CAP-XX

Supercapacitors Enable µPower Energy Harvesters to Power Wireless Sensors

and do other useful things

(Everything you wanted to know about supercapacitors and were afraid to ask)

Sensors Expo June 2019
Pierre Mars
VP Quality & Applications Engineering
www.cap-xx.com

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Energy Harvesting

- The environment has infinite energy, sensors are everywhere, so why have small energy harvesters not taken off as forecast?

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Some Forecasts

- Forecast 1, https://www.prnewswire.com/news-releases/energy-harvesting-market-worth-42-billion-by-2019-global-industry-analysis-size-share-growth-trends-and-forecast-2012---2018-237000391.html
  - Energy Harvesters markets **at $131.4 million in 2012 are projected to increase to $4.2 billion in 2019**. Growth is anticipated to be based on demand for micro power generation that can be used to charge thin film batteries. Systems provide clean energy that is good for the environment. Growth is based on global demand for sensors and wireless sensor networks that permit control of systems.
- Forecast 2, https://www.marketwatch.com/press-release/global-energy-harvesting-market-2019-industry-analysis-size-share-strategies-and-forecast-to-2023-2019-03-28
  - **$500M in 2018 and forecast $1030M in 2025**
  - List of key players shows this report also deals with micro power.

CAP-XX Hurdles for Small Energy Harvesters

- Price (CR2032 coin cell ~US$0.3)
- 10's – 100's μW
- Knowledge:
  - How do I get enough power with EH?
  - How do I keep size, cost down?
  - How do I avoid complexity?
  - Efficiency?
- Solution:

  Supercapacitors
- Case Studies – visit us at booth 942

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Batteries

- Low cost
- Good energy density

But

- Need replacing, proper disposal (high cost)
- RoHS, SVHC, REACH (e.g. Mouser would not ship CR2032 to Australia, Element14 warning:
- High Internal impedance, especially when cold

Hazardous Item
There maybe additional transit time on this item. Delivery of other items on your order will be unaffected.

- May have complex charging algorithm & capacity estimation
- Self discharge / leakage current

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Supercapacitors

- "Infinite cycle life", physical charge storage
- Excellent power density
- Wide temperature range, -40°C to +85°C
- Low leakage current [CAP-XX ~1µA/F]
- Great round trip efficiency (~99%)
- From small thin prismatic form-factors to large cans
- Simple to charge: **Show me the current**

→ **An ideal power buffer**

But

- Low voltage: may need cells in series → Need cell balancing
- Not SMD

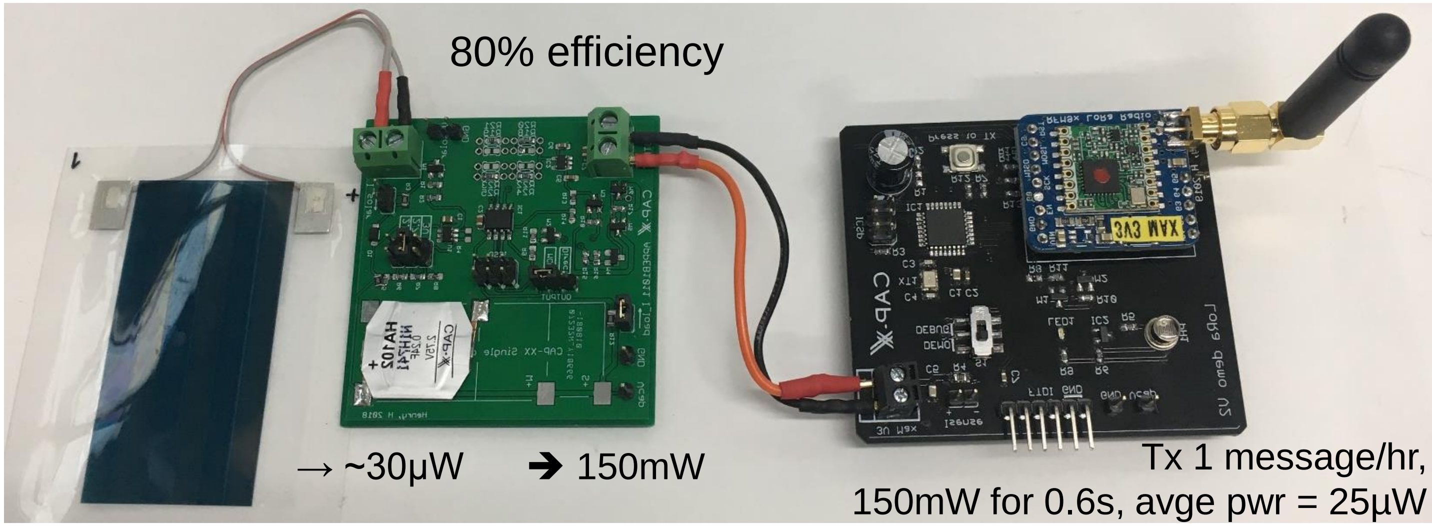
CAP-XX Supercapacitor: an Ideal Power Buffer

- Supercapacitor charged at low average power
- Supplies peak power bursts (low ESR)

And/or

- Backup power in case of energy loss (high C)

Regulate duty cycle so Avge Pwr Out ≤ Avge Pwr In



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Supercapacitor Properties

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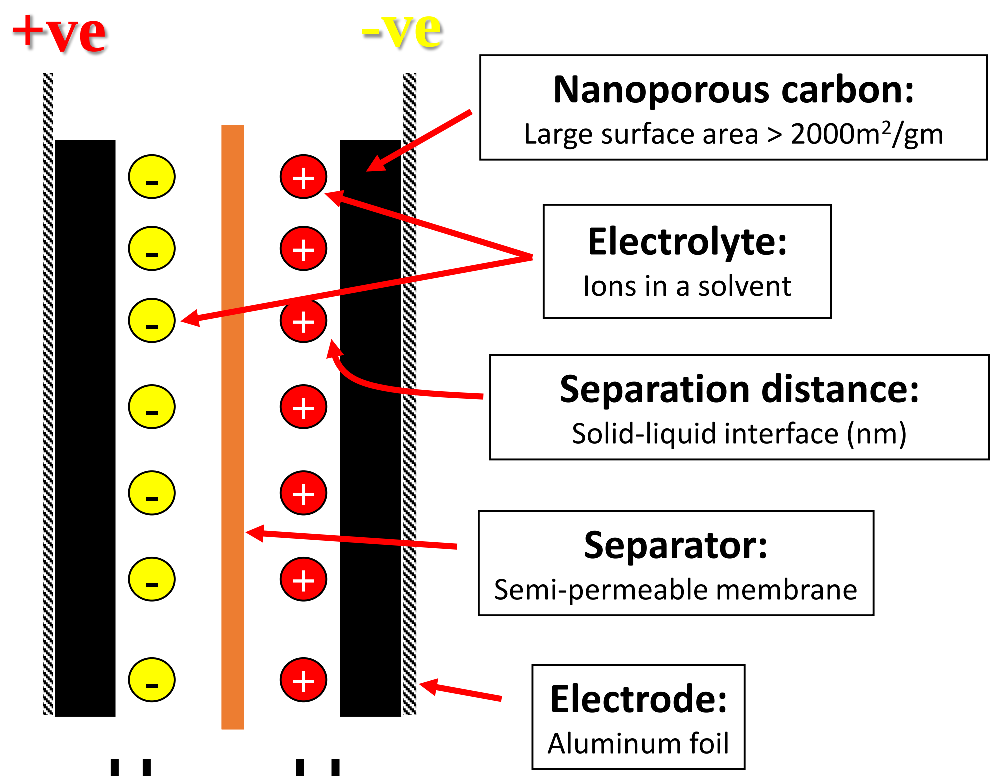
What makes a Supercap “Super”?

A supercapacitor is an energy storage device which utilizes high surface area carbon to deliver much higher energy density than conventional capacitors

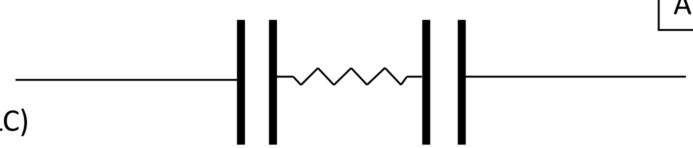
Basic Theory:
Capacitance is proportional to the charge storage area, divided by the charge separation distance (C α A / d)

As area (A) ↑, and
charge distance (d) ↓
capacitance (C) ↑↑↑↑

No dielectric, working voltage determined by electrolyte



Basic Electrical Model:
Electric Double Layer Capacitor (EDLC)



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What makes CAP-XX “Super”?

- Very small, very thin form factors
- Ultra-low impedance (ESR)
  - High power delivery (CAP-XX has world’s highest power density)
- Very high capacitance (C)
  - Provides the energy needed to keep delivering the power
- Easy to charge
  - Just need a charge current (from 20uA) & over-voltage protection
- Very low leakage current (<1µA)
- Unlimited cycle life (physical charge storage, no chemical reactions)
- Excellent low temperature performance
- Good frequency response

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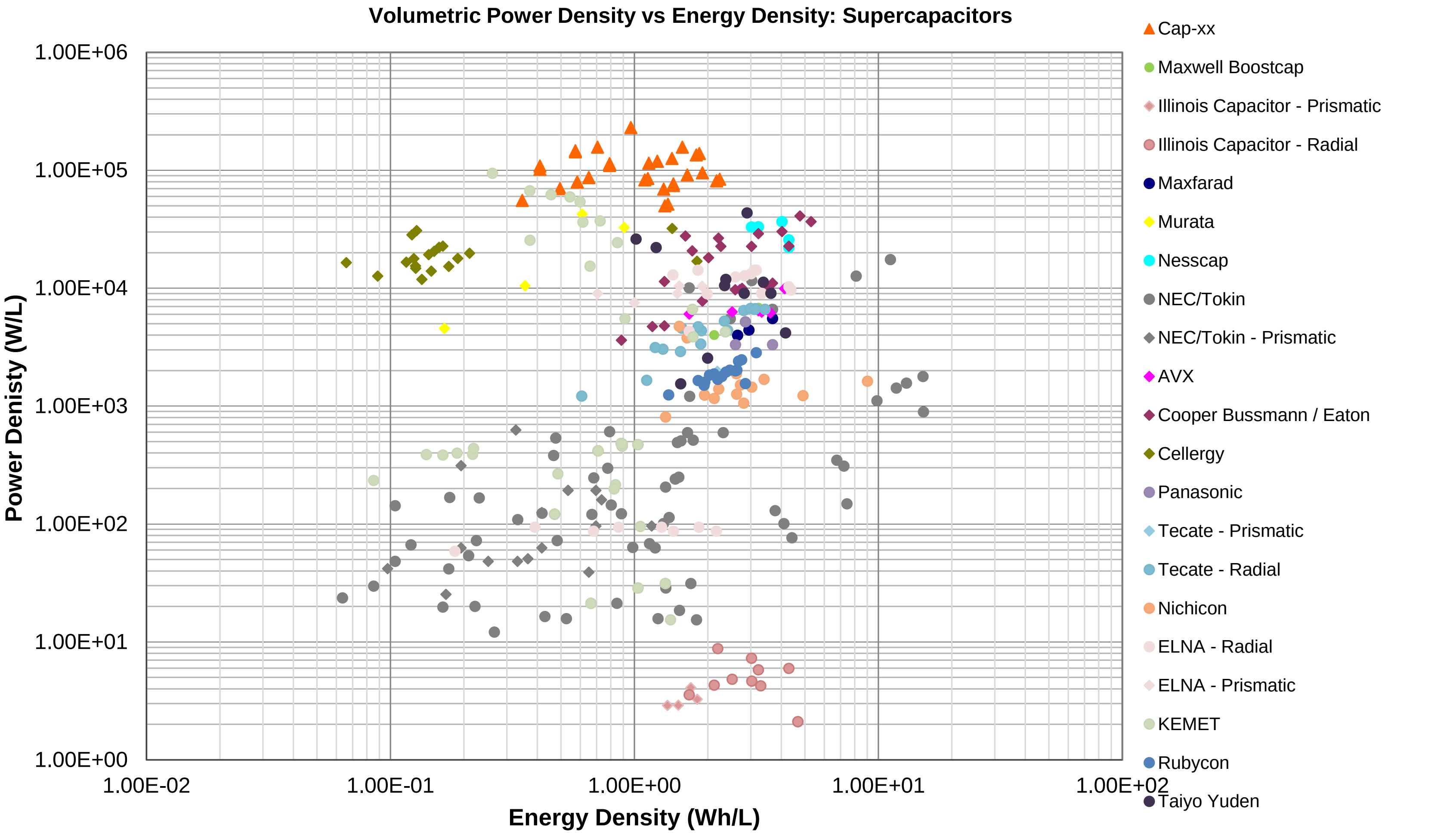
High Power & Energy Density



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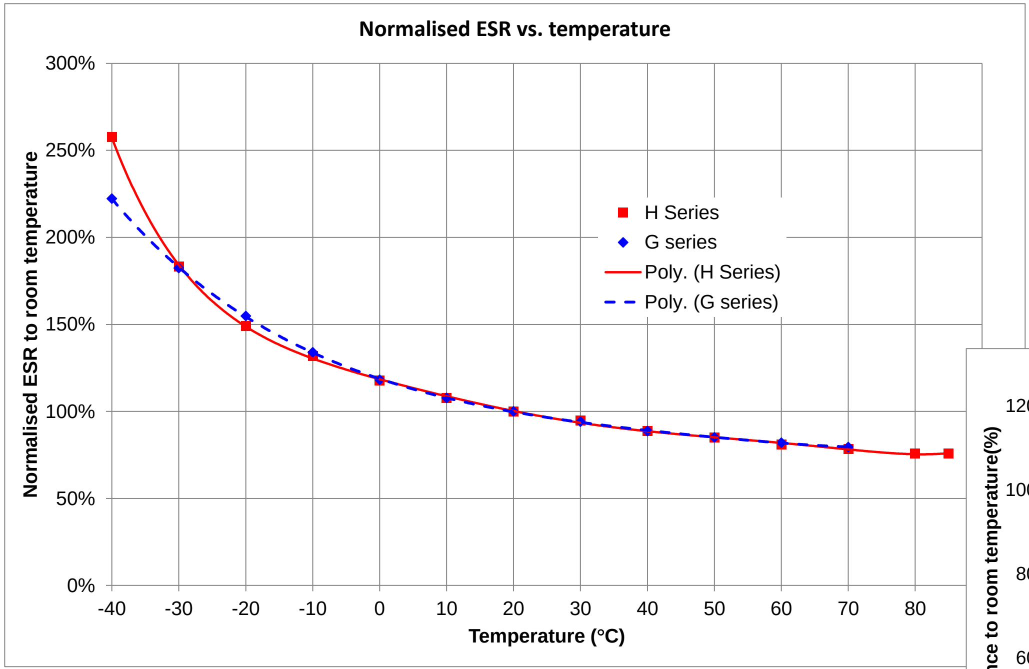
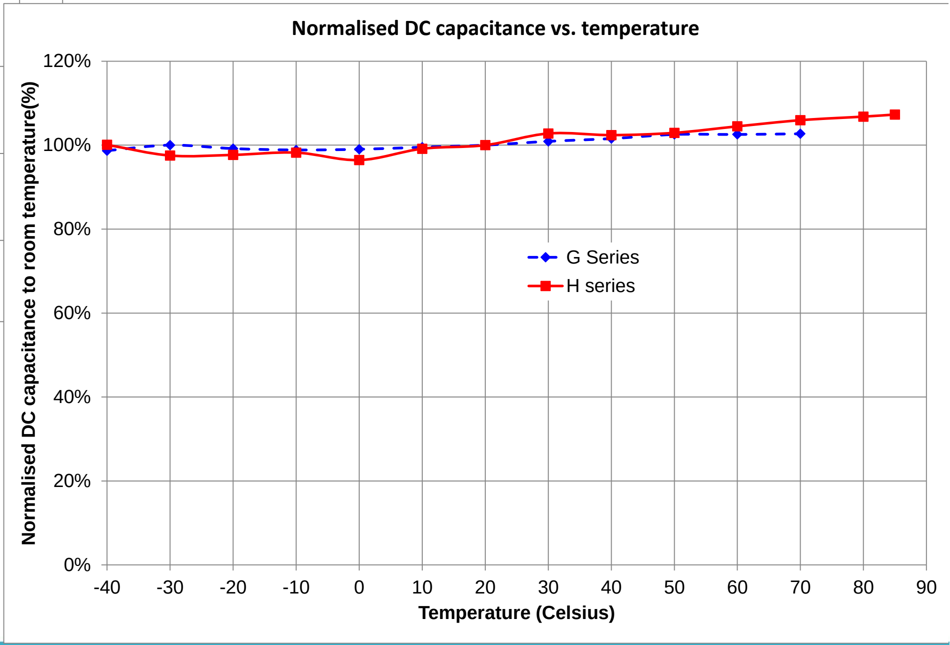
Supercapacitors operate over a wide temp range





