650.572	26	4211	1509	1514	-301	100	11	11.56393361	1471.217871			

Steps for Computing Accuracy

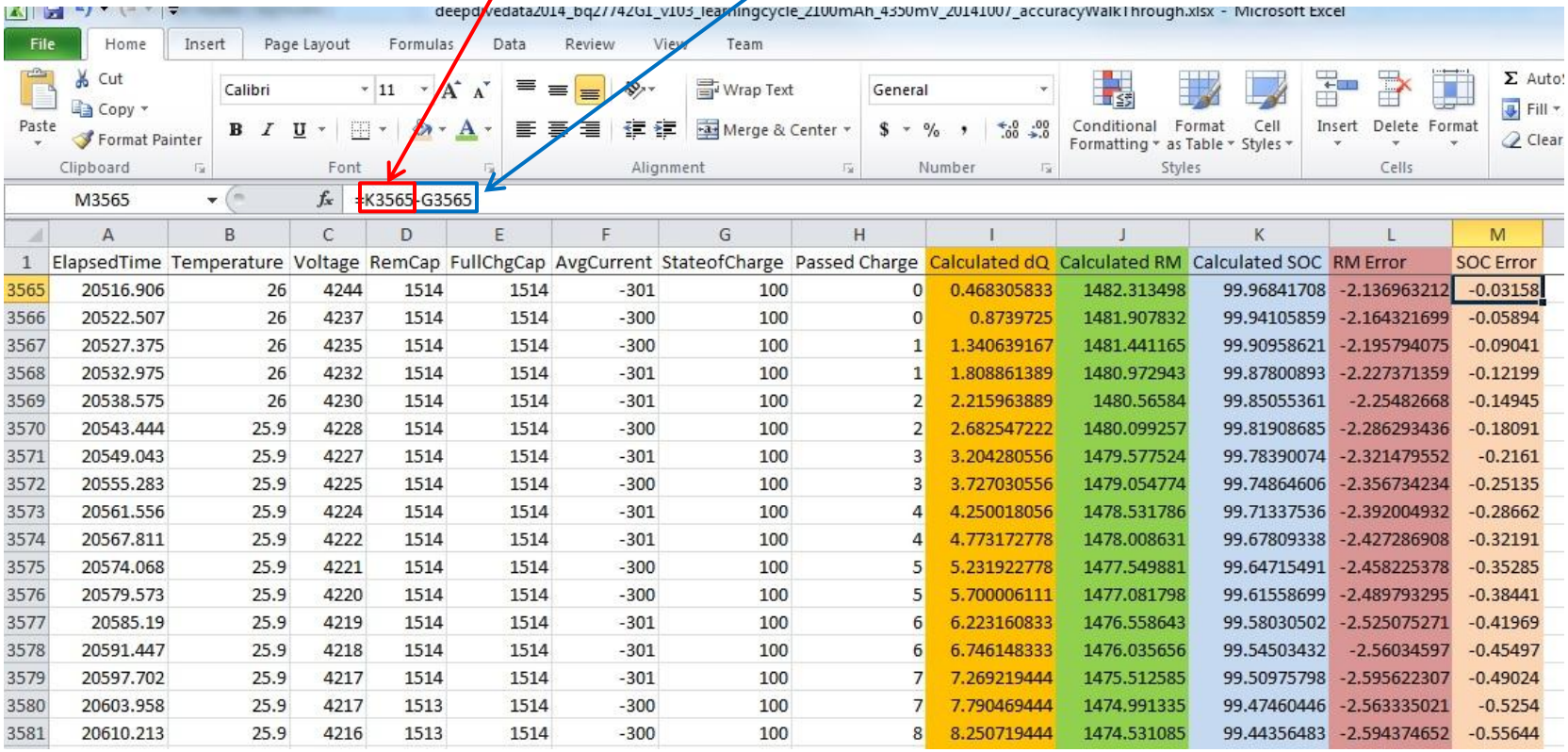
- Calculate a new column: Calculated_SOC = Calculated_RM / FCC_true * 100
  - True state of charge at any point (%)
    - Excel formula: Calculated_RM / $FCC_true * 100



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	ElapsedTime	Temperature	Voltage	RemCap	FullChgCap	AvgCurrent	StateofCharge	Passed Charge	Calculated dQ	Calculated RM	Calculated SOC	RM Error	SOC Error
3566	20522.507	26	4237	1514	1514	-300	100	0	0.8739725	1481.907832	99.94105859		
3567	20527.375	26	4235	1514	1514	-300	100	1	1.340639167	1481.441165	99.90958621		
3568	20532.975	26	4232	1514	1514	-301	100	1	1.808861389	1480.972943	99.87800893		
3569	20538.575	26	4230	1514	1514	-301	100	2	2.215963889	1480.56584	99.85055361		
3570	20543.444	25.9	4228	1514	1514	-300	100	2	2.682547222	1480.099257	99.81908685		
3571	20549.043	25.9	4227	1514	1514	-301	100	3	3.204280556	1479.577524	99.78390074		
3572	20555.283	25.9	4225	1514	1514	-300	100	3	3.727030556	1479.054774	99.74864606		
3573	20561.556	25.9	4224	1514	1514	-301	100	4	4.250018056	1478.531786	99.71337536		
3574	20567.811	25.9	4222	1514	1514	-301	100	4	4.773172778	1478.008631	99.67809338		
3575	20574.068	25.9	4221	1514	1514	-300	100	5	5.231922778	1477.549881	99.64715491		
3576	20579.573	25.9	4220	1514	1514	-300	100	5	5.700006111	1477.081798	99.61558699		
3577	20585.19	25.9	4219	1514	1514	-301	100	6	6.223160833	1476.558643	99.58030502		
3578	20591.447	25.9	4218	1514	1514	-301	100	6	6.746148333	1476.035656	99.54503432		
3579	20597.702	25.9	4217	1514	1514	-301	100	7	7.269219444	1475.512585	99.50975798		
3580	20603.958	25.9	4217	1513	1514	-300	100	7	7.790469444	1474.991335	99.47460446		
3581	20610.213	25.9	4216	1513	1514	-300	100	8	8.250719444	1474.531085	99.44356483		
3582	20615.736	25.9	4215	1512	1514	-301	100	8	8.719108889	1474.062695	99.41197627		
3583	20621.338	25.9	4214	1512	1514	-300	100	9	9.240358889	1473.541445	99.37682275		
3584	20627.593	26	4214	1511	1514	-300	100	9	9.761692222	1473.020112	99.34166361		
3585	20633.849	25.9	4213	1511	1514	-300	100	10	10.16735889	1472.614445	99.31430512		
3586	20638.717	25.9	4212	1510	1514	-301	100	10	10.63558111	1472.146223	99.28272784		

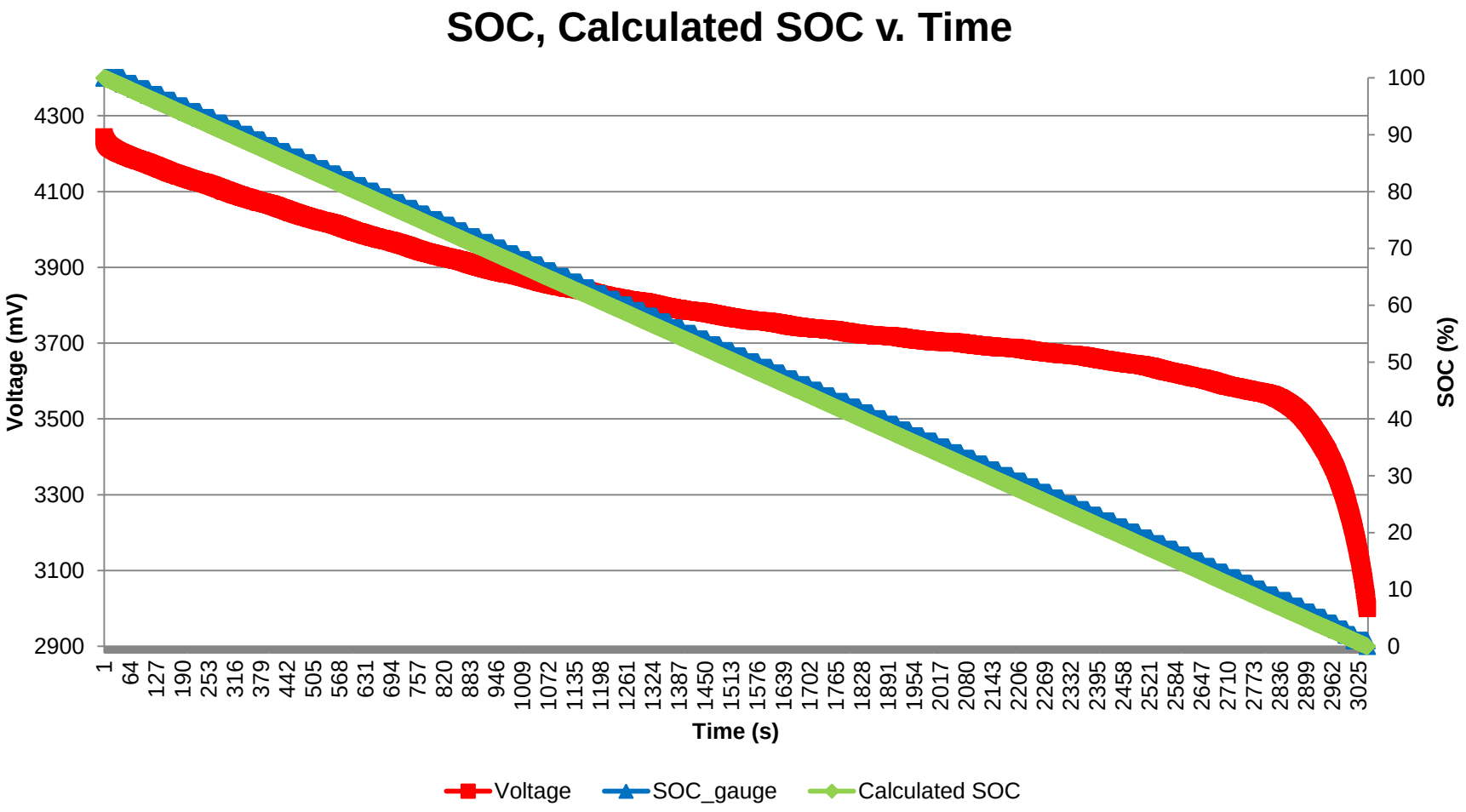
Steps for Computing Accuracy

- Calculate a new column: SOC_error = SOC_true – SOC_gauge
  - Excel formula: Calculated_SOC$_N$ – SOC_gauge$_N$

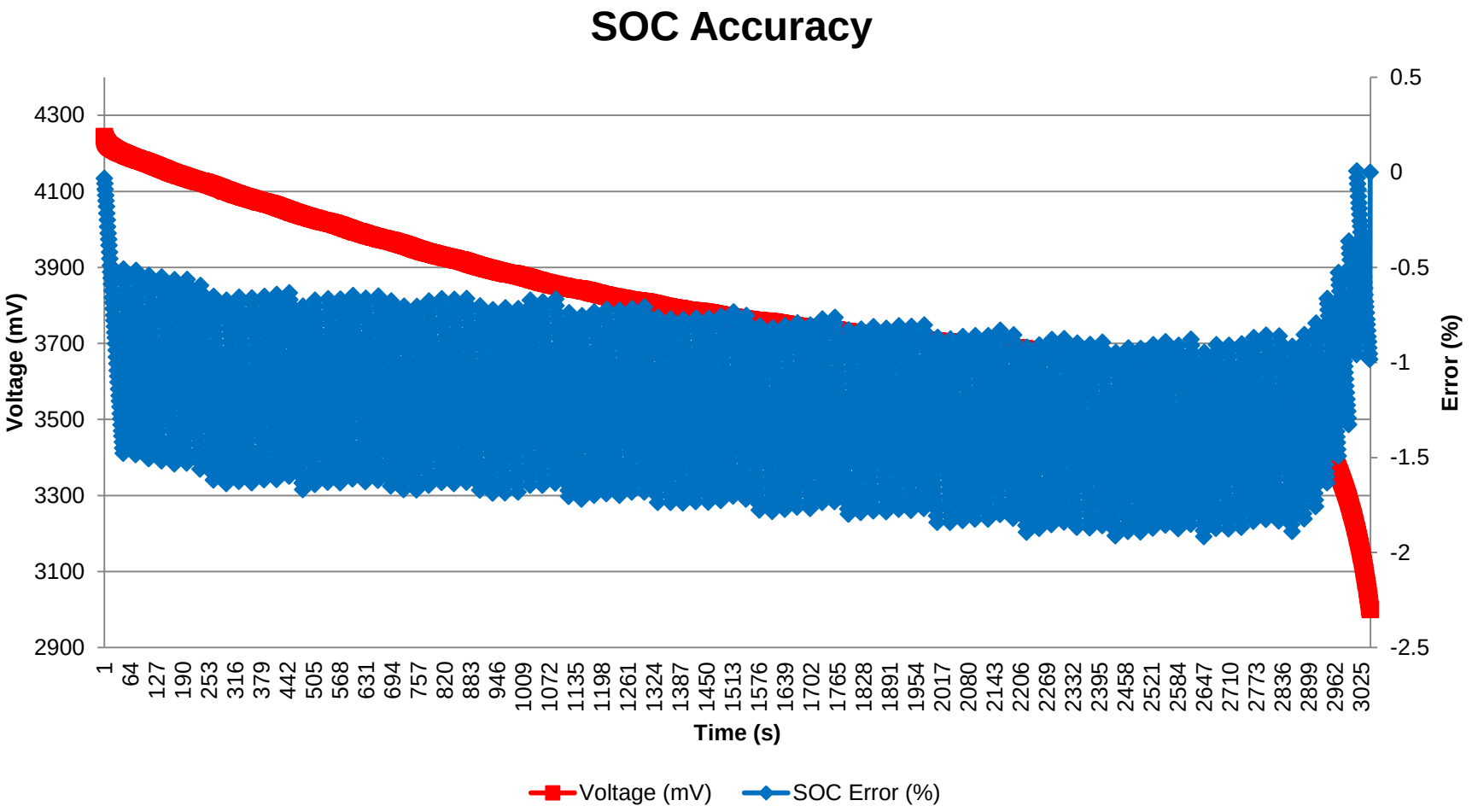


	A	B	C	D	E	F	G	H	I	J	K	L	M
1	ElapsedTime	Temperature	Voltage	RemCap	FullChgCap	AvgCurrent	StateofCharge	Passed Charge	Calculated dQ	Calculated RM	Calculated SOC	RM Error	SOC Error
3565	20516.906	26	4244	1514	1514	-301	100	0	0.468305833	1482.313498	99.96841708	-2.136963212	-0.03158
3566	20522.507	26	4237	1514	1514	-300	100	0	0.8739725	1481.907832	99.94105859	-2.164321699	-0.05894
3567	20527.375	26	4235	1514	1514	-300	100	1	1.340639167	1481.441165	99.90958621	-2.195794075	-0.09041
3568	20532.975	26	4232	1514	1514	-301	100	1	1.808861389	1480.972943	99.87800893	-2.227371359	-0.12199
3569	20538.575	26	4230	1514	1514	-301	100	2	2.215963889	1480.56584	99.85055361	-2.25482668	-0.14945
3570	20543.444	25.9	4228	1514	1514	-300	100	2	2.682547222	1480.099257	99.81908685	-2.286293436	-0.18091
3571	20549.043	25.9	4227	1514	1514	-301	100	3	3.204280556	1479.577524	99.78390074	-2.321479552	-0.2161
3572	20555.283	25.9	4225	1514	1514	-300	100	3	3.727030556	1479.054774	99.74864606	-2.356734234	-0.25135
3573	20561.556	25.9	4224	1514	1514	-301	100	4	4.250018056	1478.531786	99.71337536	-2.392004932	-0.28662
3574	20567.811	25.9	4222	1514	1514	-301	100	4	4.773172778	1478.008631	99.67809338	-2.427286908	-0.32191
3575	20574.068	25.9	4221	1514	1514	-300	100	5	5.231922778	1477.549881	99.64715491	-2.458225378	-0.35285
3576	20579.573	25.9	4220	1514	1514	-300	100	5	5.700006111	1477.081798	99.61558699	-2.489793295	-0.38441
3577	20585.19	25.9	4219	1514	1514	-301	100	6	6.223160833	1476.558643	99.58030502	-2.525075271	-0.41969
3578	20591.447	25.9	4218	1514	1514	-301	100	6	6.746148333	1476.035656	99.54503432	-2.56034597	-0.45497
3579	20597.702	25.9	4217	1514	1514	-301	100	7	7.269219444	1475.512585	99.50975798	-2.595622307	-0.49024
3580	20603.958	25.9	4217	1513	1514	-300	100	7	7.790469444	1474.991335	99.47460446	-2.563335021	-0.5254
3581	20610.213	25.9	4216	1513	1514	-300	100	8	8.250719444	1474.531085	99.44356483	-2.594374652	-0.55644