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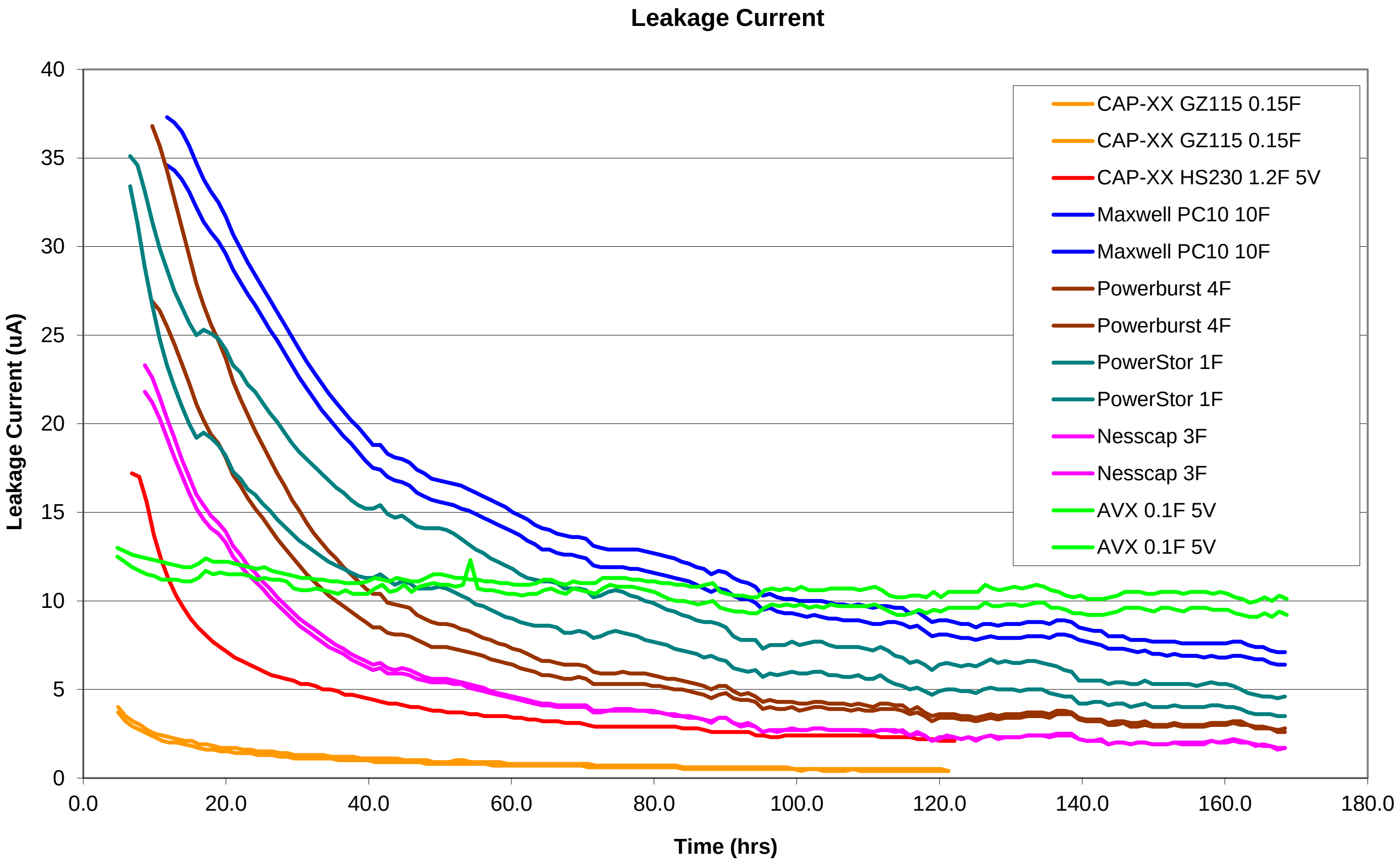
Leakage Current
Leakage Current (uA)
40
35
30
25
20
15
10
5
0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (hrs)
CAP-XX GZ115 0.15F
CAP-XX GZ115 0.15F
CAP-XX HS230 1.2F 5V
Maxwell PC10 10F
Maxwell PC10 10F
Powerburst 4F
Powerburst 4F
PowerStor 1F
PowerStor 1F
Nesscap 3F
Nesscap 3F
AVX 0.1F 5V
AVX 0.1F 5V

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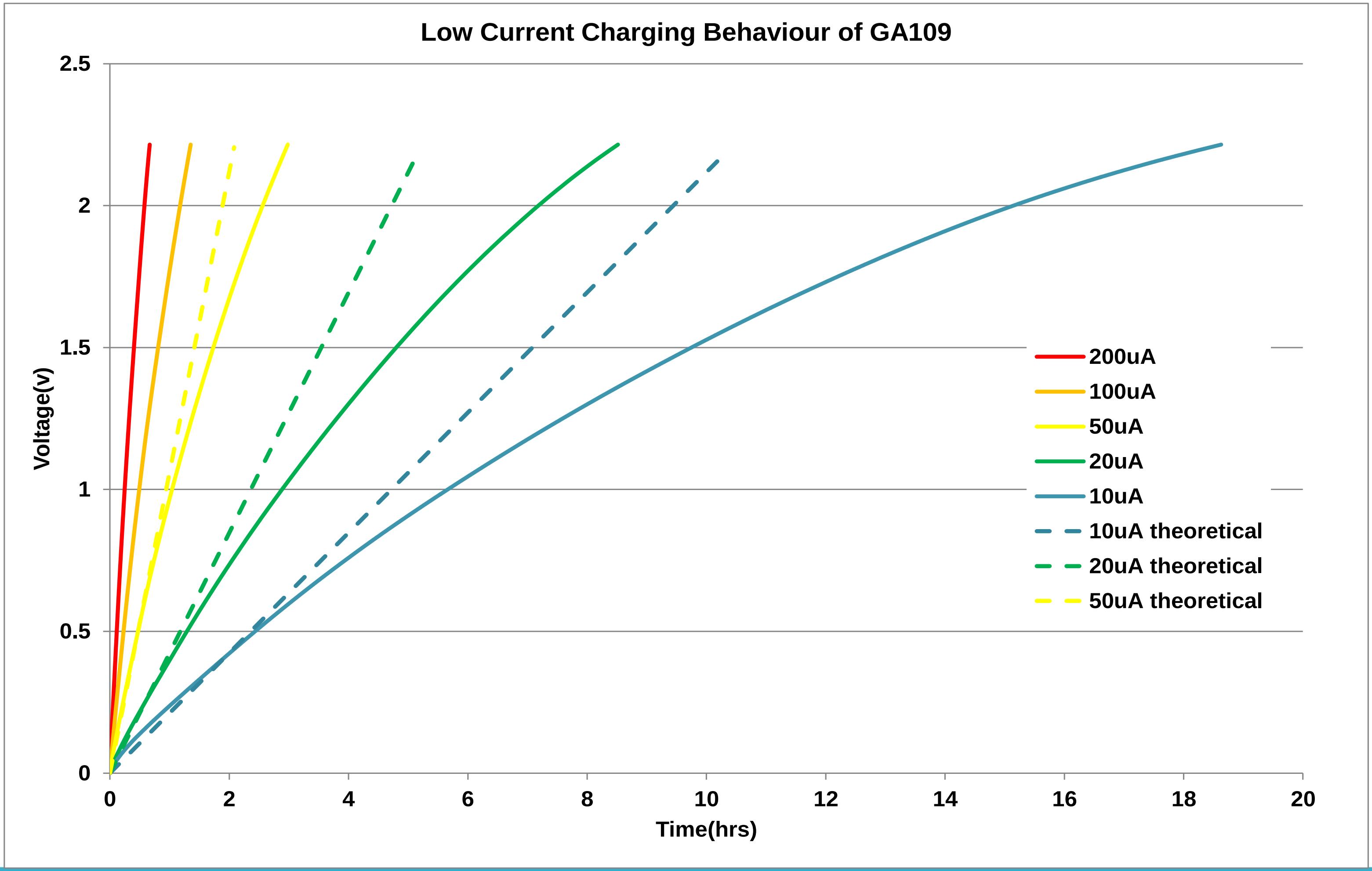
…translates to Low Charge Current



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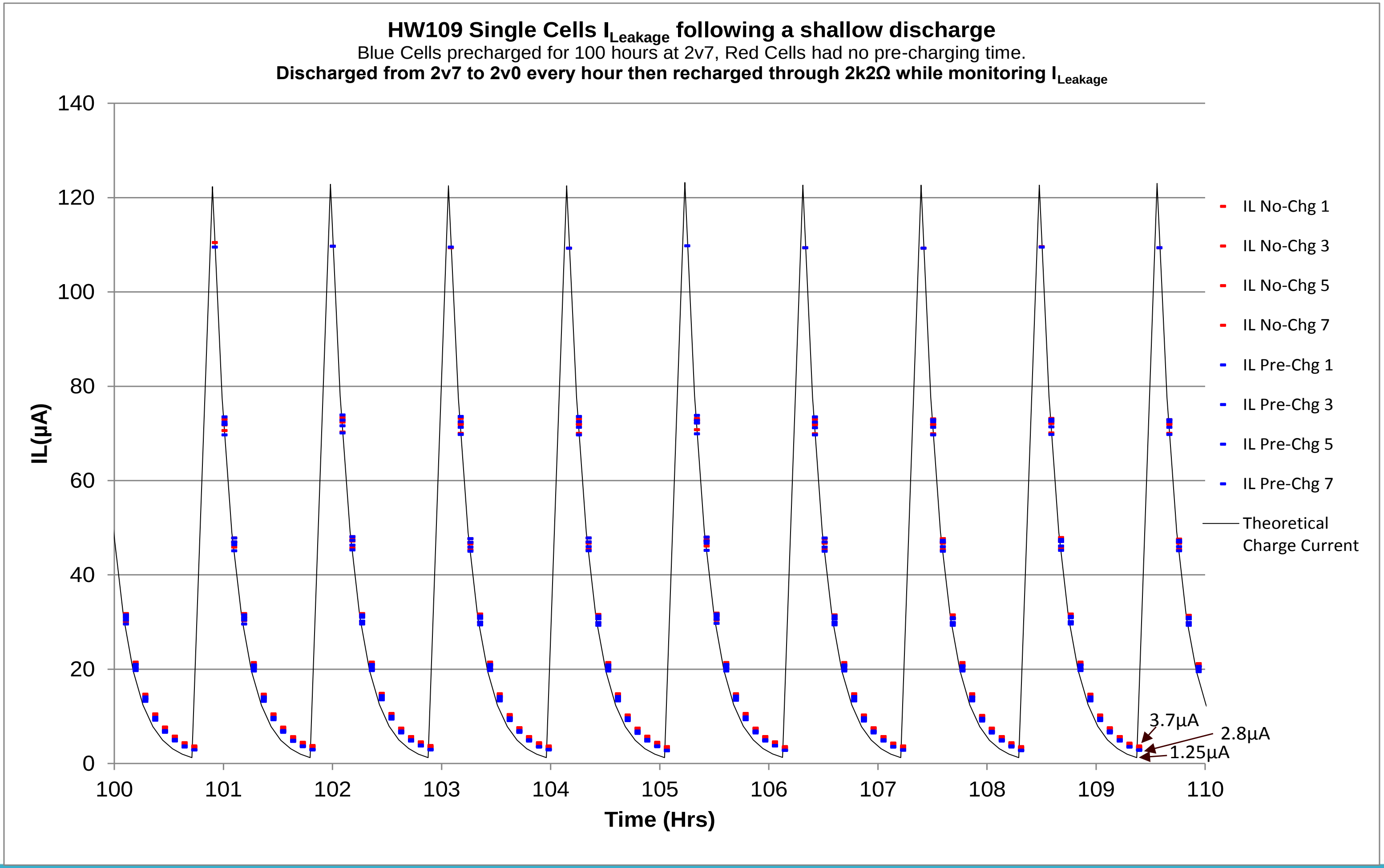
Shallow discharge steady state $I_{LEAKAGE}$



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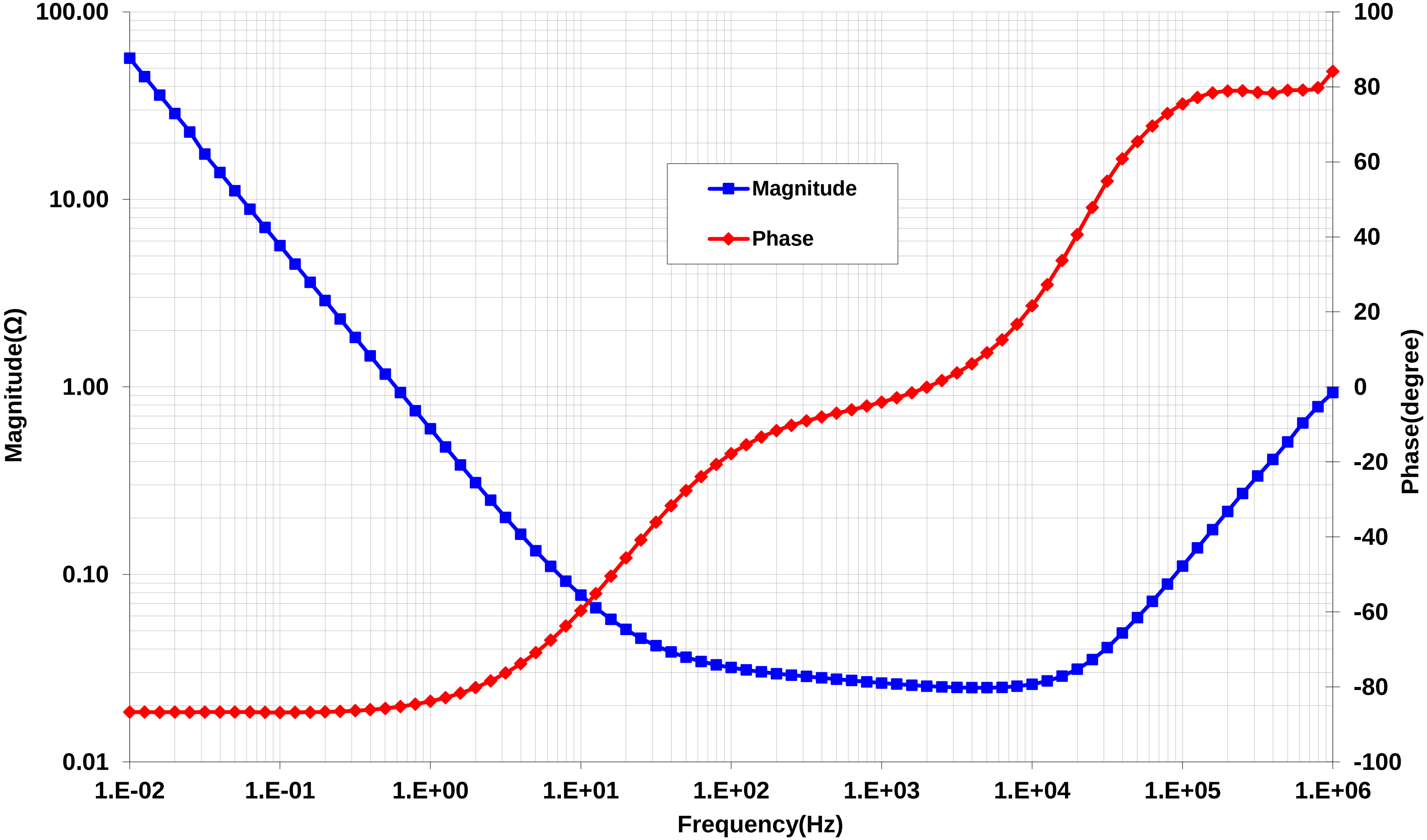
Poor Frequency Response ...



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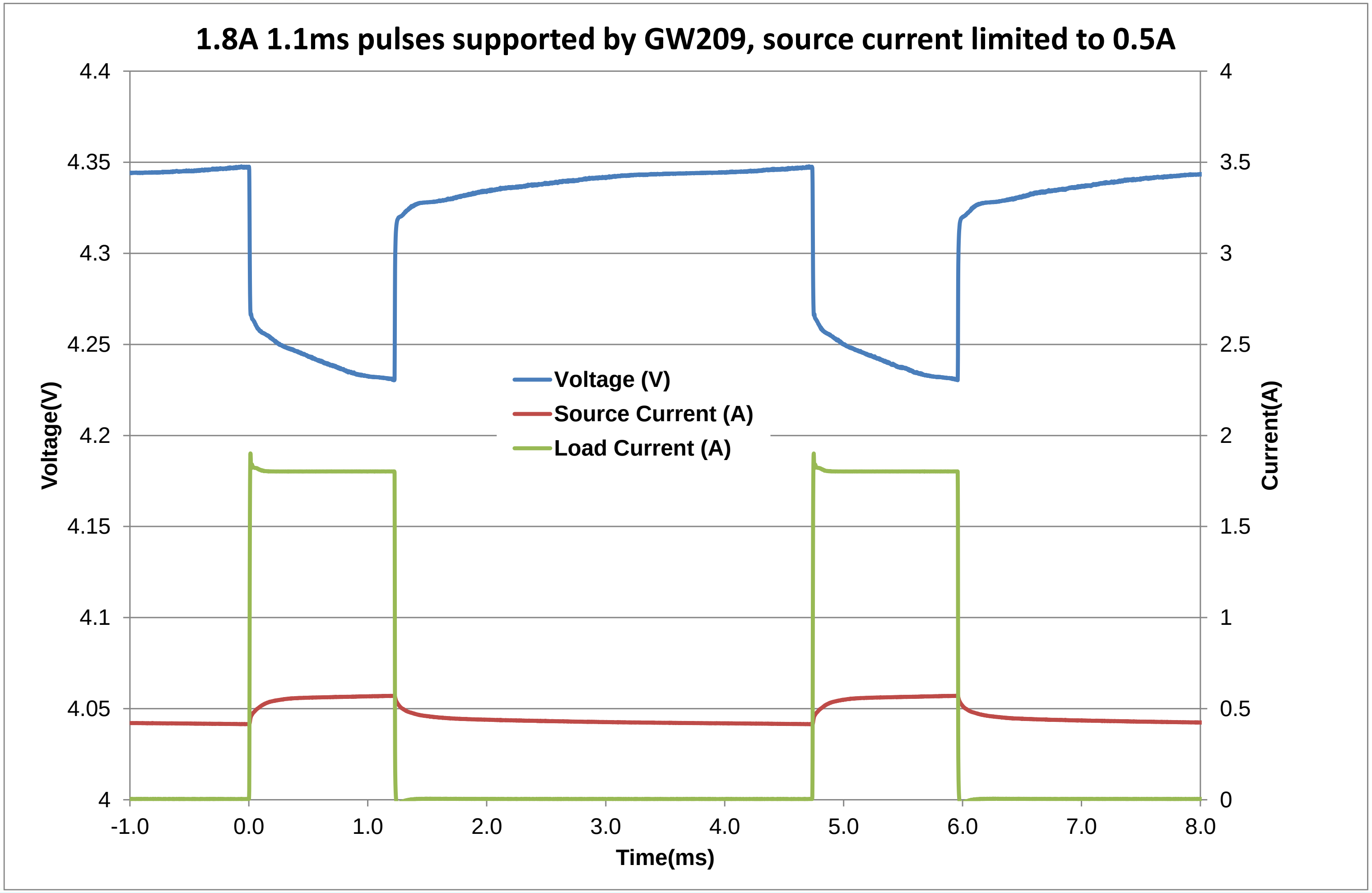
... But excellent pulse response



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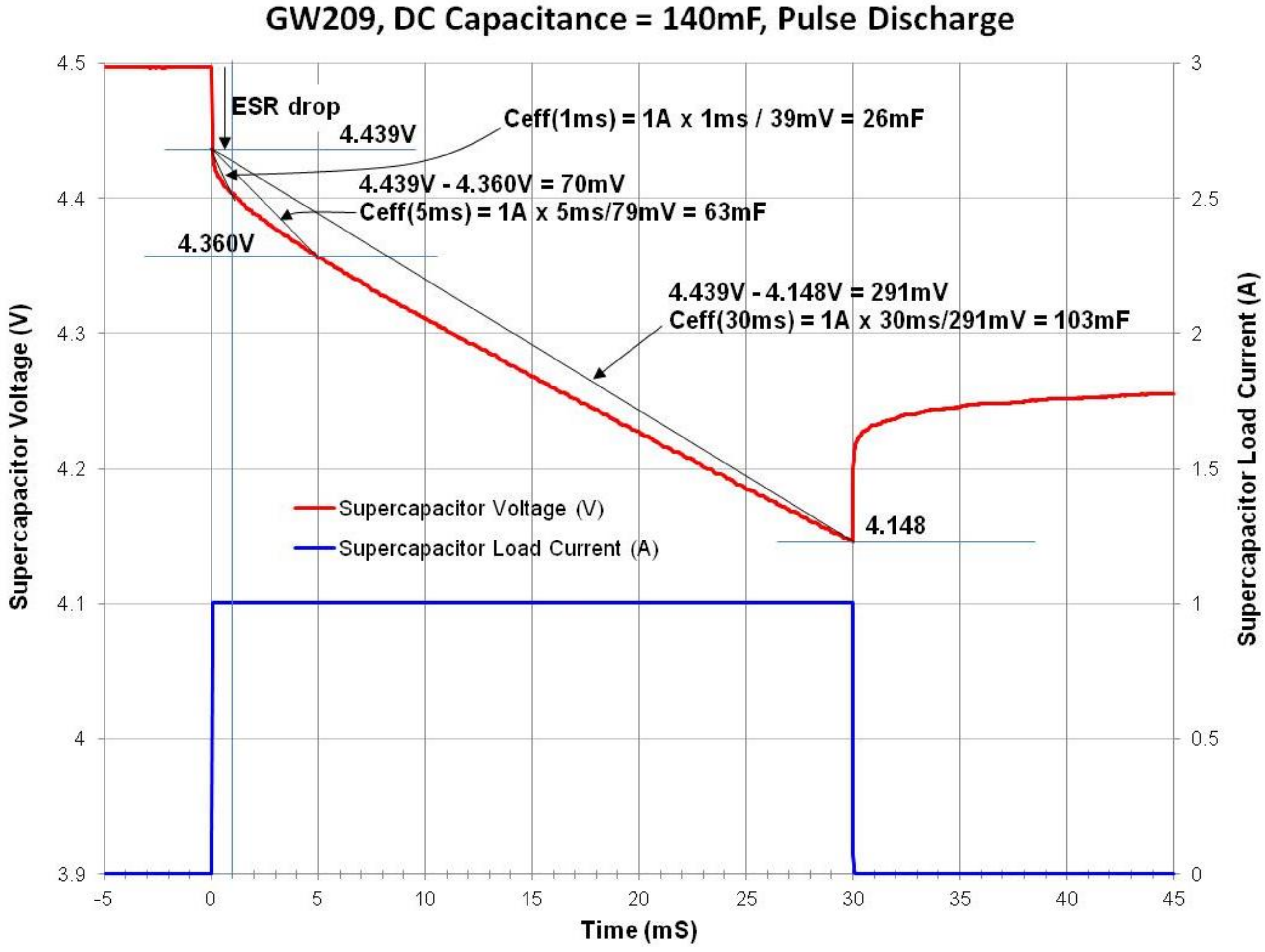
What is effective capacitance?



Effective capacitance is a time domain representation of freq response that can be used for a quick estimate of pulse response

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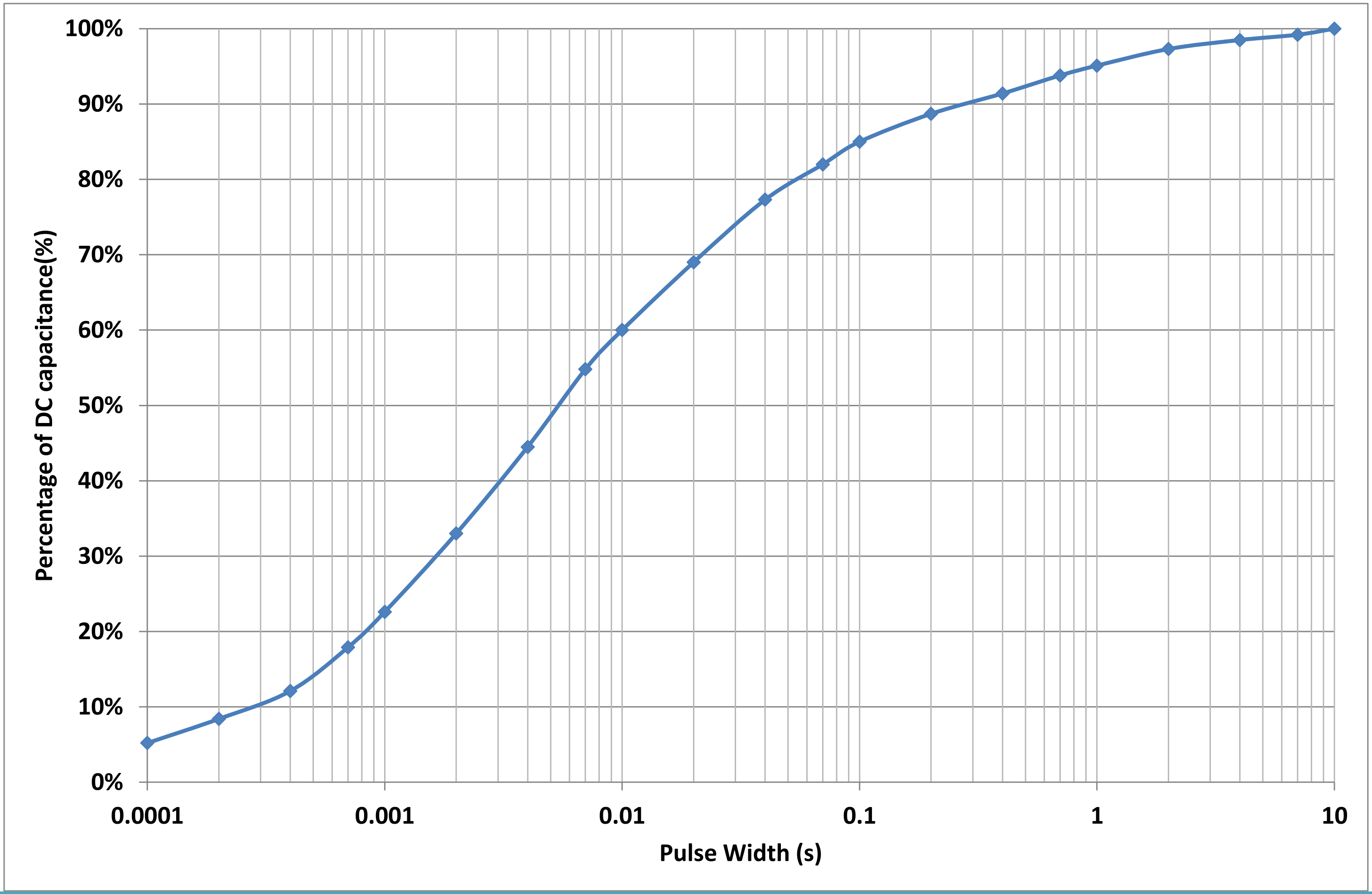
Effective Capacitance (GW209)



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Efficient Charge / Discharge Cycle

- Losses = I^2R x duration during charge, discharge
- Energy in/out = 2 x ½ C ($V^2_{MAX} - V^2_{MIN}$)
- Efficiency = $\dfrac{\text{Energy in/out}}{\text{Energy in/out + Losses}} = \dfrac{\text{Energy in/out}}{\text{Energy in/out} + i^2.\text{ESR.t}}$

$$= \frac{\frac{1}{2}C(V_2^2 - V_1^2)}{\frac{1}{2}C(V_2^2 - V_1^2) + i^2.ESR.C\frac{(V_2 - V_1)}{i}}$$

For *i* = constant

$$= \frac{V_2 + V_1}{V_2 + V_1 + 2.i.ESR}$$

- Ex 1: GPRS 2A disch from 3.8V to 3.2V, ESR = 50mΩ, →η = 97.2%
- Ex 2: Charge @ 50mA from 3.2V to 3.8V, →η = 99.9%

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Cell Voltage Balancing

- Supercapacitors are low voltage devices
- Modules containing 2 or more supercapacitors in series are needed to achieve higher operating voltages
- Multi-cell modules need voltage balancing to ensure that slight differences in leakage current do not cause voltage imbalances between the cells
- Without adequate voltage balancing, one cell may go over-voltage, leading to accelerated ageing & premature failure
- Balancing can be:
  - Passive (simple, but costly in terms of energy lost), or
  - Active (to achieve the minimum possible leakage current)

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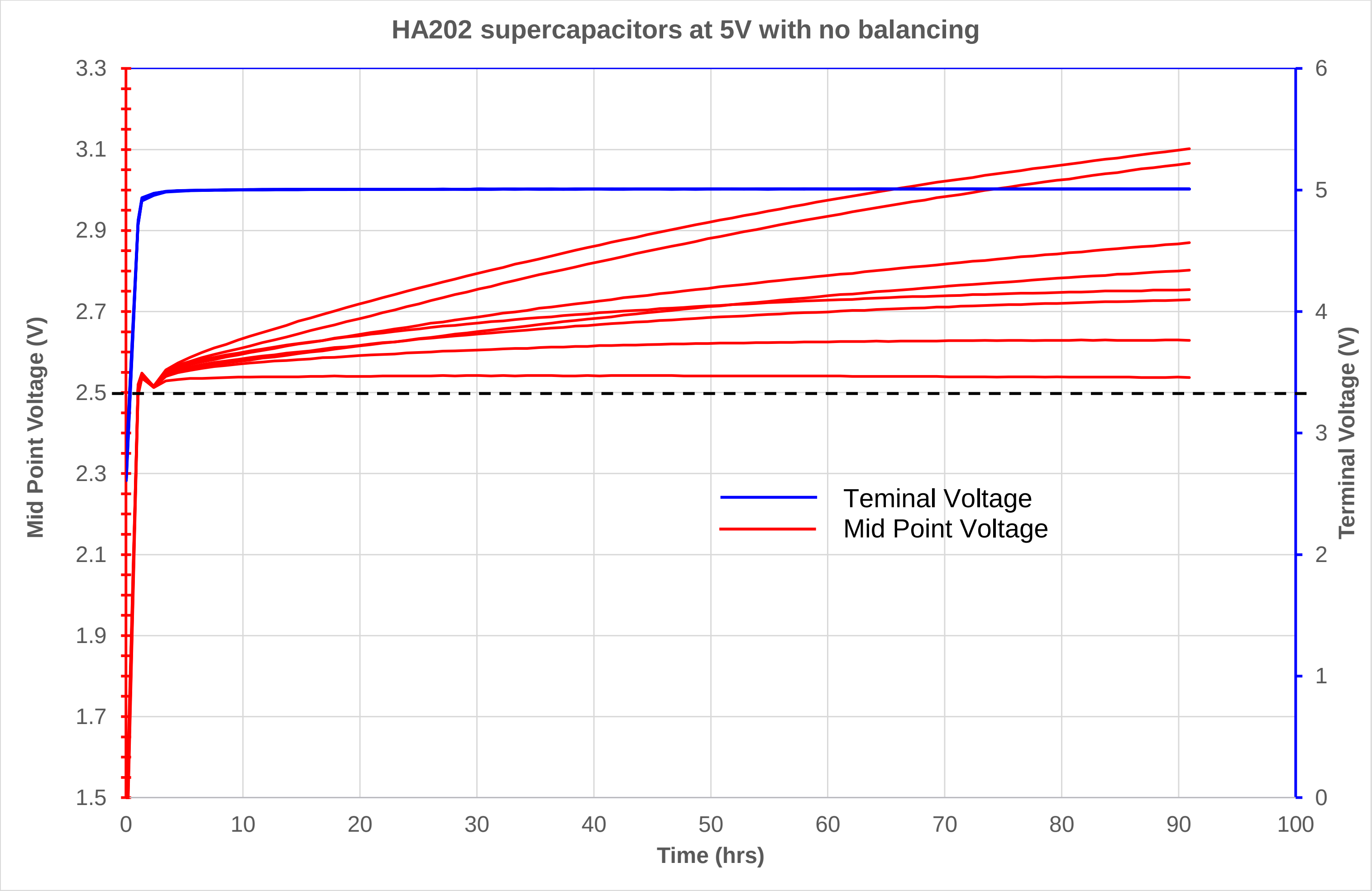
No balancing



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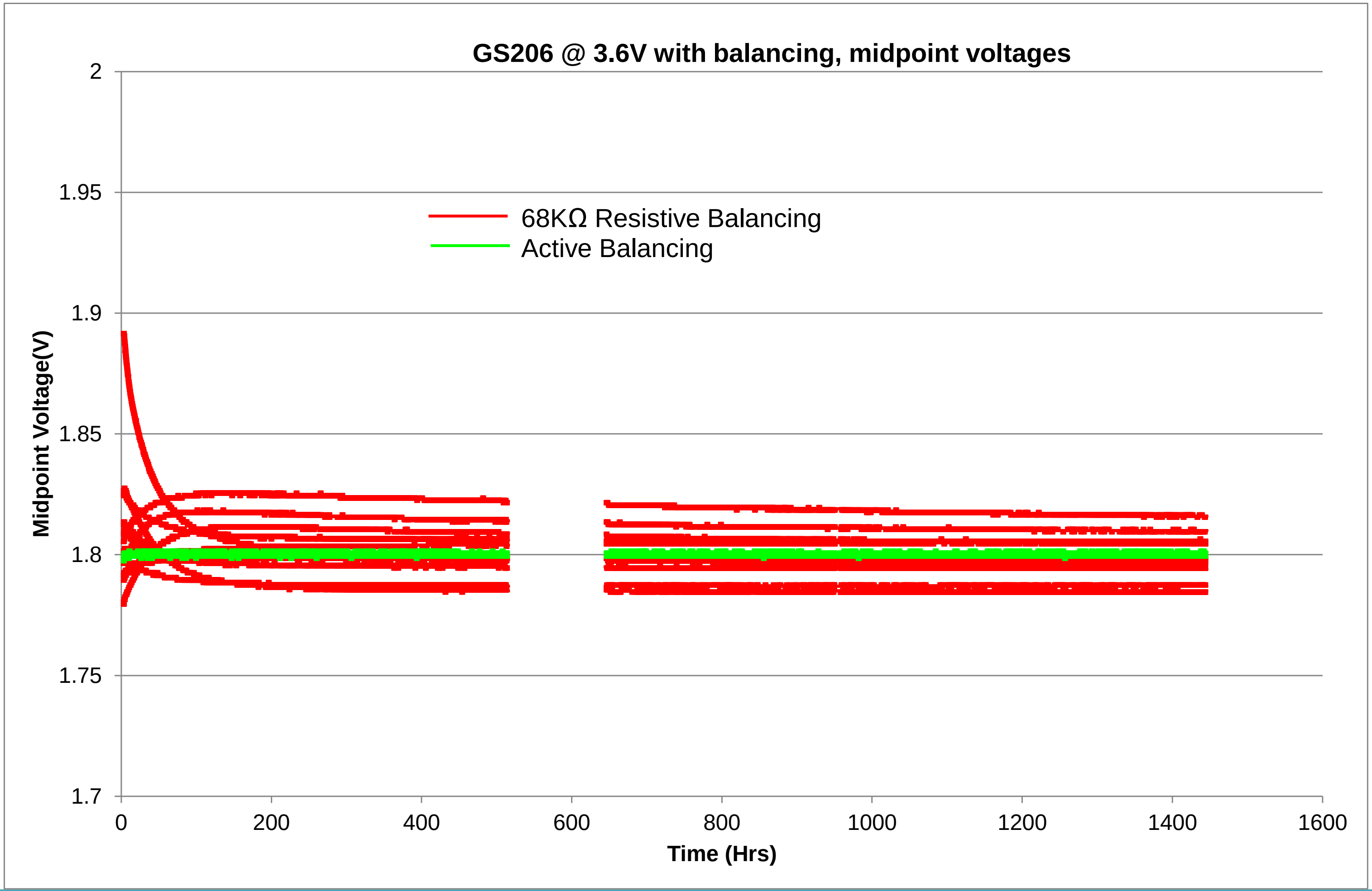
With balancing