Steps for Computing Accuracy

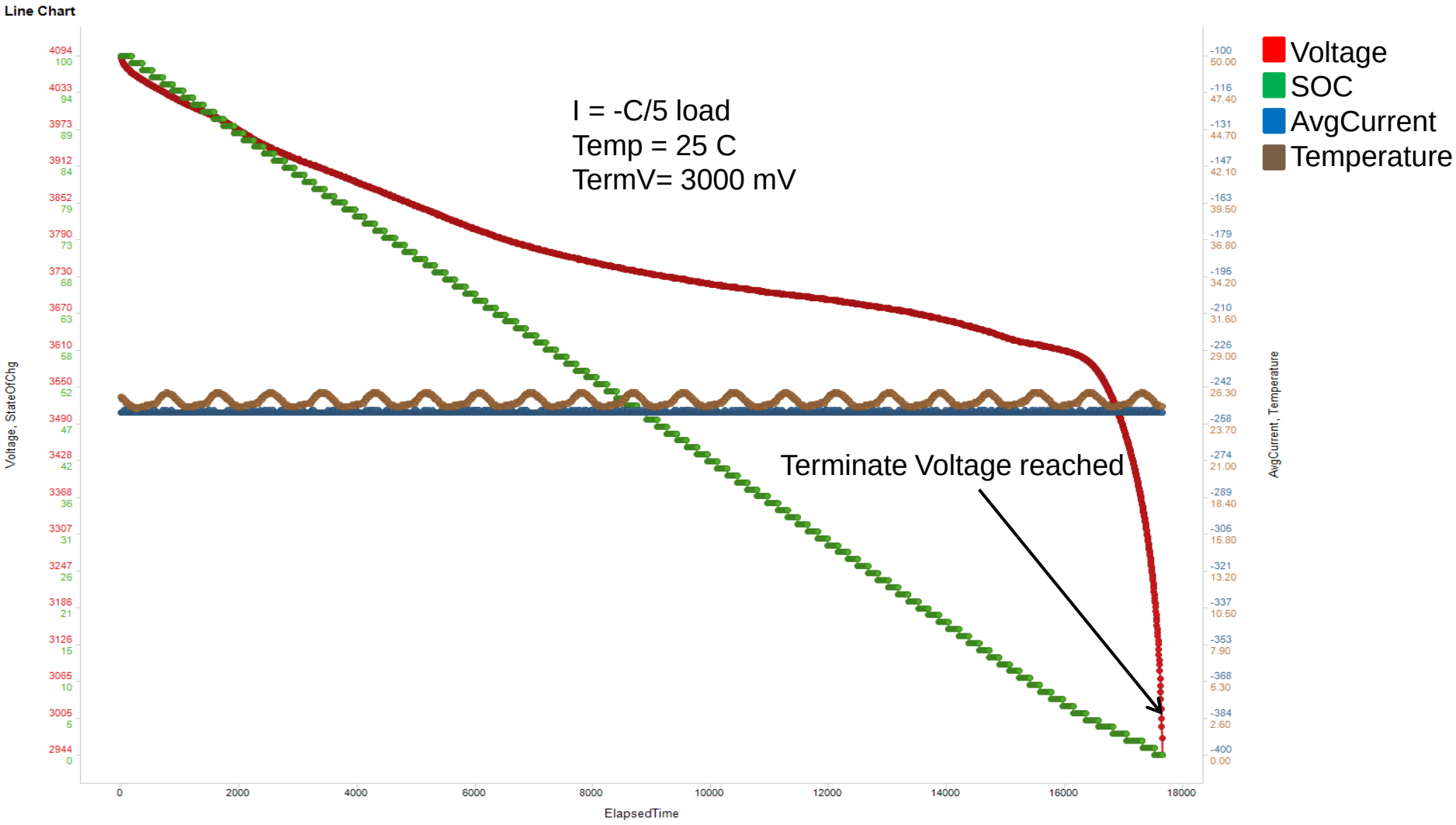


Steps for Computing Accuracy

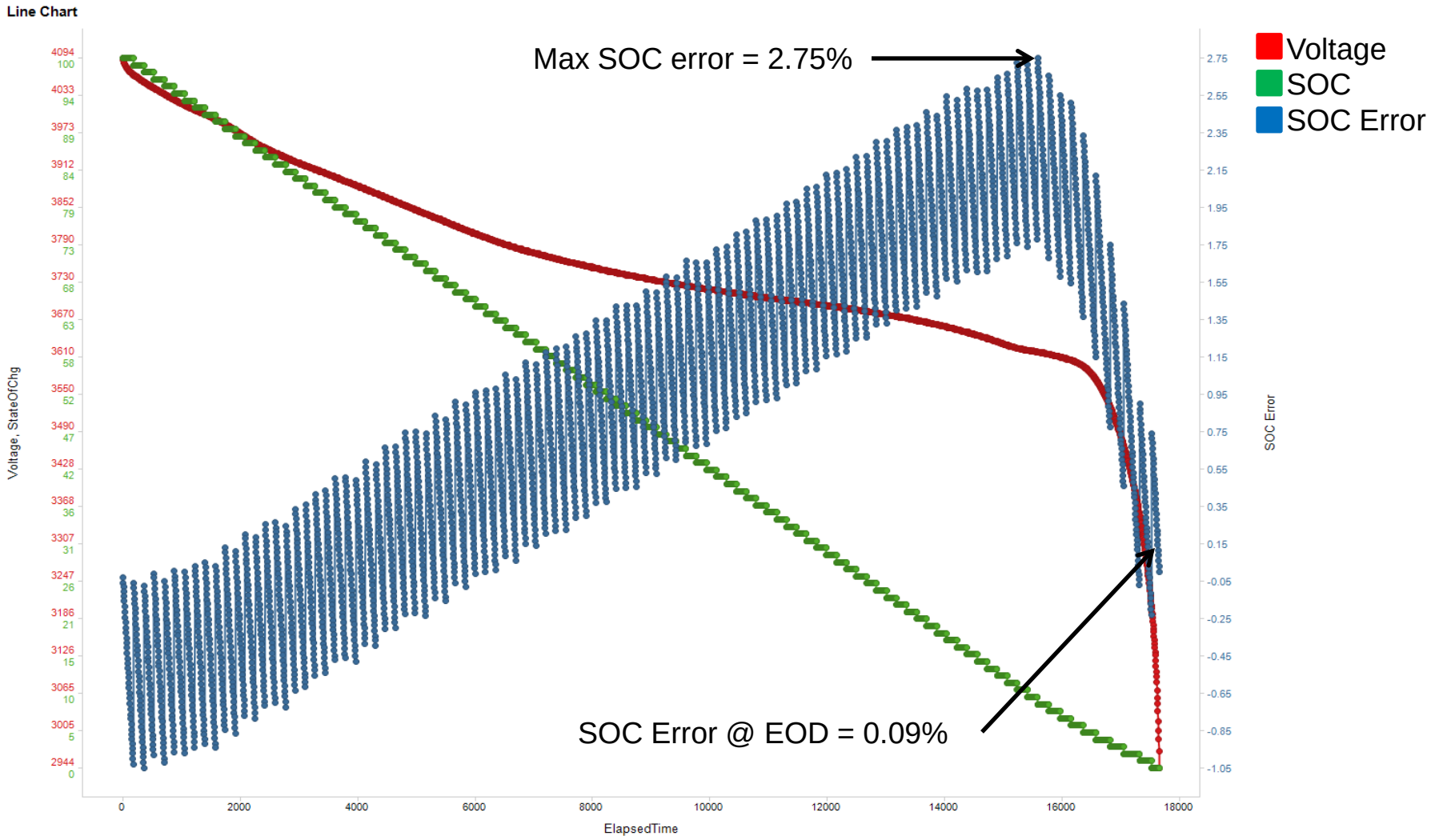


Test Cases

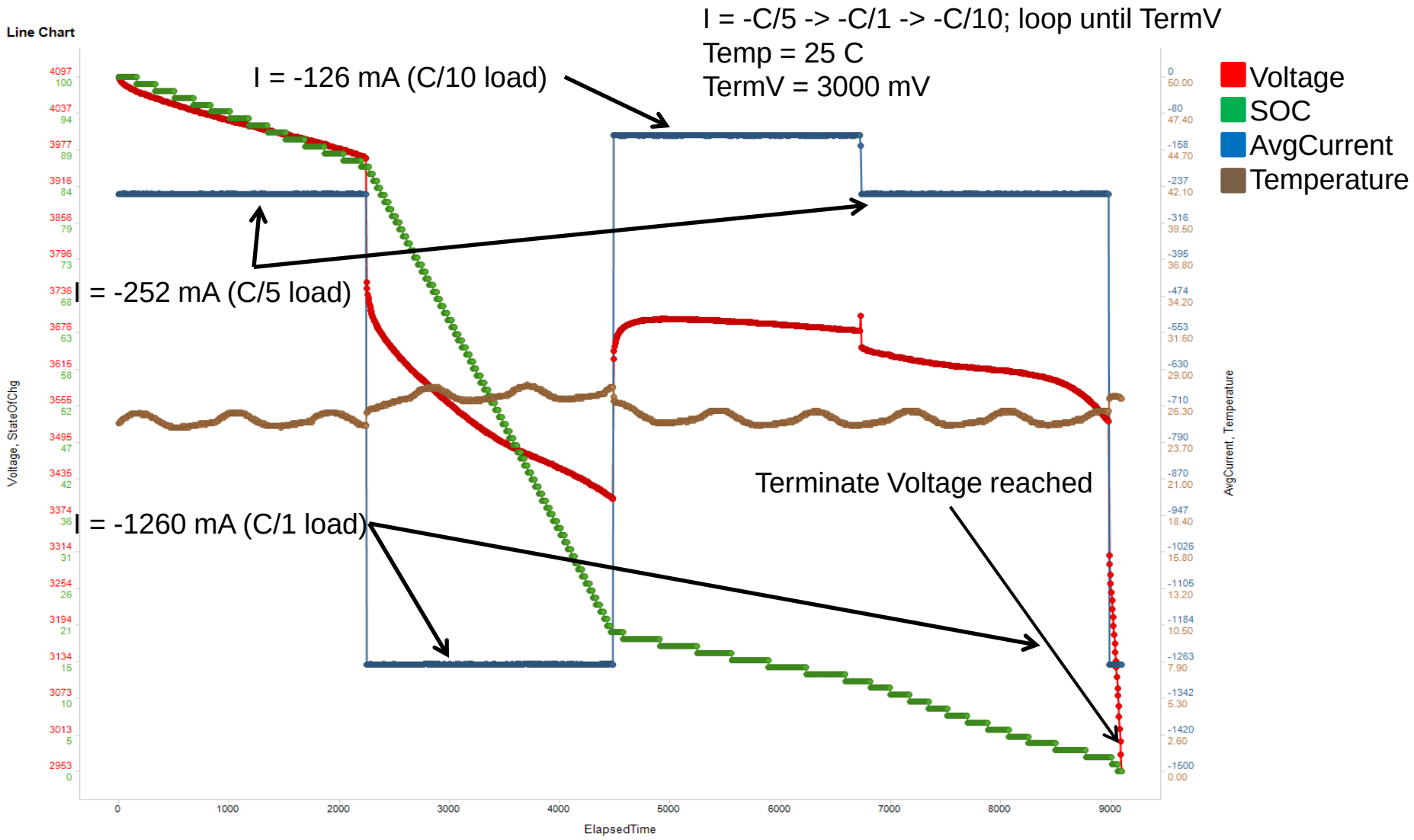