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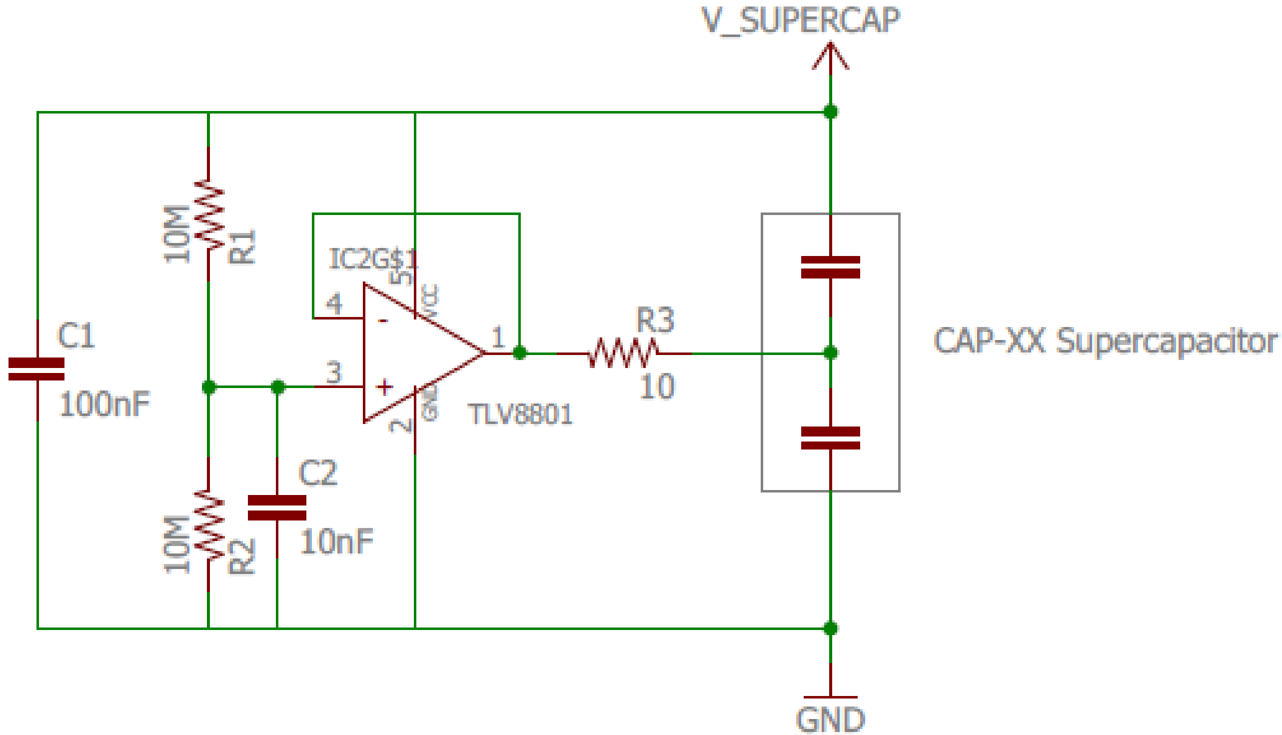
Active Balancing with an Op Amp

- Low current rail-rail op amp, ~500nA
- Can source or sink current, 4.7mA
- Supplies or sinks the difference in leakage current between the 2 cells to maintain balance
- Total current, supercapacitor leakage + balancing circuit ~2µA
- Low cost op amp



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Or Use a Single Cell

- If your circuit can run at 2.7V (prismatic) or 3V (cylindrical) or less, use a single cell
  - Simpler (no balancing required)
  - Cheaper
  - Thinner
- If source > 2.7V (or 3V) use a low power buck, e.g. TPS62743 (Iq 360nA), or LDO TPS78227 (Iq 500nA)
- Depends on energy / power required
- It’s a cost / size trade-off
- 3V prismatic cell coming !!

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Sizing the Supercapacitor

- Energy balance approach often used:

  Avg Load Power x Time = E = ½ $C(V_{init}^2 – V_{final}^2)$,

  $\therefore C = 2E/(V_{init}^2 – V_{final}^2)$
- But this implicitly assumes ESR = 0!
- This may lead to undersizing the supercapacitor.
- For constant current pulse of duration T:

  Vdrop = I_{LOAD} x [ESR + T/Ceff(T)]
- For constant power it will be worse as I_{LOAD} increases as Vsupercap decreases to keep V x I = const. See CAP-XX website for tools that solve this problem

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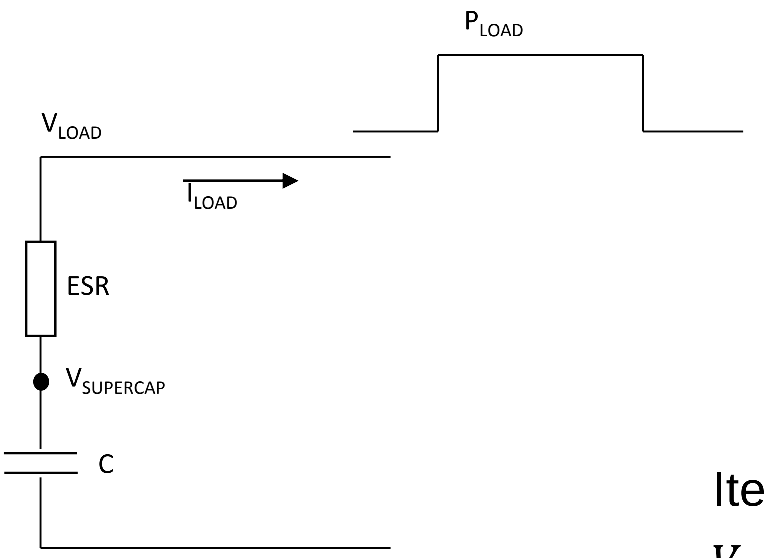
Equation for Constant Power



$$V_{LOAD} = V_{SUPERCAP} - I_{LOAD} \bullet ESR$$

$$P_{LOAD} = V_{LOAD} \bullet I_{LOAD}$$

$$P_{LOAD} = (V_{SUPERCAP} - I_{LOAD} \bullet ESR) \bullet I_{LOAD}$$

$$\therefore I_{LOAD}^2 \bullet ESR - V_{SUPERCAP} \bullet I_{LOAD} + P_{LOAD} = 0$$

$$I_{LOAD} = \frac{V_{SUPERCAP} \pm \sqrt{V_{SUPERCAP}^2 - 4 \bullet ESR \bullet P}}{2 \bullet ESR}$$

Iterate:

$$V_{SUPERCAP}(t + dt) = V_{SUPERCAP}(t) - \frac{I_{LOAD}(t).dt}{C}$$

If load current is very small, I_{LOAD} x ESR << $V_{SUPERCAP}$ so use energy balance approach. Otherwise, use a spreadsheet to solve the above & simulate V & I over time, or use SPICE

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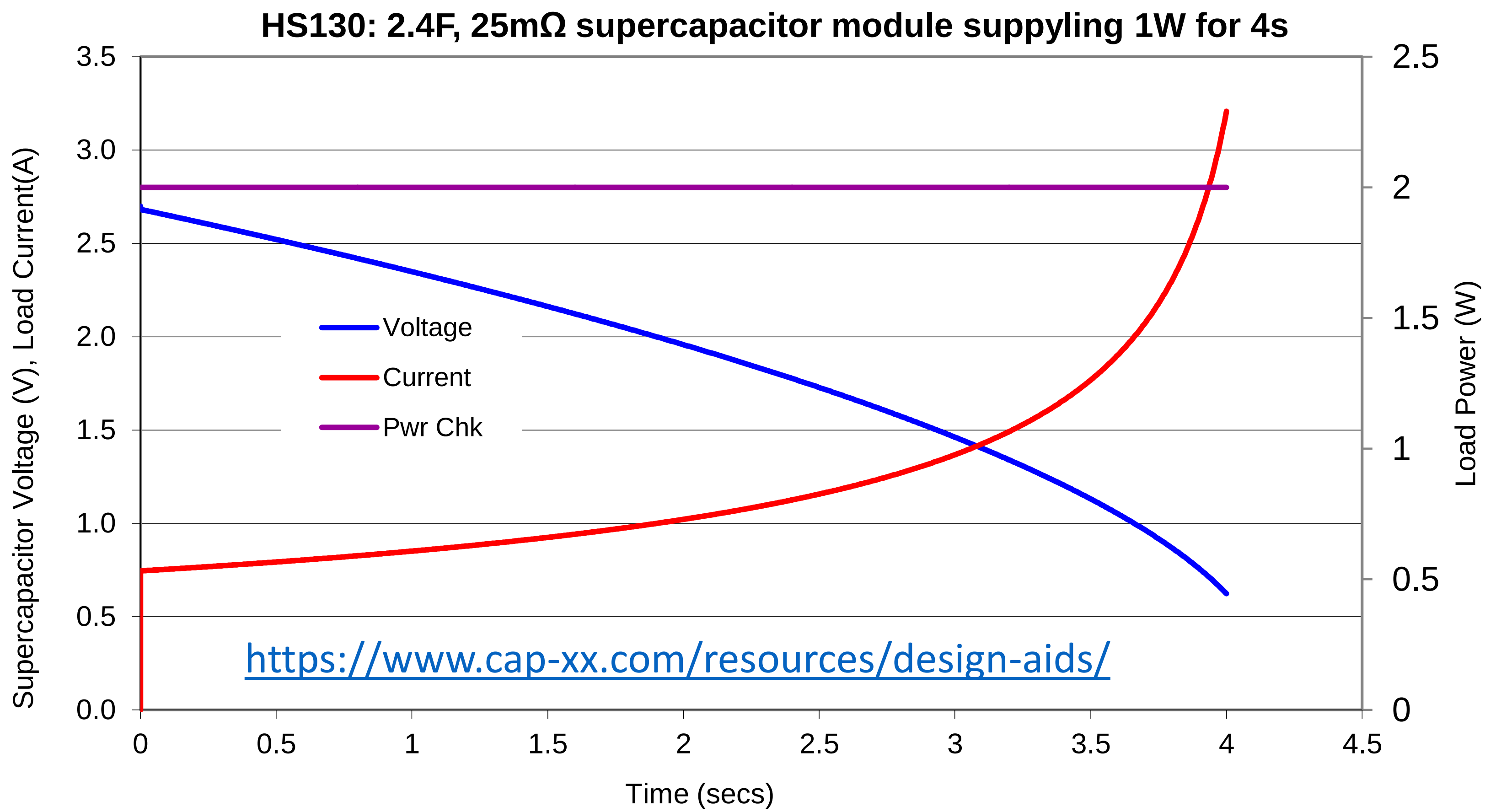
Constant Power Example



https://www.cap-xx.com/resources/design-aids/

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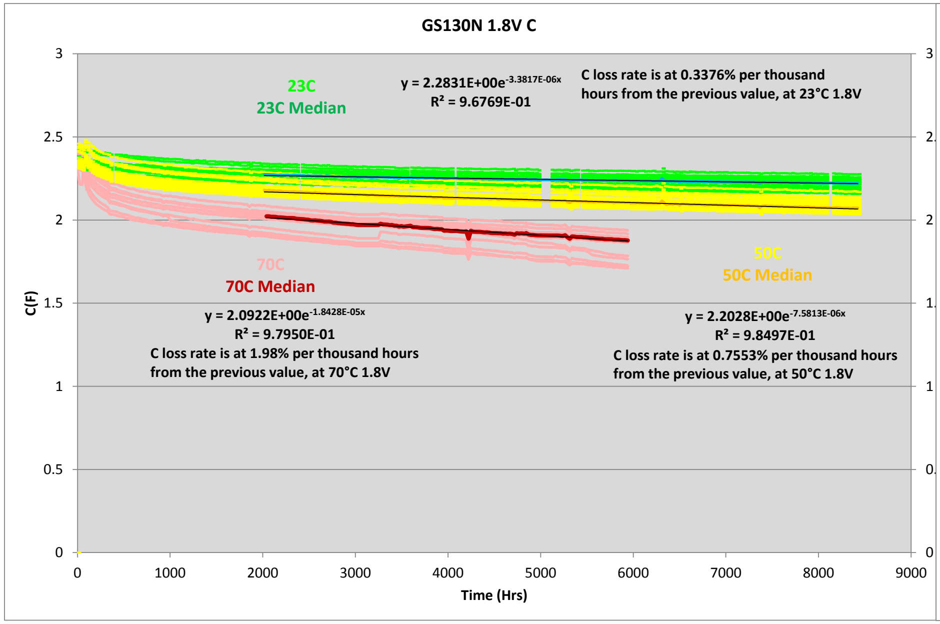
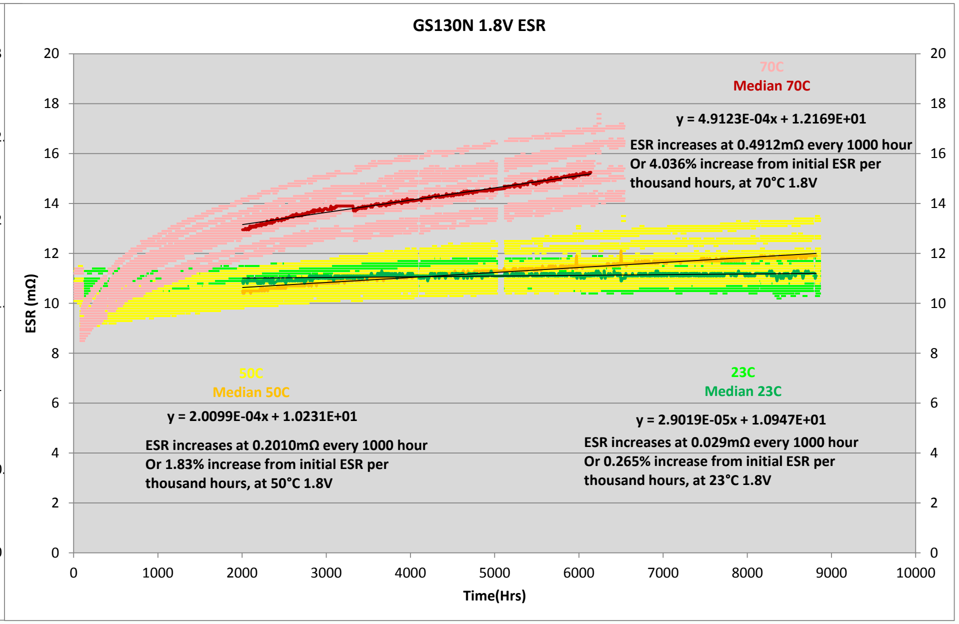
Supercapacitor Ageing

- Supercapacitors will slowly lose C and increase ESR over time.
- The rate of C loss, ESR rise is a function(V,T)
- CAP-XX has placed a range of parts at different voltage-temp combinations for ~1yr to determine ageing rates as functions of V, T.





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Life Estimates

- Life is not a fixed end date. It is when the supercapacitor has lost C, increased ESR so it no longer supports your load.
- You can increase life by starting with a higher C, lower ESR supercapacitor
- You should have a typical V-T operating profile:
  - Using the corner case (e.g. 5V, 70°) is lazy and won't work
- Common Arrhenius assumptions:
  - Ageing rate halves for every 10°C decrease and every 0.2V decrease
  - Only applicable if reactions stay the same – they don't!
- CAP-XX has regressed eqns for Closs, ESRrise with V, T.

Temperature	Voltage	% Time
-40°C	5	0%
-30°C	5	0%
-20°C	5	5%
-10°C	5	5%
0°C	5	10%
+10°C	4.8	20%
+20°C	4.8	20%
+30°C	4.8	10%
+40°C	4.6	10%
+50°C	4.6	10%
+60°C	4.5	5%
+70°C	4.2	5%
		100%

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Arrhenius Ridiculous

- Claim: 0.77yrs @ 5V, 85°C
- At 3.6V, using assumption of life doubling for every 0.2V reduction, life increased by $2^{(5V-3.6V)/0.2V} = 2^7 = 128$

➔ Life at 3.6V, 85°C = 0.75 x 128 = 99yrs

- Reducing temperature to 25°C increases life by a factor of $2^{(85-25)/10} = 2^6 = 64$

➔ Life at 3.6V, 25°C = 99 x 64yrs = 6308yrs!

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Size for Ageing

- Use real estimates of Closs, ESRrise
- Determine min C / max ESR that will support your application
  - I.ESR Vdrop
  - Constant power or constant current
  - Ceff for short PW
- Estimate a realistic V-T operating profile
- Apply C loss / ESR rise factor over required life to EOL C, ESR to determine initial C, ESR.

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Supercapacitor Charging

A supercapacitor charging circuit must:

1. behave gracefully into a short circuit since a discharged supercapacitor will look like a short, or the in-rush current will have to be limited
2. be able to charge from 0V
3. provide over voltage protection for the supercapacitor
4. prevent the supercapacitor from discharging into the source when $V_{SOURCE} < V_{SUPERCAP}$

and

5. should be designed for maximum efficiency

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SMALL SOLAR CELL REPORTING OVER A WIDE CAMPUS AREA

LoRa Case Study

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Small Solar Cells

- Power output for solar cells is typically defined at 50,000 lux (bright sunlight) or 100,000 lux (1kW/m2)
- If used indoors, light levels are MUCH lower:
  Typically between 300 lux (minimum for easy reading) & 500 lux (well it office) AND with different spectrum (LED/CCFL)
- Select & characterise your solar cell for the conditions in which it will be used!

	LUX	DESCRIPTION
	50,000	British summer sunshine
	5,000	Overcast sky
	500	Well-lit office
	300	Minimum for easy reading
	50	Passageway/outside working area
	15	Good main road lighting
	10	Sunset

Indoor use: LED/CCFL spectrum, typically 200 – 400 lux. Silicon cells will not do well!

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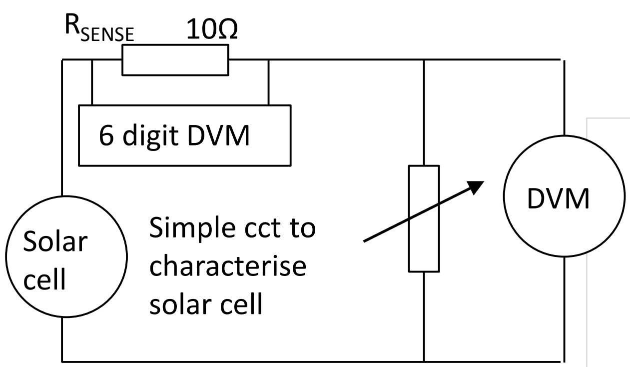
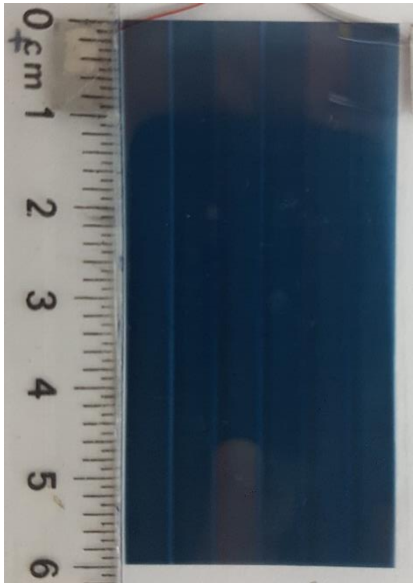
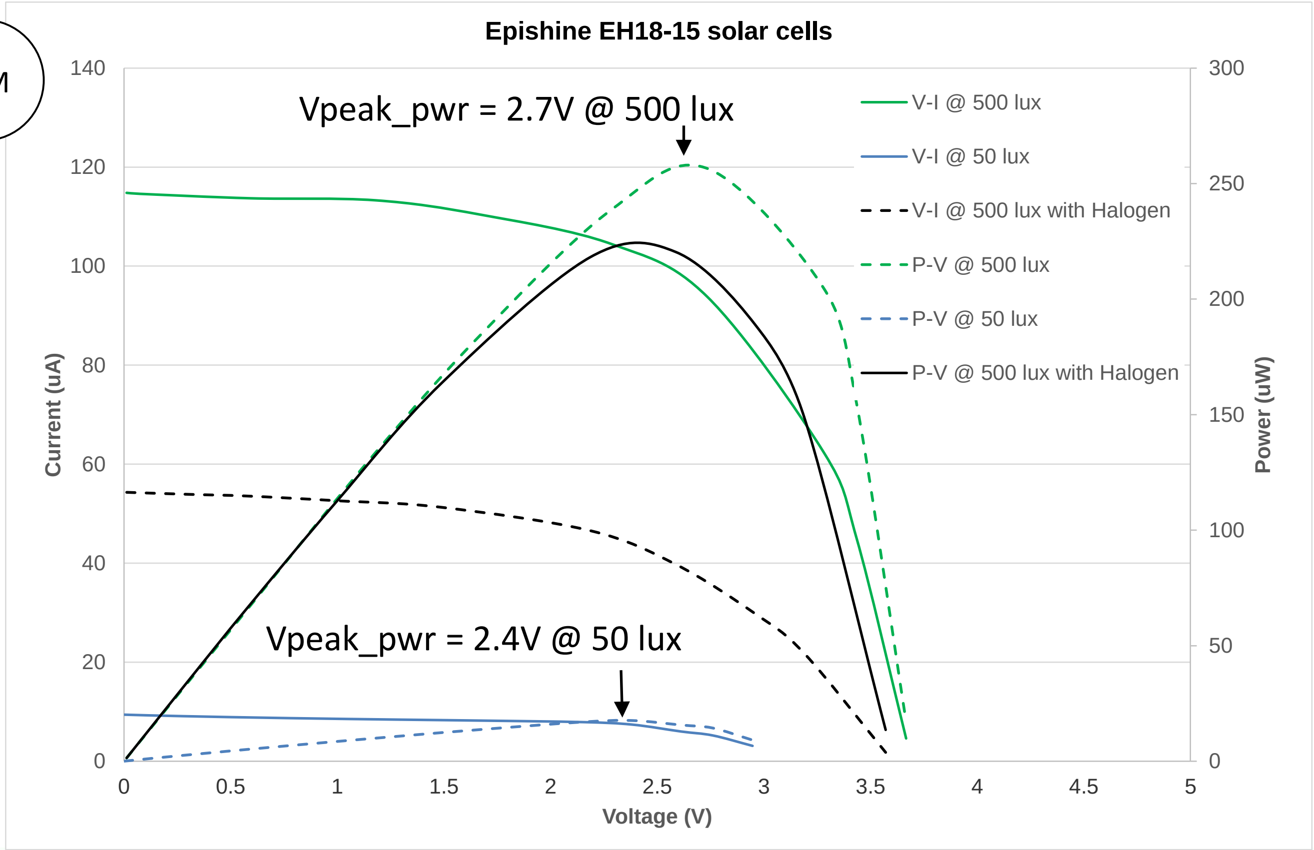
Characterise your Solar Cell

Epishine: Organic solar cell, lower cost and more responsive to indoor LED / CCFL. 250µW @ 500 lux LED spectrum, 29mm x60mm, 14.4µW/cm². Voc, Vpp approx. constant







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What is the best charging circuit?

It depends:

- Direct charging or use a Power Management IC?
- Direct Charging
  - Simple, low cost
  - Sufficient light when application needs to run, e.g. working hrs in a supermarket, office, factory; in daylight
- Energy Harvesting PMIC
  - Boost with Max Peak Power Tracking
  - Will still charge when light low, Vsolar < Vmin for application to work
  - May include cell balancing
  - May include duty cycle regulation

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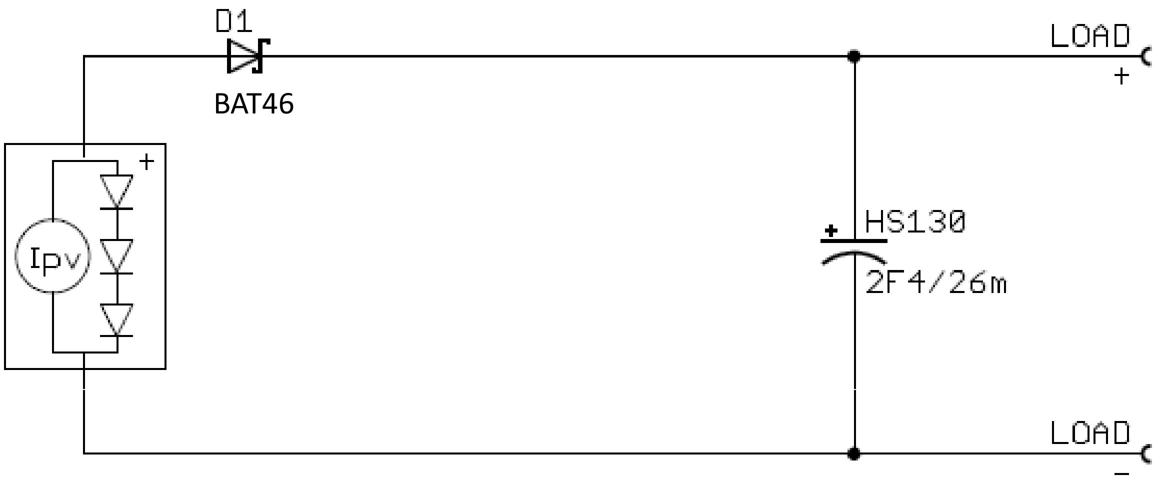
Simplest Solar Charging Circuit



- Single cell supercapacitor. No balancing. Starts charging from 0V
- Vsolar – Vdiode ≥ Vload_min when the application needs to run
- Vsolar_oc ≤ Vscap_rated at the maximum light level in the application (2.7V in this case) [Vdiode → 0 as supercap fully charged]
- D1 prevents the supercapacitor from discharging back into the solar cell when light levels fall
- BAT46 chosen for D1 due to low V_F. V_F at currents < 10μA, <0.1V

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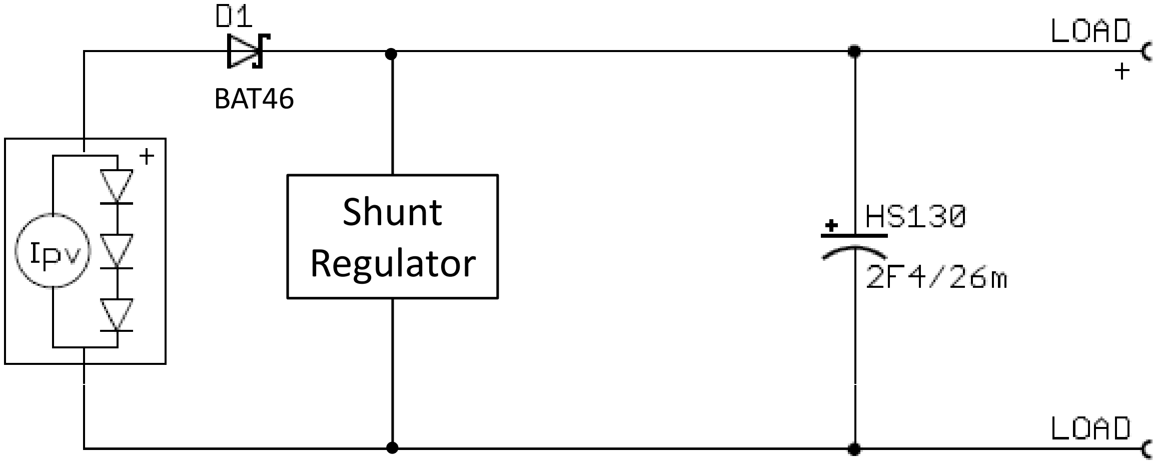
Direct Charging Solar Charging Circuit



- Single cell supercapacitor. No balancing. Starts charging from 0V
- Vsolar – Vdiode ≥ Vload_min when the application needs to run
- Shunt regulator limits Vload ≤ Vscap_rated.
  - Low current
  - No losses when Vsolar < Vscap_rated
- D1 prevents the supercapacitor from discharging back into the solar cell when light levels fall
- BAT46 chosen for D1 due to low V_F. V_F at currents < 10µA, <0.1V

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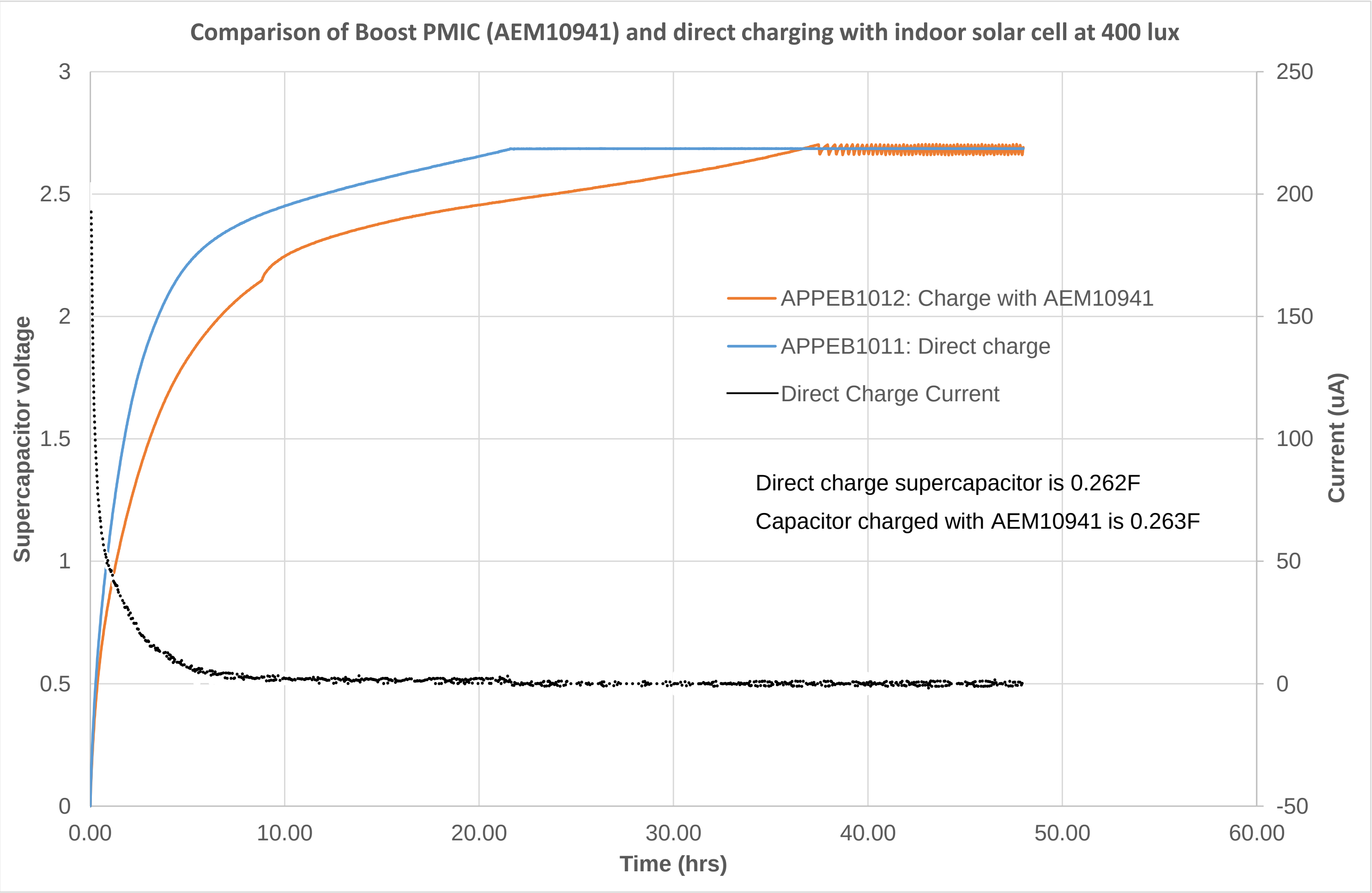
Direct Charge or use EH PMIC?

If Voc > Vtarget at all light levels when app must run then direct charging is a good option.

Epishine Voc not dropping significantly at lower light levels is suitable for direct charging.