bq27421 – Standard C/5 Discharge



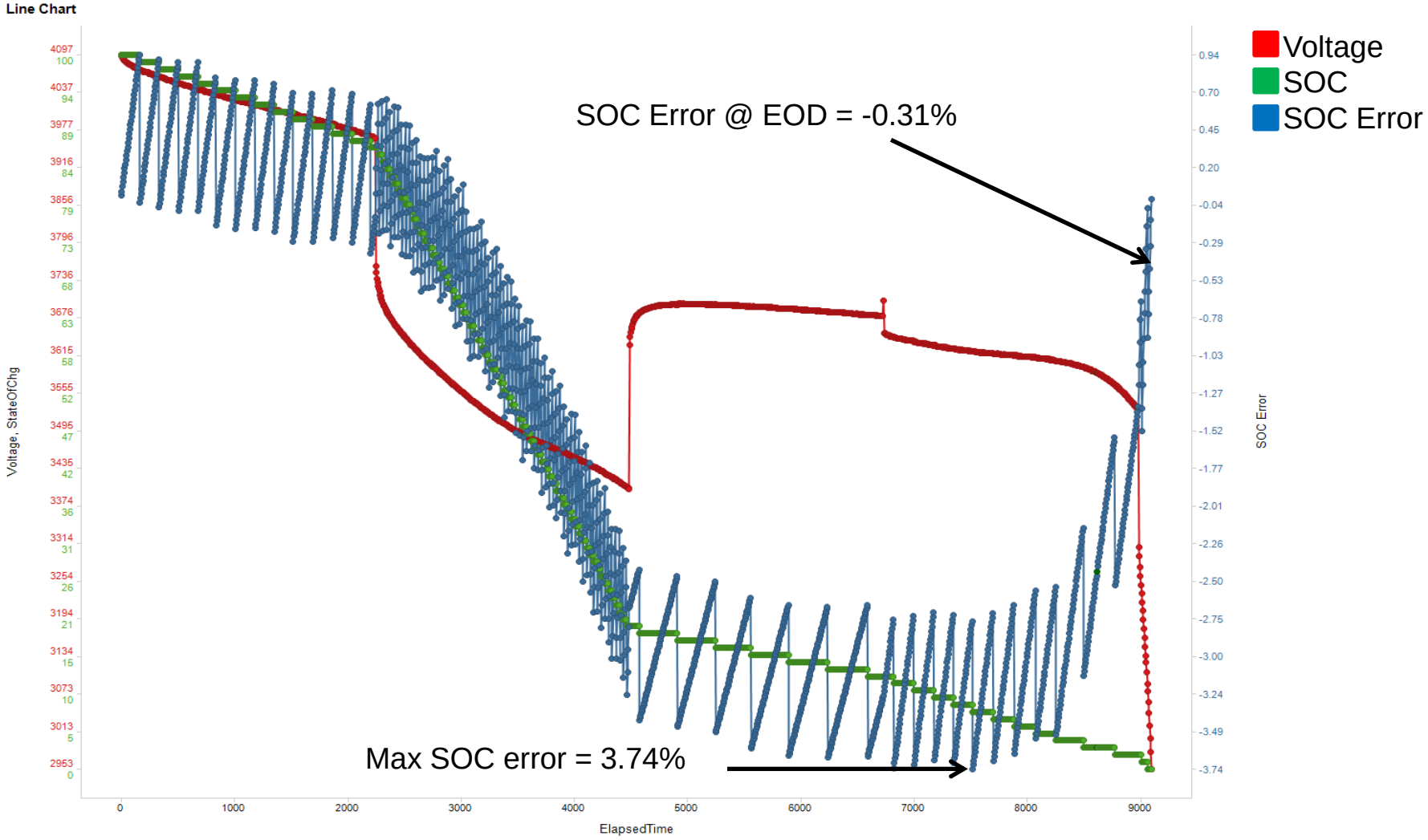
bq27421 – Standard C/5 Discharge



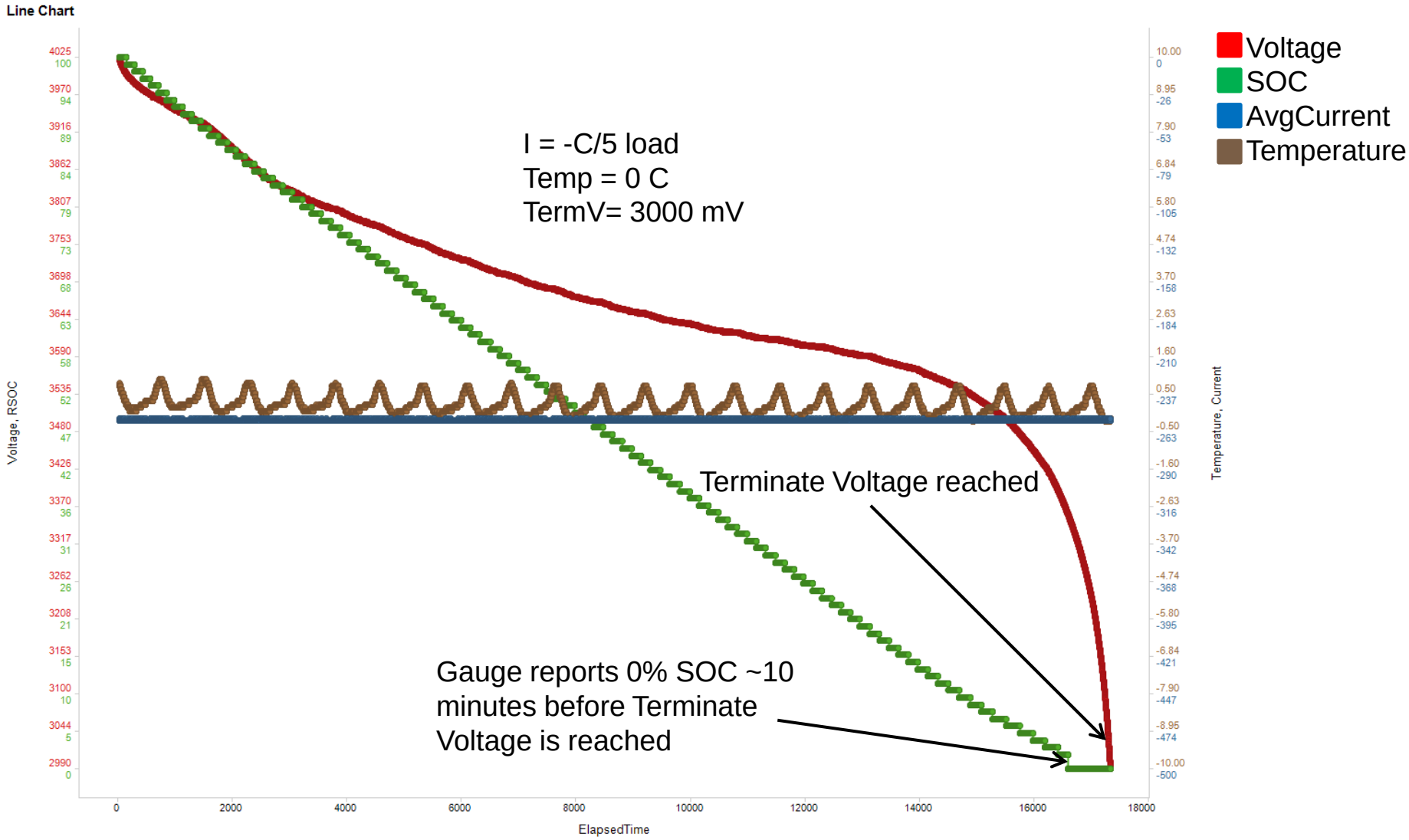
bq27421 – Variable Load



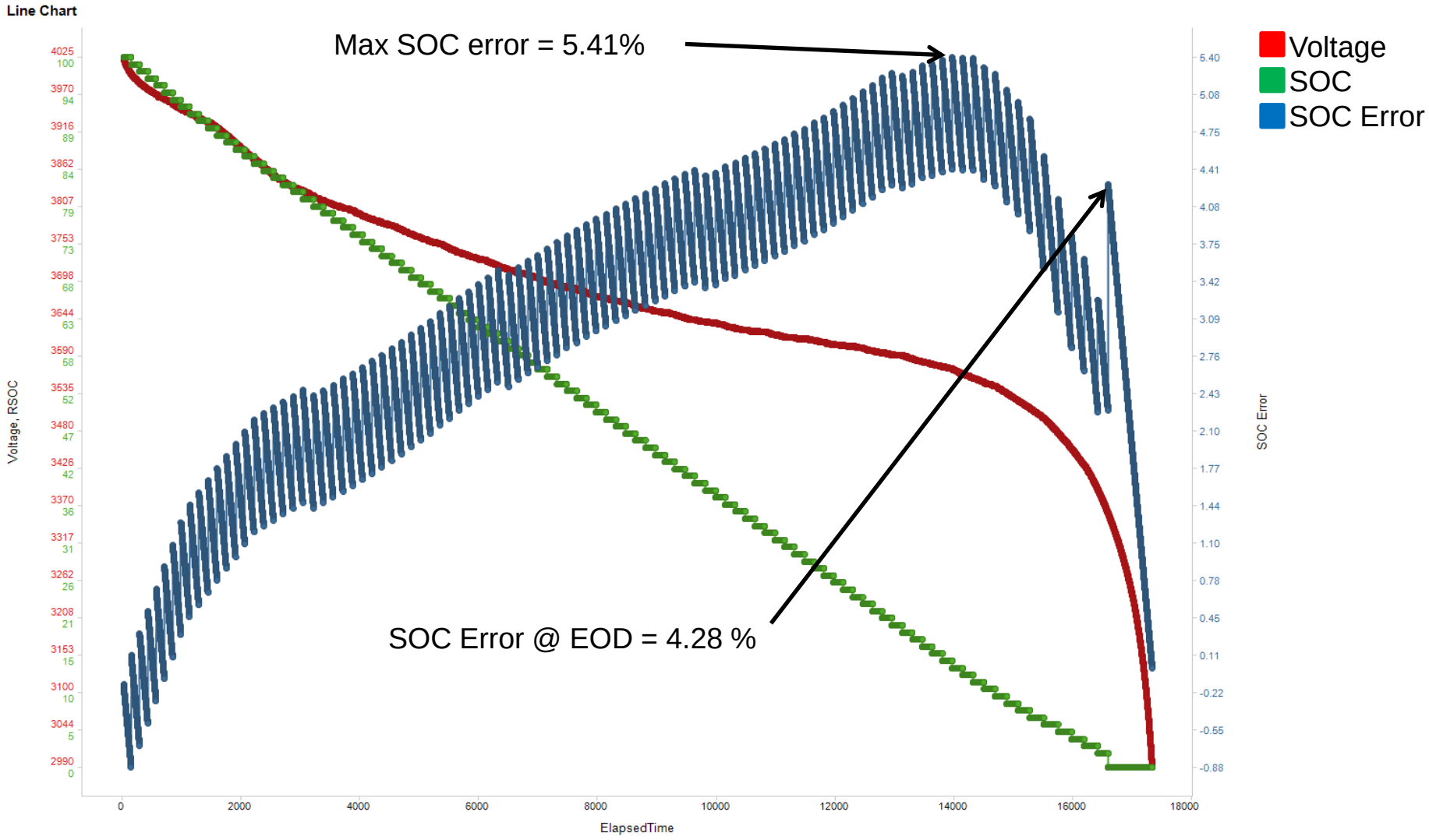
bq27421 – Variable Load



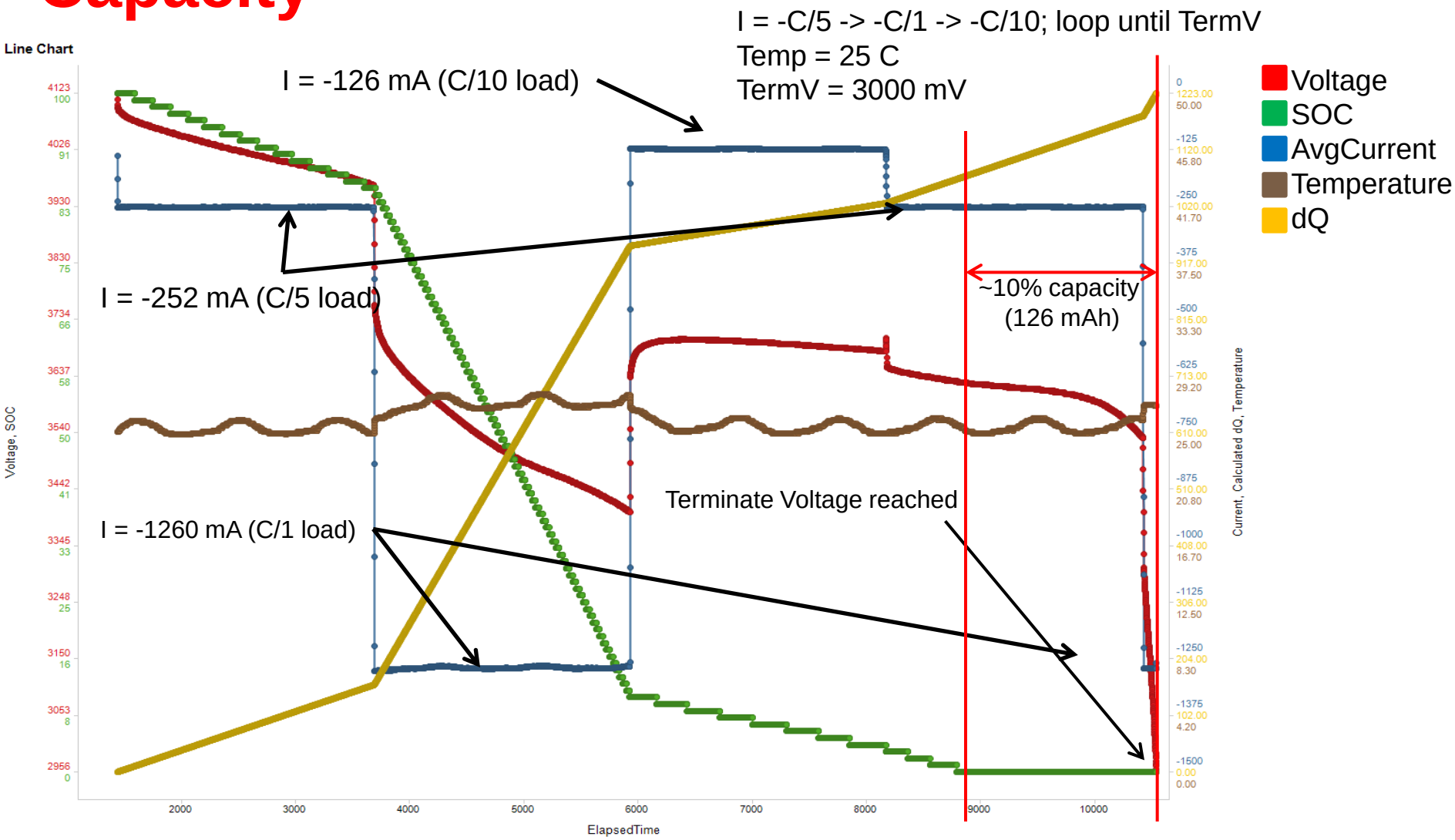
bq27421 – C/5 Discharge, Cold Temp



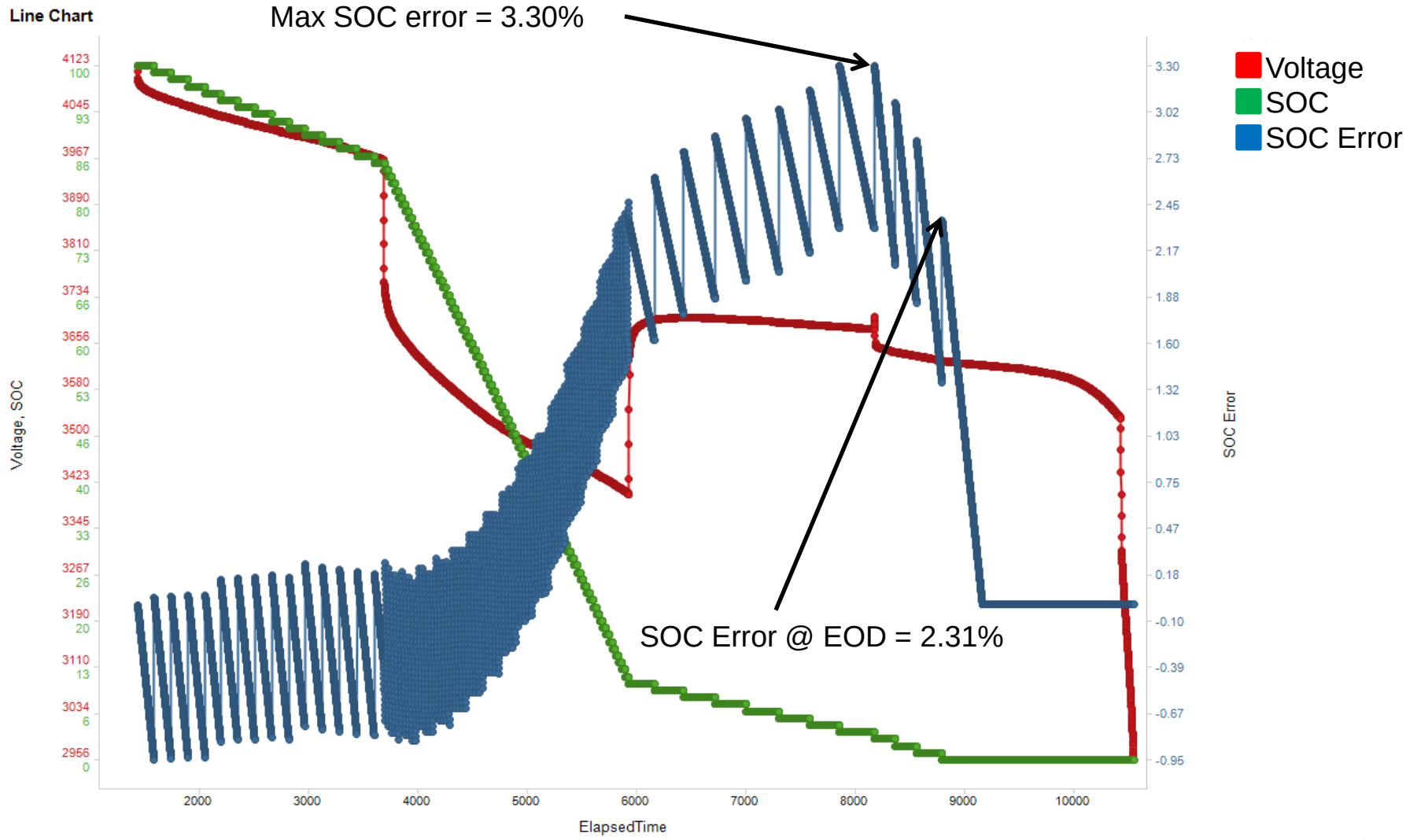
bq27421 – C/5 Discharge, Cold Temp