PMIC has ~80% - 90% efficiency



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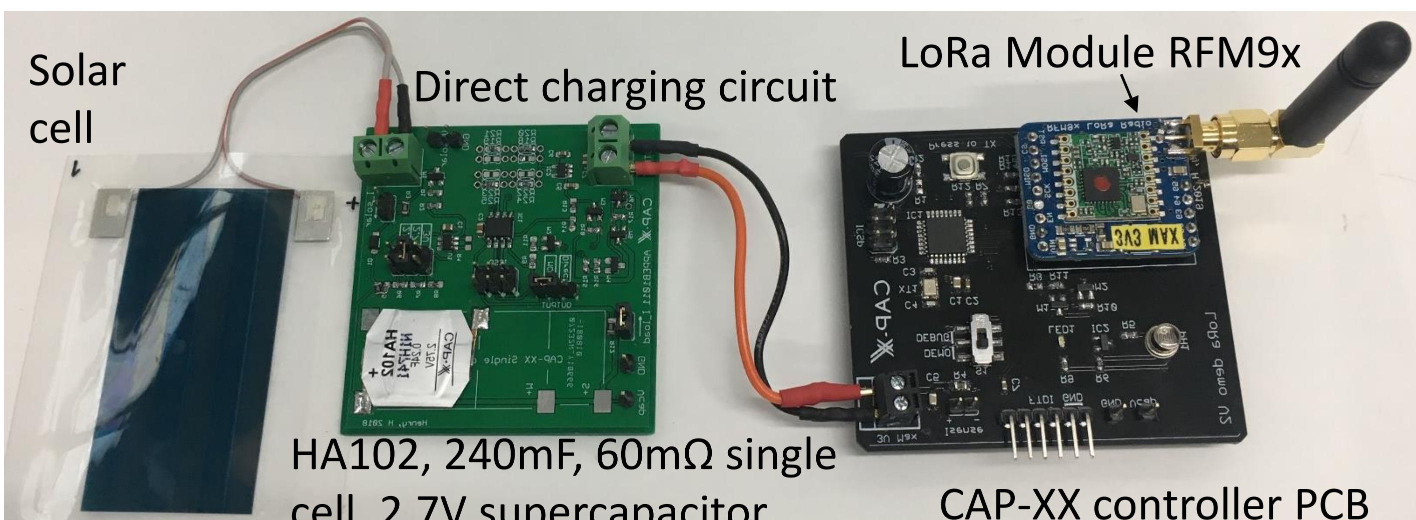
LoRa Setup

- Supply voltage range, 3.3V – 1.8V
- Use Epishine solar cell to directly charge a HA102 supercapacitor to 2.7V, using CAP-XX eval board APPEB1011, see www.cap-xx.com
- Supercapacitor can support multiple transmissions
- Regulate duty cycle so Vscap does not discharge below 2.4V



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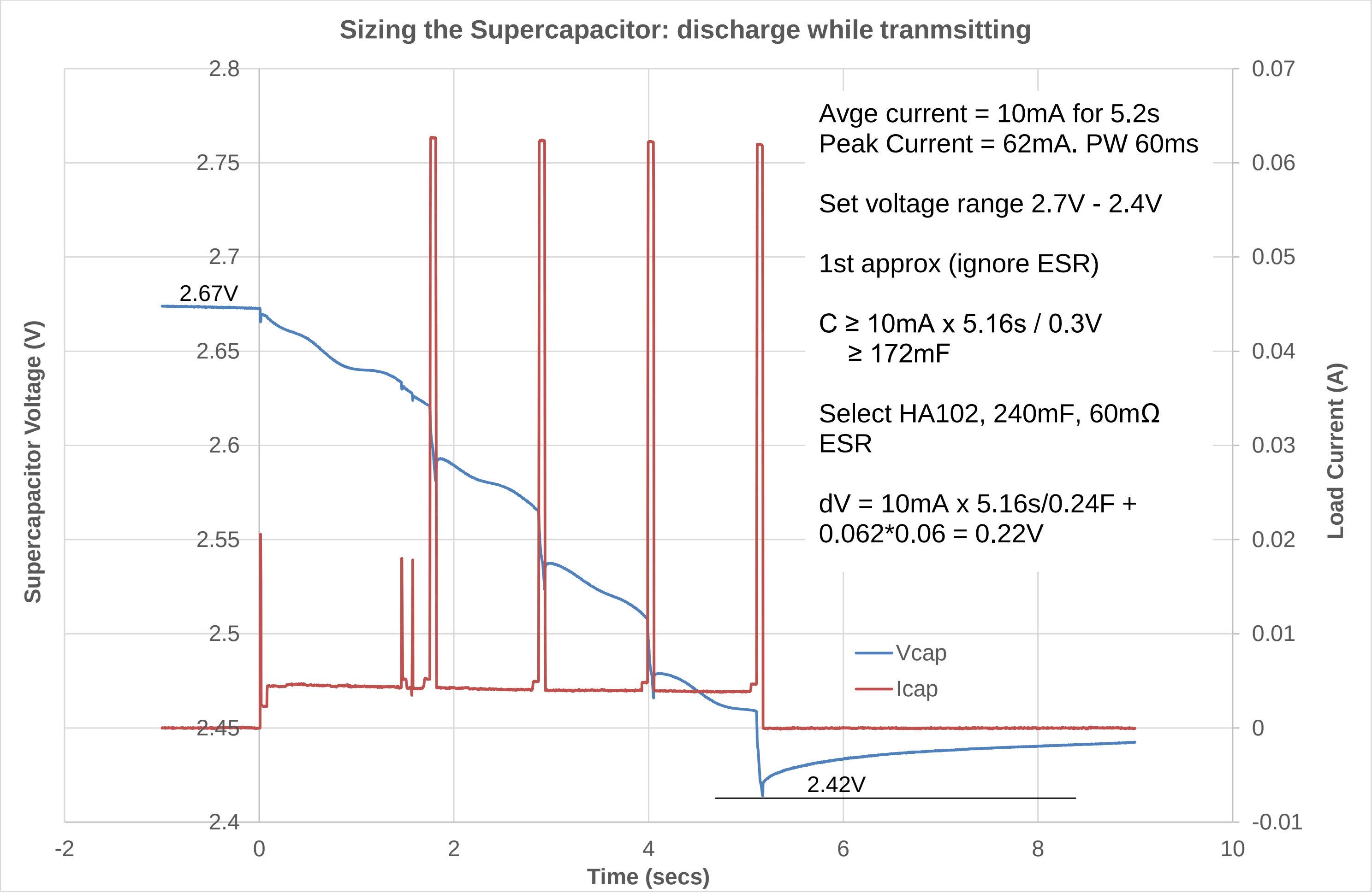
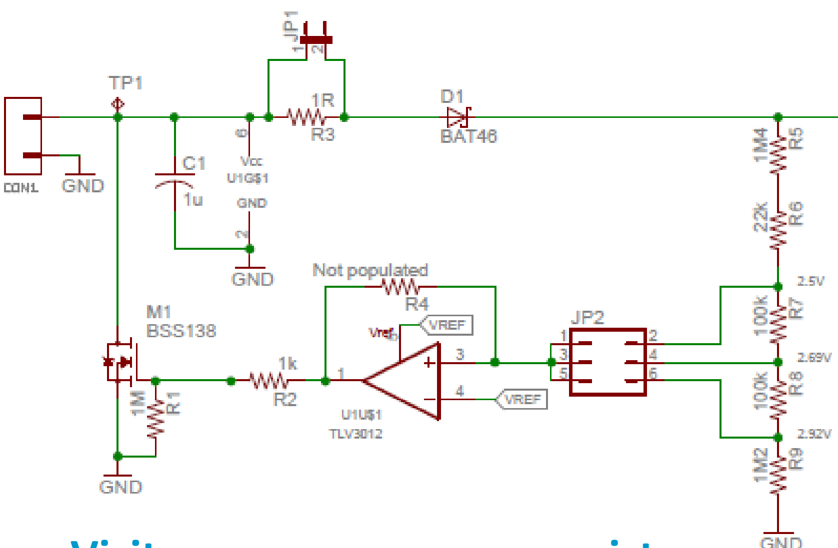
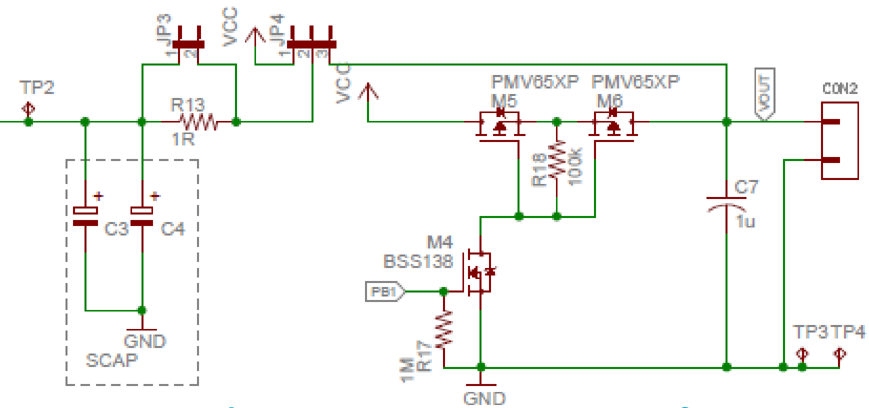
Sizing the Supercapacitor: LoRa Transmission



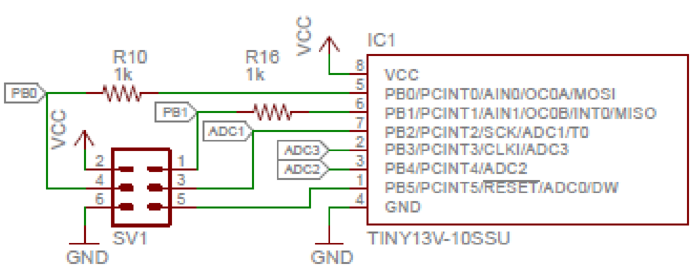
CAP-XX Supercapacitor Direct Charging Circuit

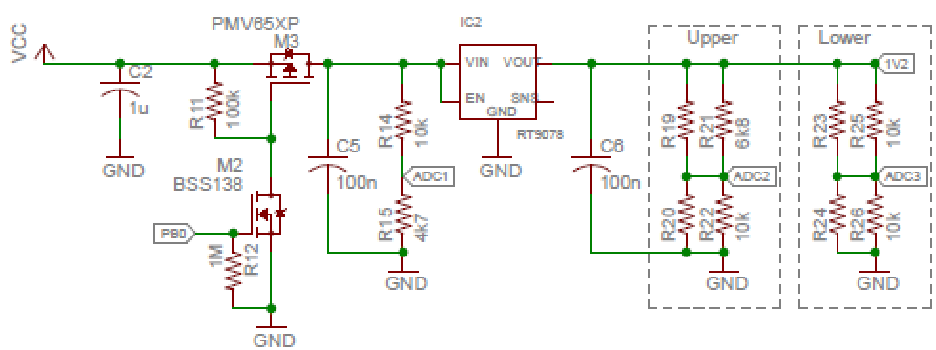




- AN1007 Charging a Supercapacitor from a Solar Cell Energy Harvester
- APPEB1011 Direct Solar Cell Charging
- APPEB1012 Solar cell charging with PMIC

Visit www.cap-xx.com , register, look at Design Services.





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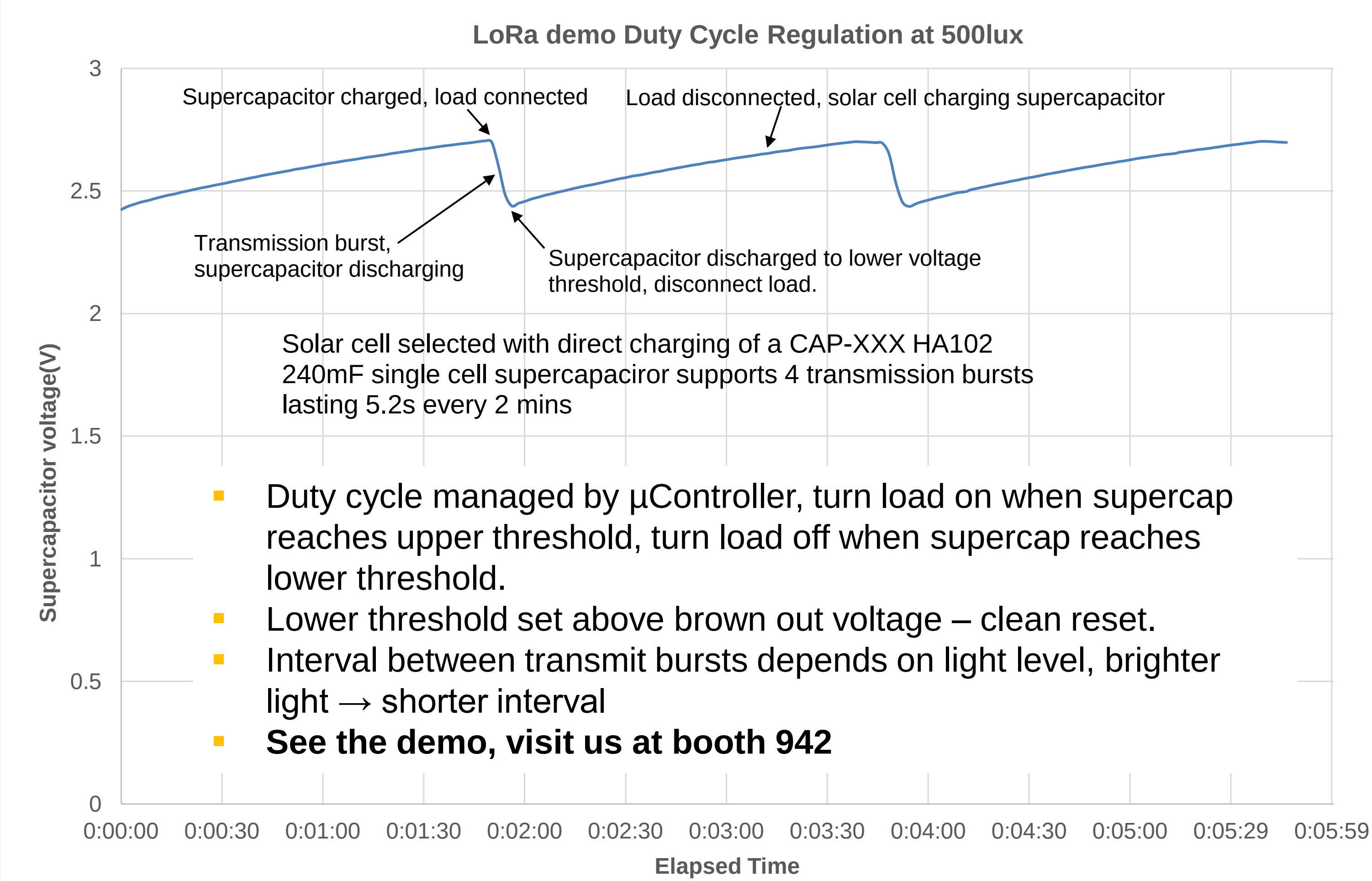
Operation



- Duty cycle managed by µController, turn load on when supercap reaches upper threshold, turn load off when supercap reaches lower threshold.
- Lower threshold set above brown out voltage – clean reset.
- Interval between transmit bursts depends on light level, brighter light → shorter interval
- **See the demo, visit us at booth 942**

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SMALL SOLAR CELL SUPPORTING CELLULAR IoT

NB IoT/LTE CAT M1 Case Study

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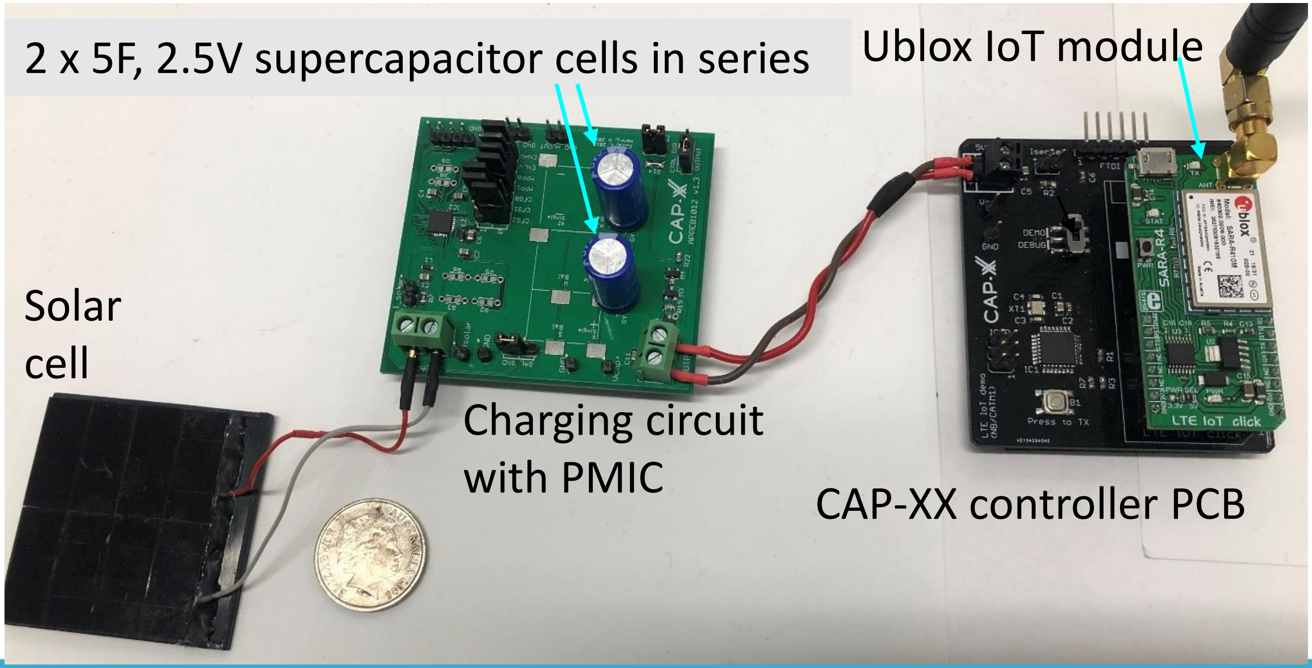
NB IoT / LTE CAT M1 Setup

- Report messages from the Arduino µC managing a Ublox IoT module
- Supply voltage range, 4.5V – 3.3V
- Use GaAs solar cell to charge 2.5F supercapacitor to 4.5V with a PMIC using CAP-XX eval board APPEB1012, see www.cap-xx.com



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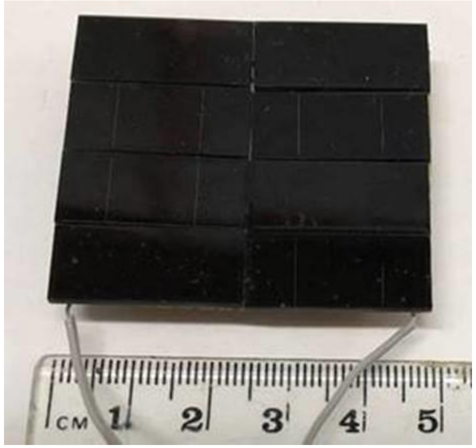
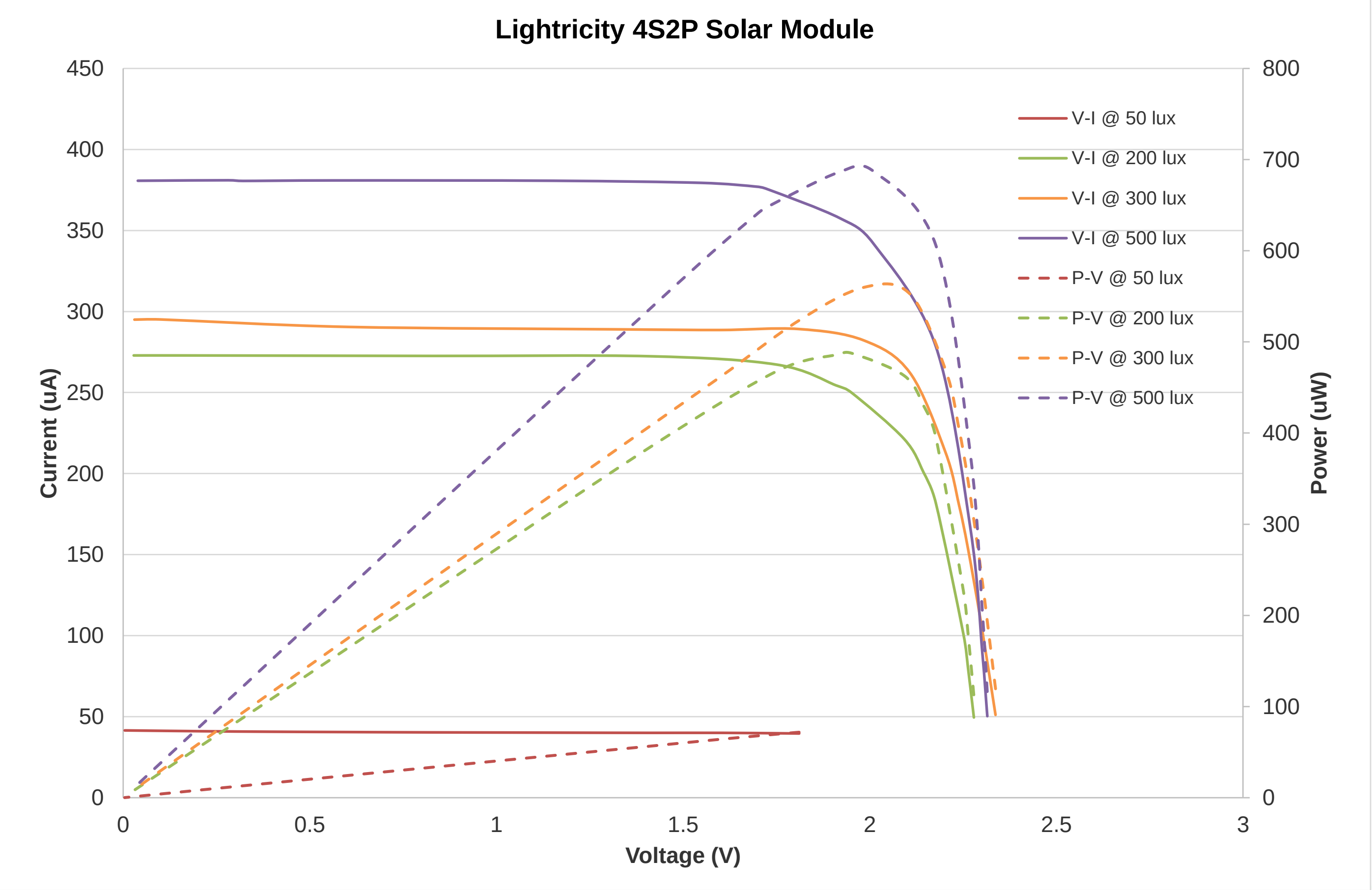
Characterise your solar cell

Lightricity: GaAs solar cell, most efficient in indoor LED / CCFL light.
687µW @ 500 lux LED spectrum, 48mm x41mm, 34.9µW/cm^2.

4s2p configuration, Voc < Vtarget, use a boost to charge the supercap





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Selecting Your Charging IC

Attribute	AEM10941	Comment
Min cold start voltage	380mV	The lower the better.
Cold start charge	Rapid. Boost charges 22µF (typ) cap.	How the IC boosts the input voltage during cold start to reach the internal voltage required to run as a boost.
Cold start power	3µW	The lower the better, but must be < power available from the solar cell at min light levels at which the unit must charge.
Cold start threshold	380mV	Voltage at which the IC starts operating as a boost converter, the lower the better
Vin min after start up	50mV	Min i/p voltage for the boost to keep operating once it has started
Quiescent current	< 1µA	Current drawn by the IC while operating as a boost. Vbatt ≥ 2.5VThis is reflected in the low power efficiency.
Max Peak Power Tracking	Samples Vsolar_oc every 5s to set MPPT	Periodically disconnecting the i/p to sample Voc is the preferred method. MPPT then set as % of Voc. Can set MPPT at 70%, 75%, 85%, 90% of Voc. Some ICs set this as a fixed value which only works in constant light.
SCAP Bal.	Yes	Includes balancing cct for dual cell supercaps
Duty Cycle Ctrl	Yes	Status bit that reflects if supercap within desired voltage range
Efficiency	~90% at Peak Pwr Pt	90% is excellent efficiency at such low power. Vscap > Vsolar
Hysteric operation	Yes	The boost converter turns off when Vcap reaches its desired voltage and turns on again when Vcap has discharged to a lower threshold. Saves power.
Max current	100mA	From energy harvester to boost converter

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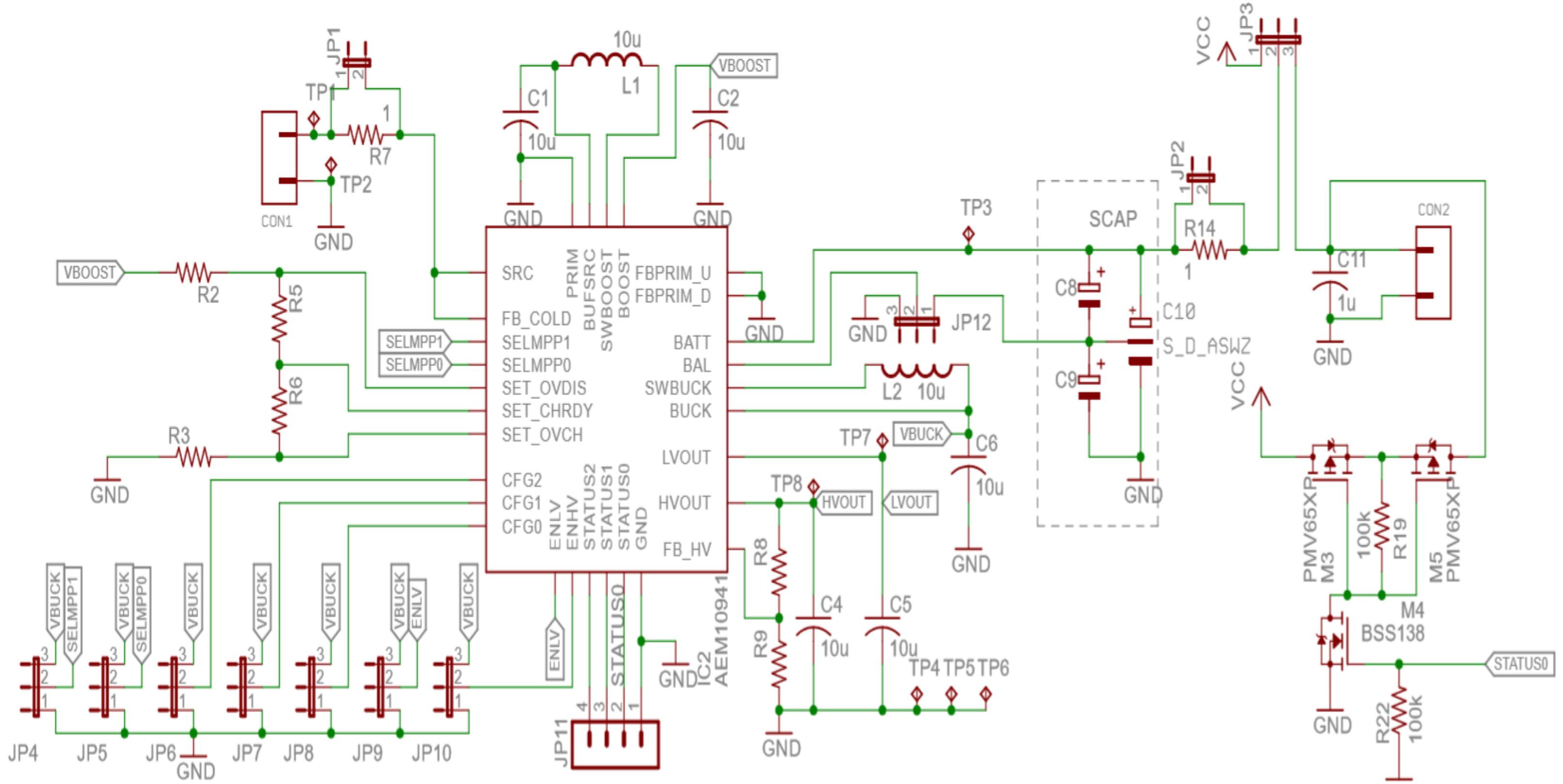
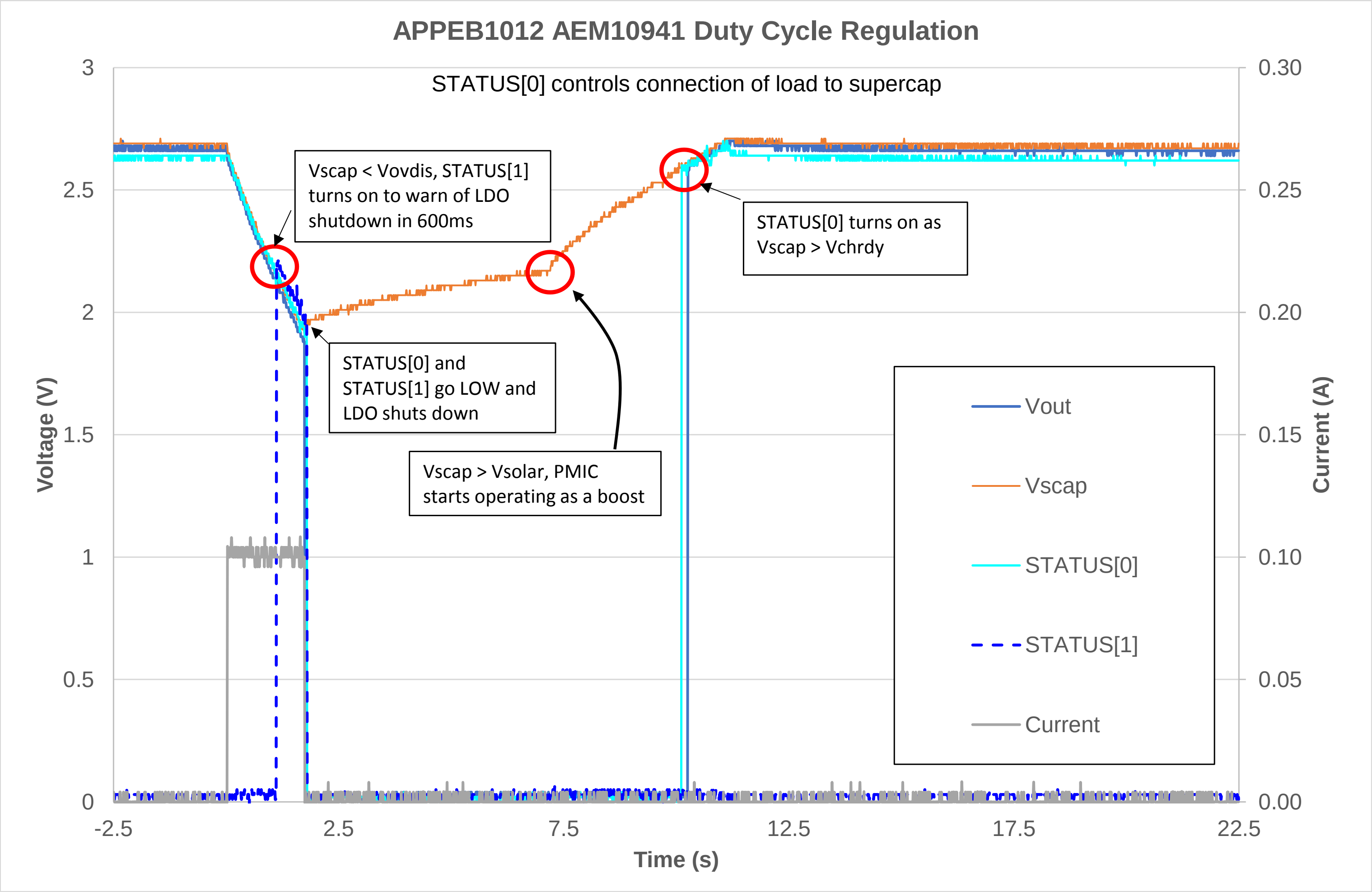
Supercapacitor charging cct with PMIC

Refer to: AN1007 Charging a Supercapacitor from a Solar Cell Energy Harvester
AN1012 Supercapacitor powered NB IoT LTE CAT-M1
User Manual for APPEB1012 Solar cell charging with PMIC



CAP-XX Duty cycle regulation integrated in PMIC



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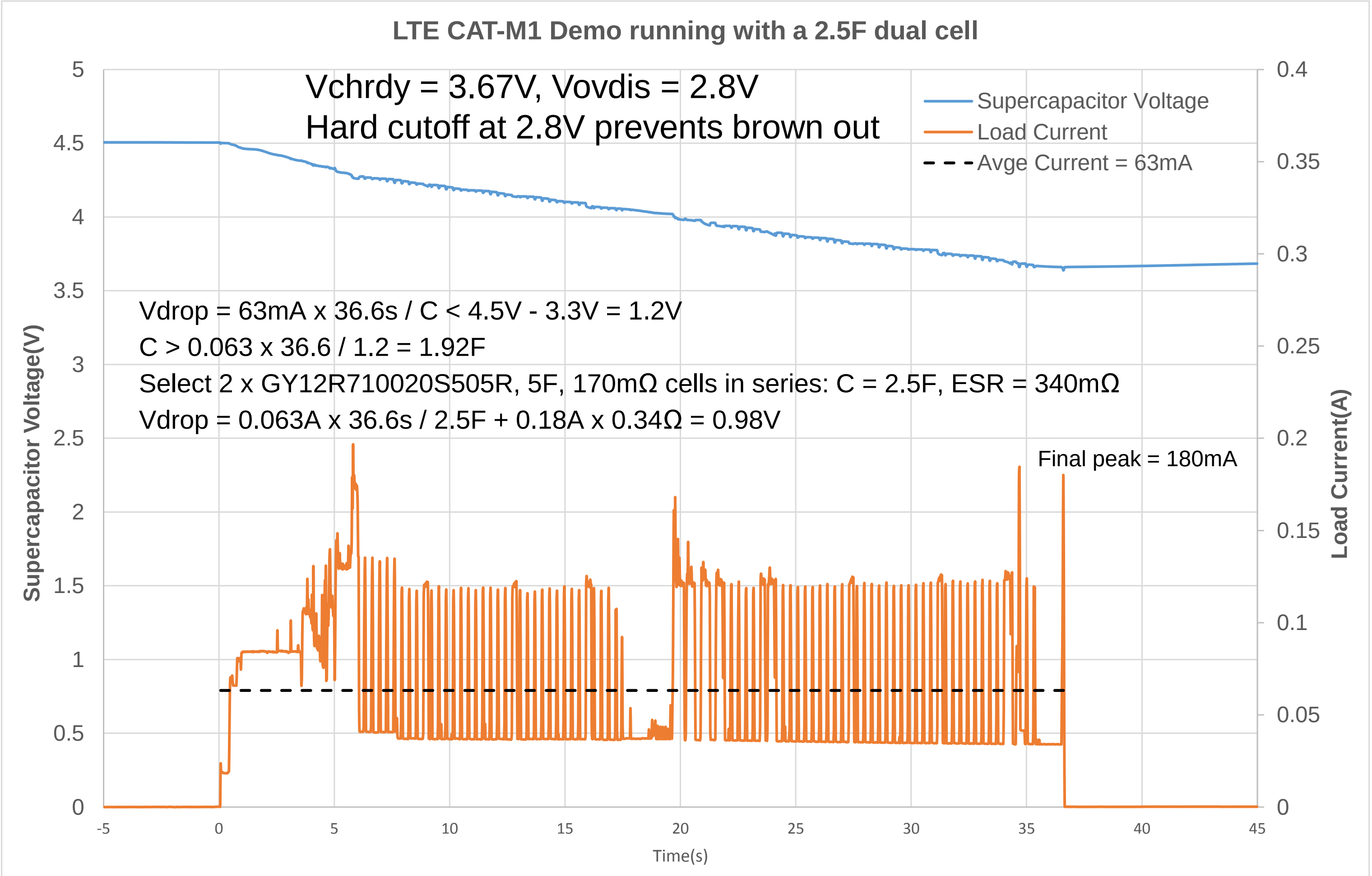
Load Power & Energy, Sizing the Scap



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Regulating the load, Tx interval

- At 500 lux, solar cell delivers 687µW
- Supercapacitor discharge (excl ESR drop) = 0.92V
- Energy loss = ½ x 2.5F x ($4.5^2 – 3.6^2$) = 9.1J
- Time to re-charge supercapacitor = 9.1J / 687µW = 13246s = 3.7hrs
- Fine if this is suitable for whatever you are monitoring, e.g. a slowly moving variable
- Otherwise increase power by: larger solar cell, more light, other energy source, etc.
- Large energy requirement for Tx since unit disconnected between transmissions to reduce power, so need to log on to network every time. If you can increase EH power to support unit being always connected to the network, then energy for each transmission greatly reduced.