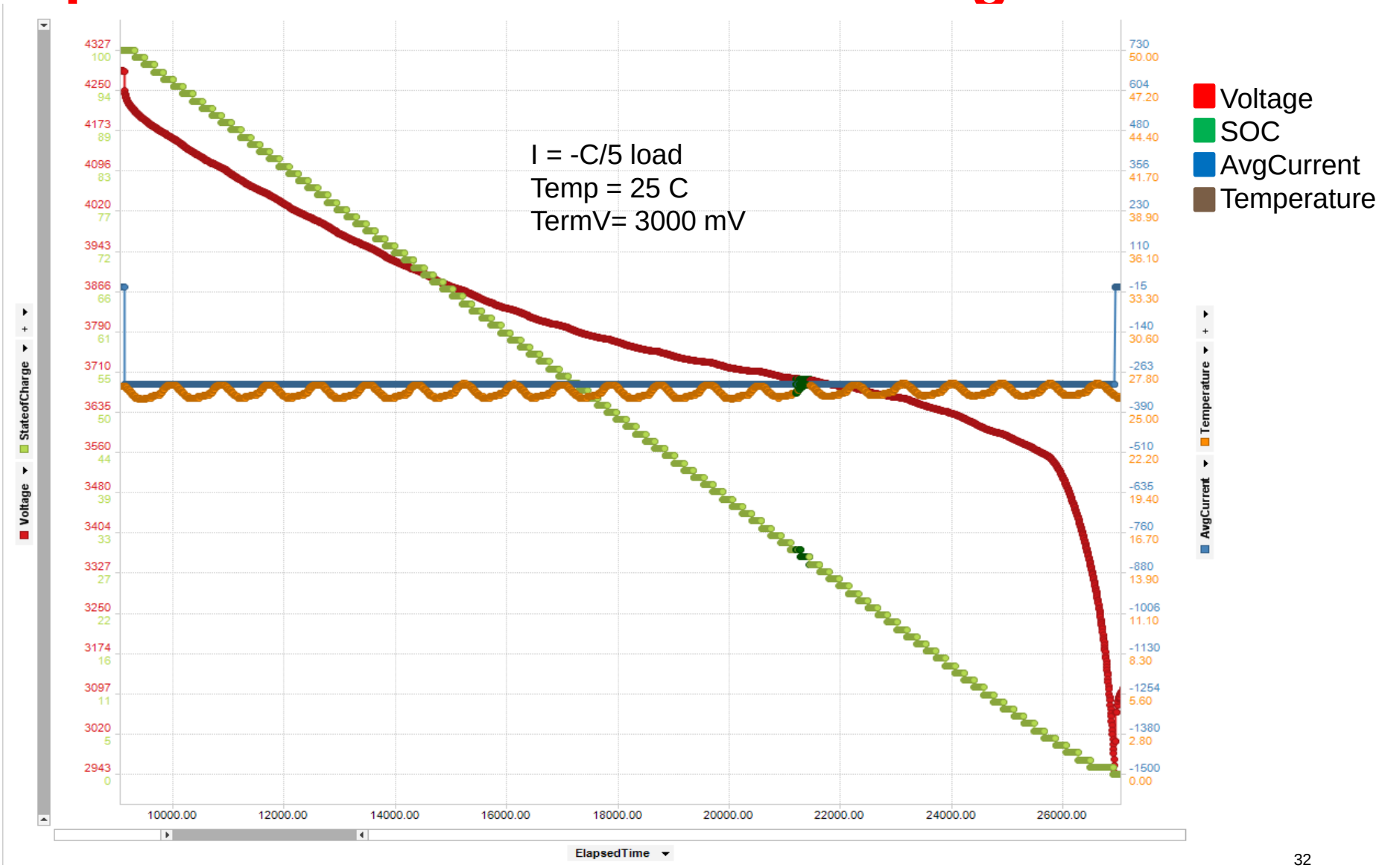
bq27421 – Variable Load with Reserve Capacity



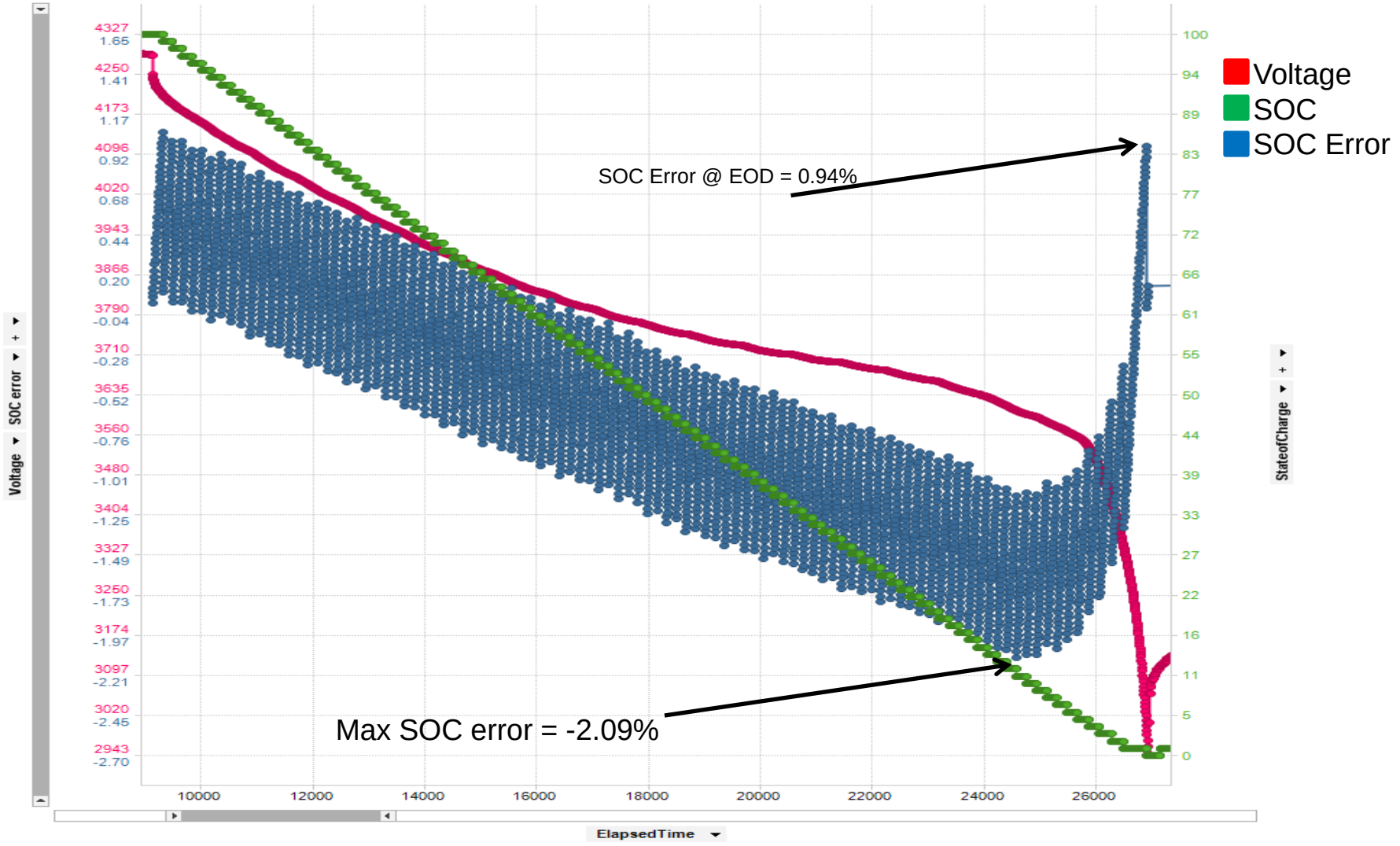
bq27421 – Variable Load with Reserve Capacity



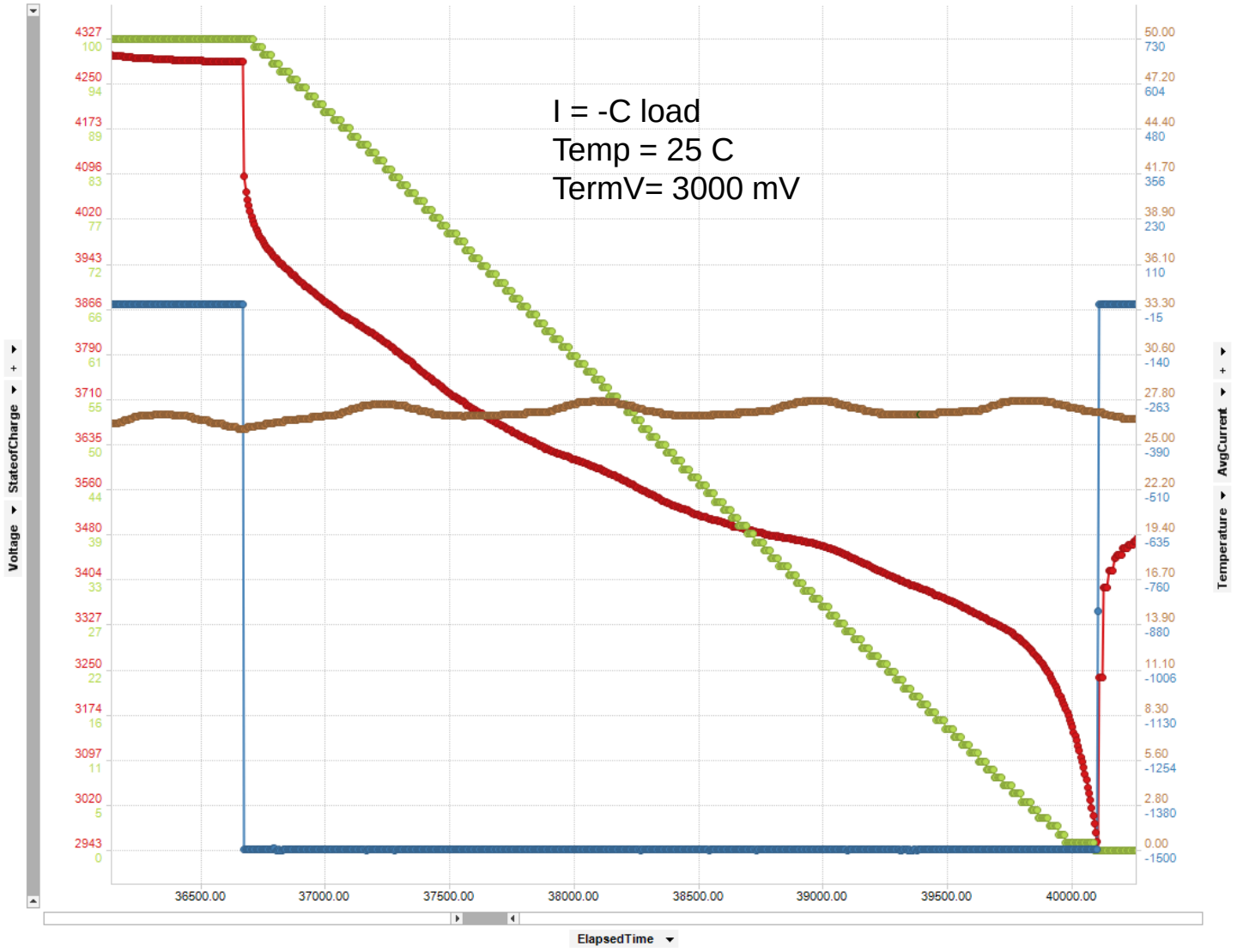
bq27742 – Standard C/5 Discharge



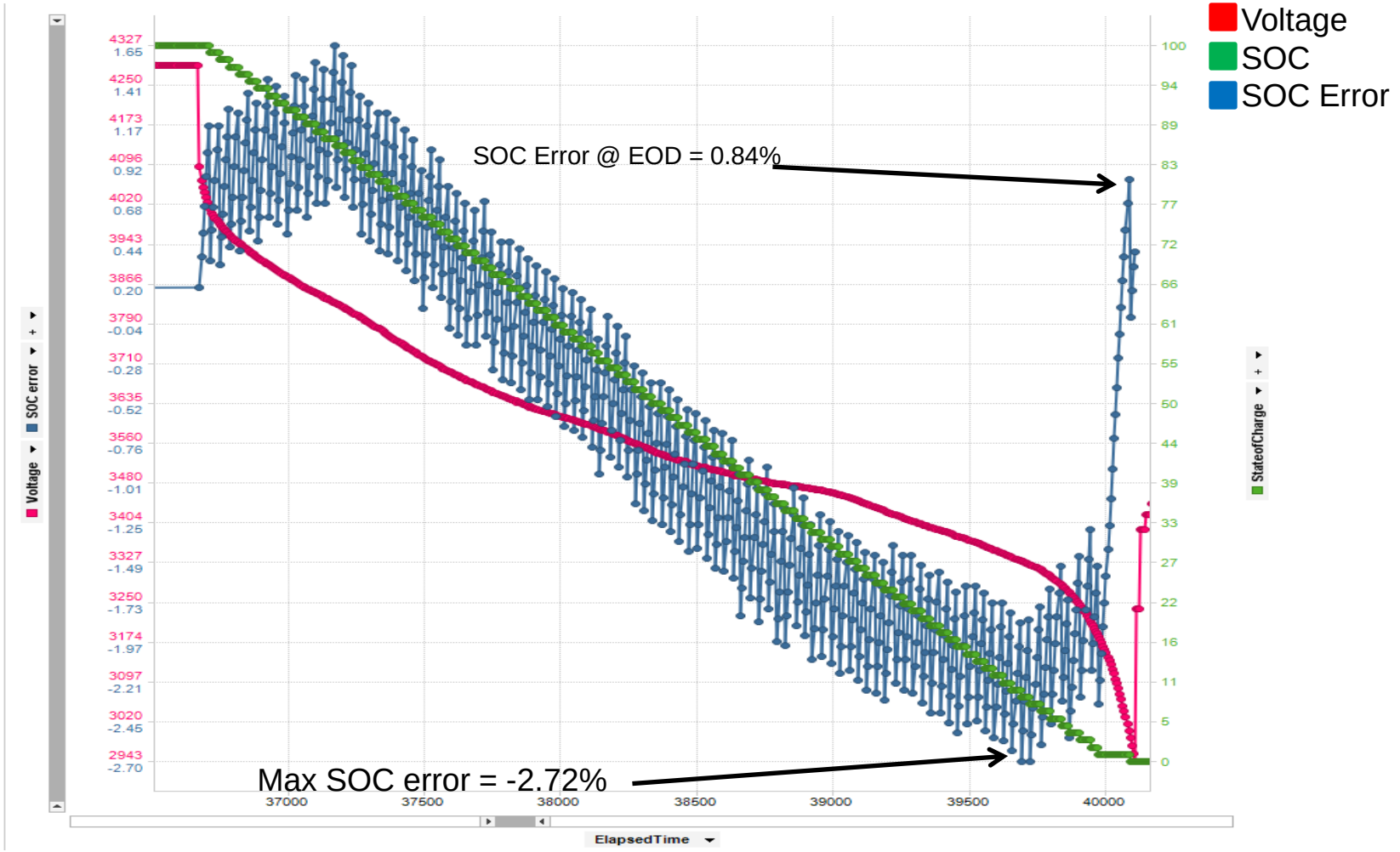
bq27742 – Standard C/5 Discharge



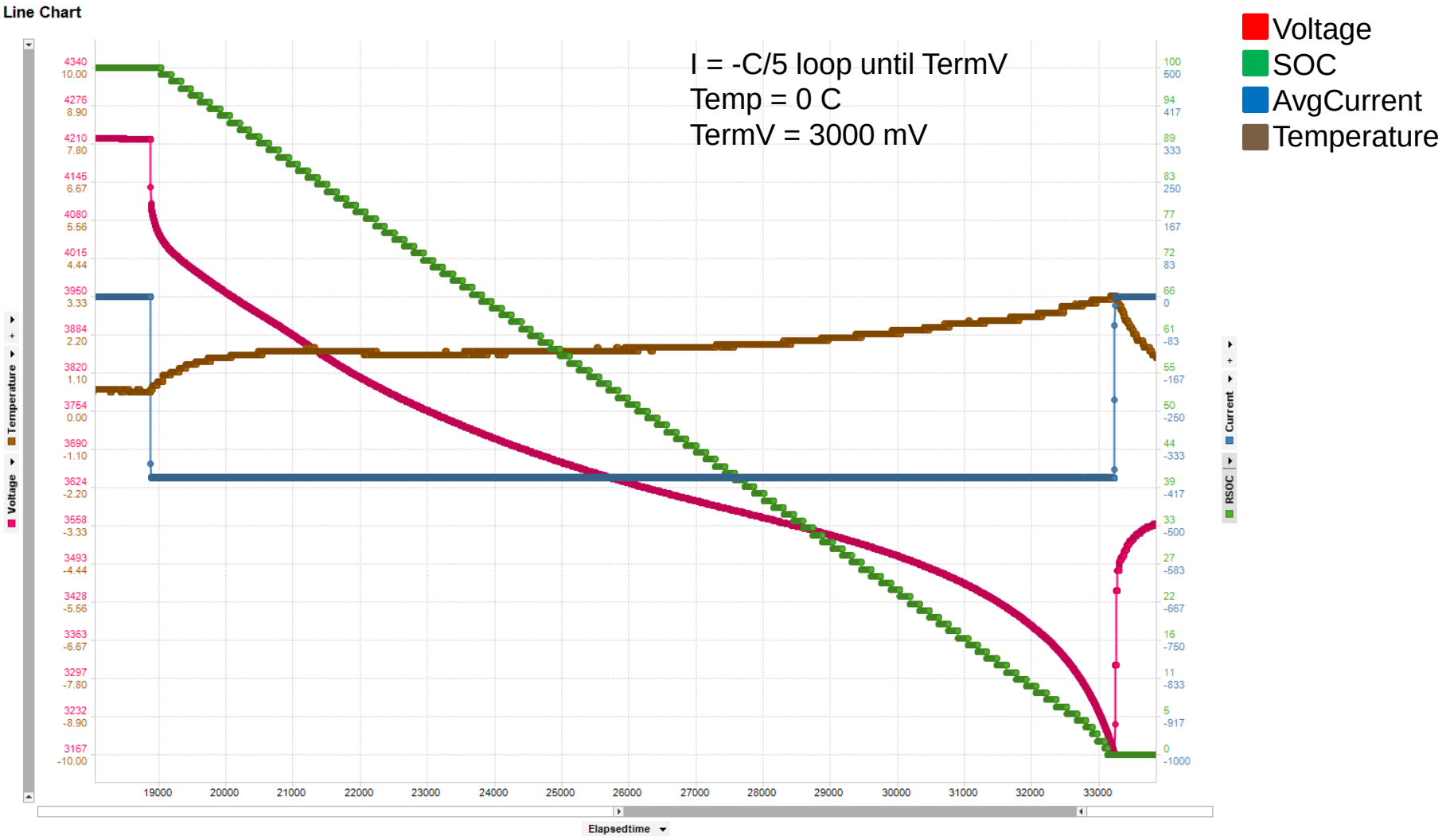
bq27742 –C Discharge



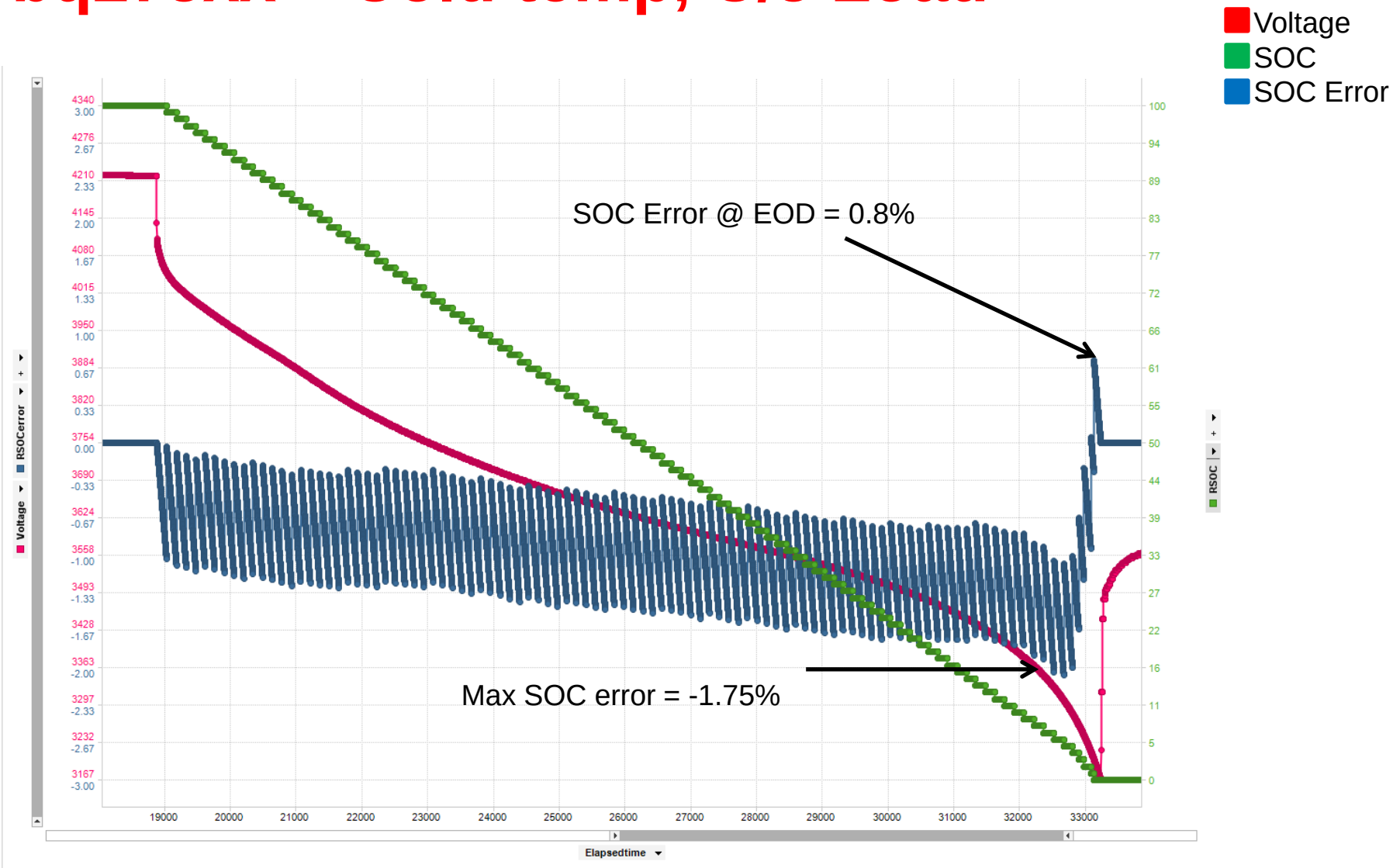
bq27742 –C Discharge



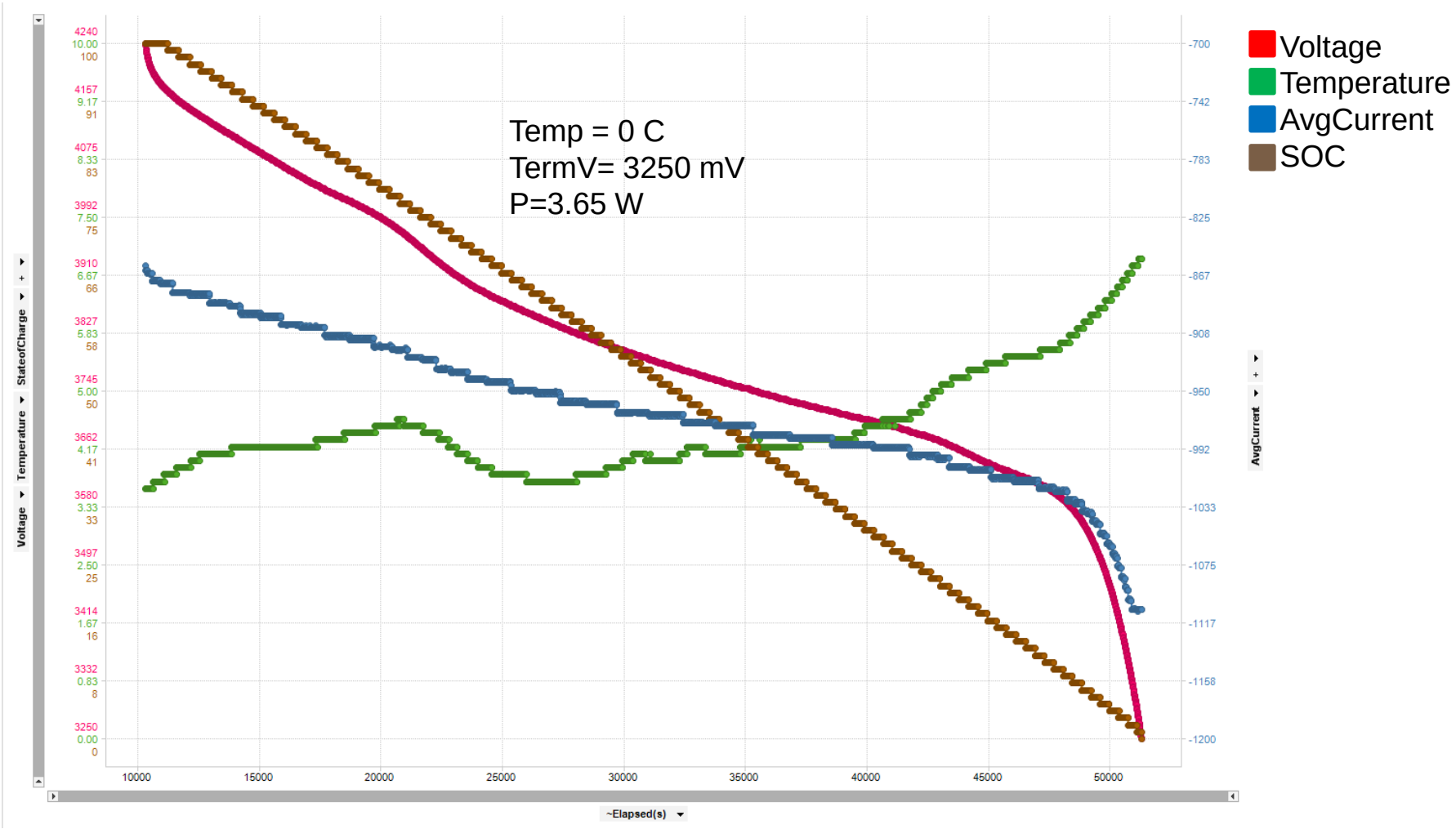
bq275xx – Cold temp, C/5 Load



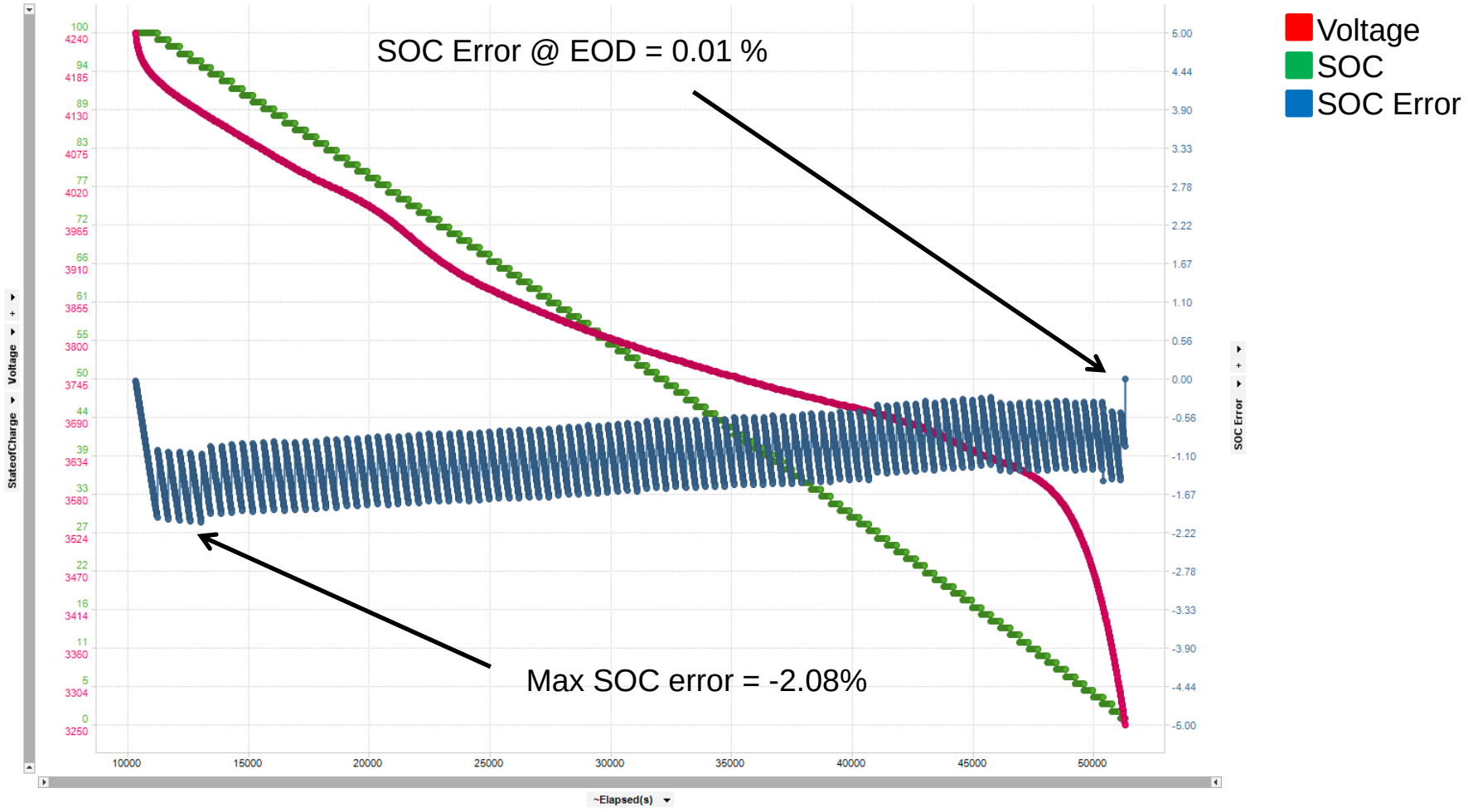
bq275xx – Cold temp, C/5 Load



bq275xx – Constant Power, Cold Temperature



bq275xx – Constant Power, Cold Temperature



Conclusions

Conclusion

- Gauging accuracy is dependent on the hardware measurement accuracy
- A more robust algorithm provides better accuracy. Impedance Tracking is the industry's most robust algorithm.
- To compute true accuracy, you need to know the actual capacity extracted from the battery for that particular test scenario.
- To compute true accuracy:
  - Integrate current in order to compute actual capacity extracted from the battery (FCC true)
  - Compute true remaining capacity (RM) by subtracting the integrated current from FCC true
  - Compute true SOC by dividing RM by FCC True.
  - Subtract gauge reported SOC from true SOC
- Use Impedance track for best gauging accuracy.

Questions??