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SUPPORTING a WiFi GATEWAY by WIRELESS CHARGING A SUPERCAPACITOR

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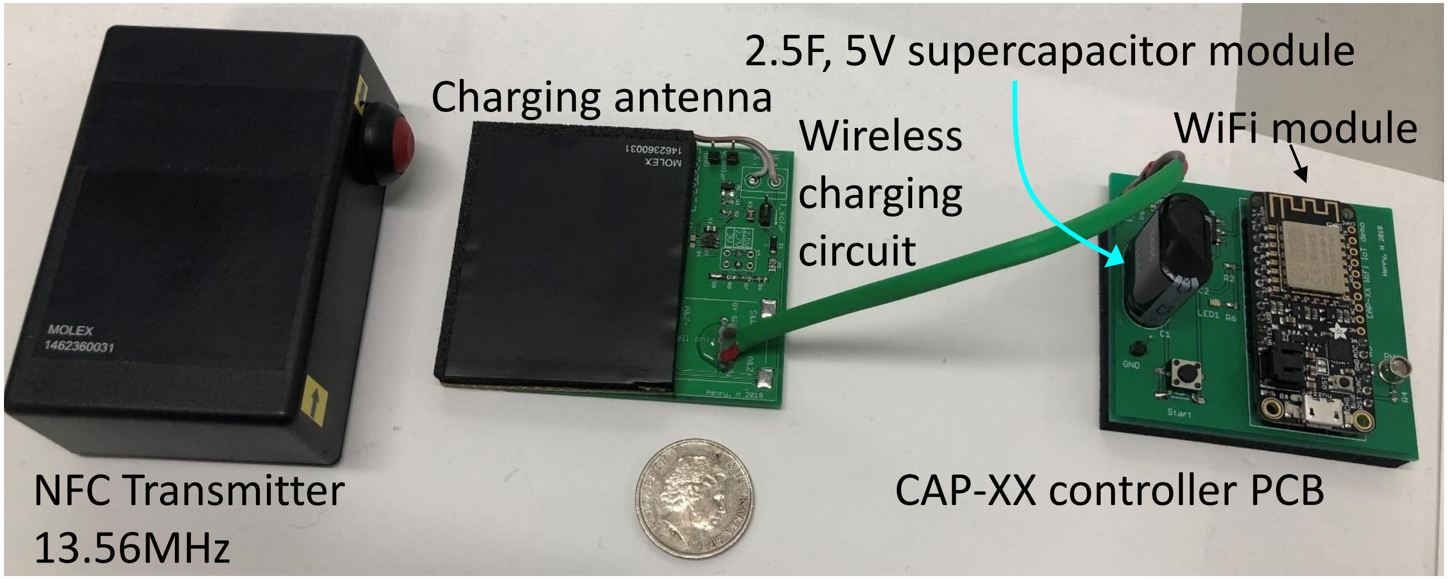
WiFi Gateway Setup

- Report light level from the Adafruit to a web page
- Supply voltage range, 5V – 3.3V
- Use NFC Wireless Charger, see App Notes AN1009 Wireless Charging and AN1014 Supercapacitor Powered Wifi IoT, www.cap-xx.com



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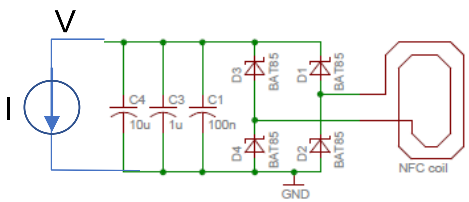
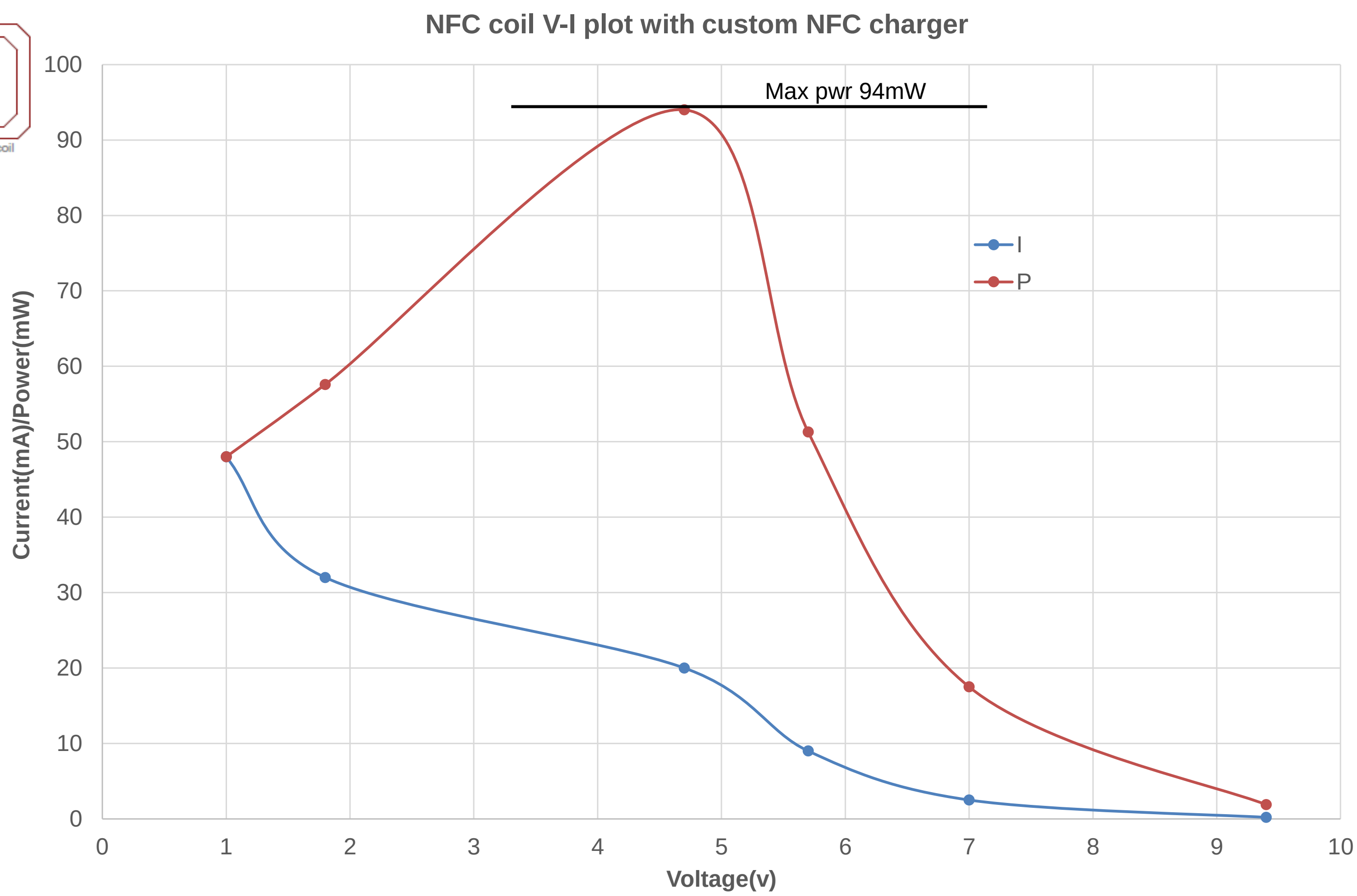
Characterising the Charger





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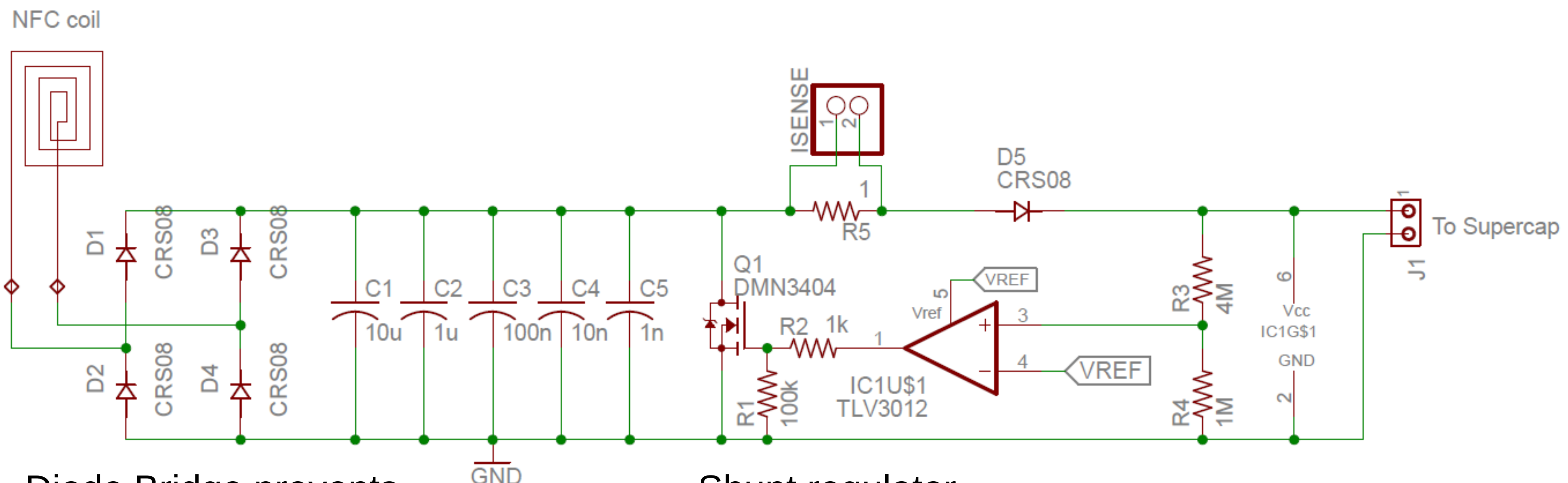
Charging Circuit



Diode Bridge prevents supercapacitor discharging back into the coil

Shunt regulator protects supercapacitor from over voltage.

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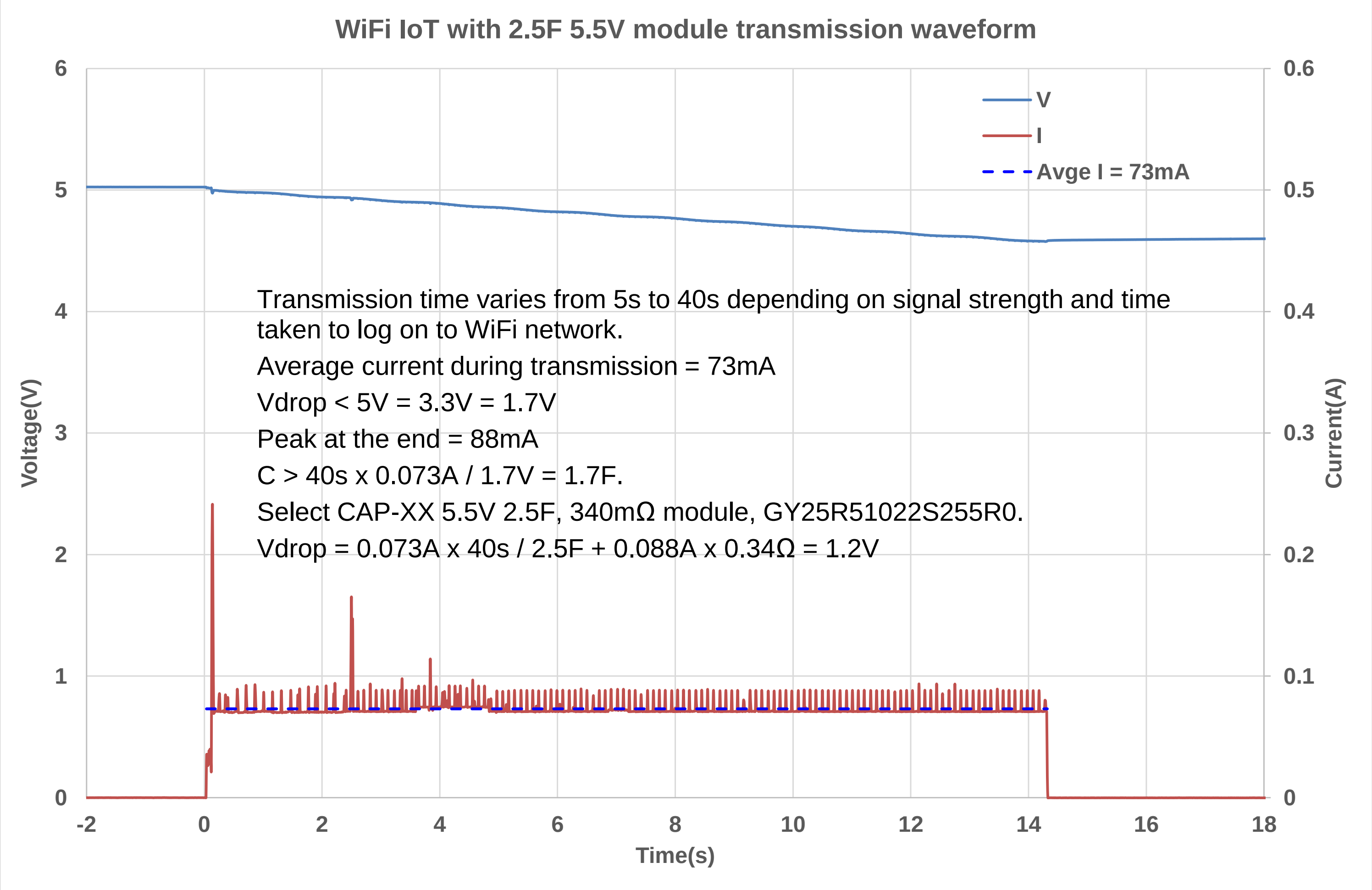
Load Profile, Sizing the Supercapacitor



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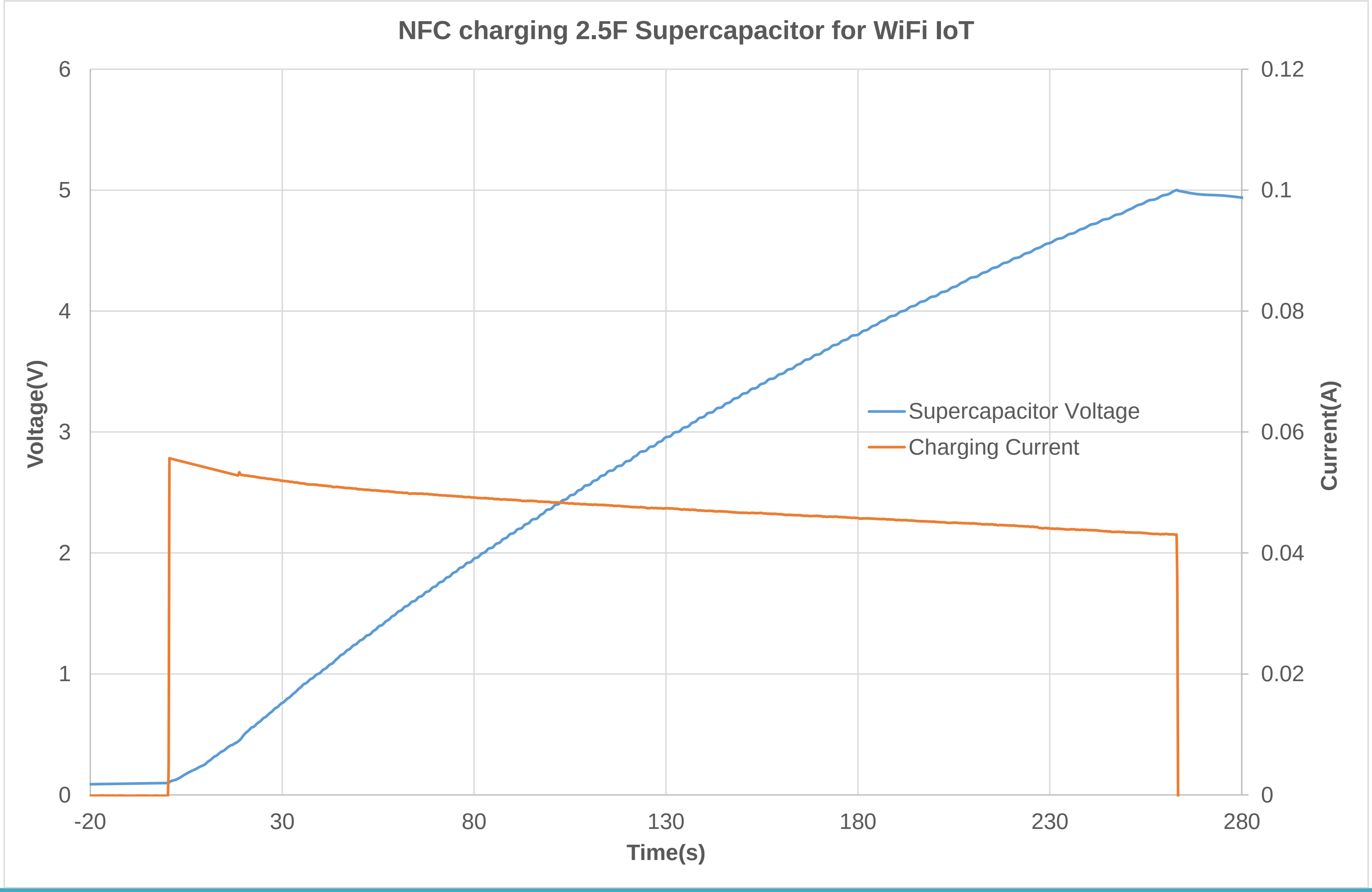
Charging the supercapacitor



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COMING SOON
THIN 3V PRISMATIC CELLS
SAMPLES Q4 2019

We have 3V cylindrical cells now.

Thin prismatic cells are more challenging.

Ideal across CR2032 3V coin cells (no cct reqd) or with a small EH to store more energy or to enable direct charging.

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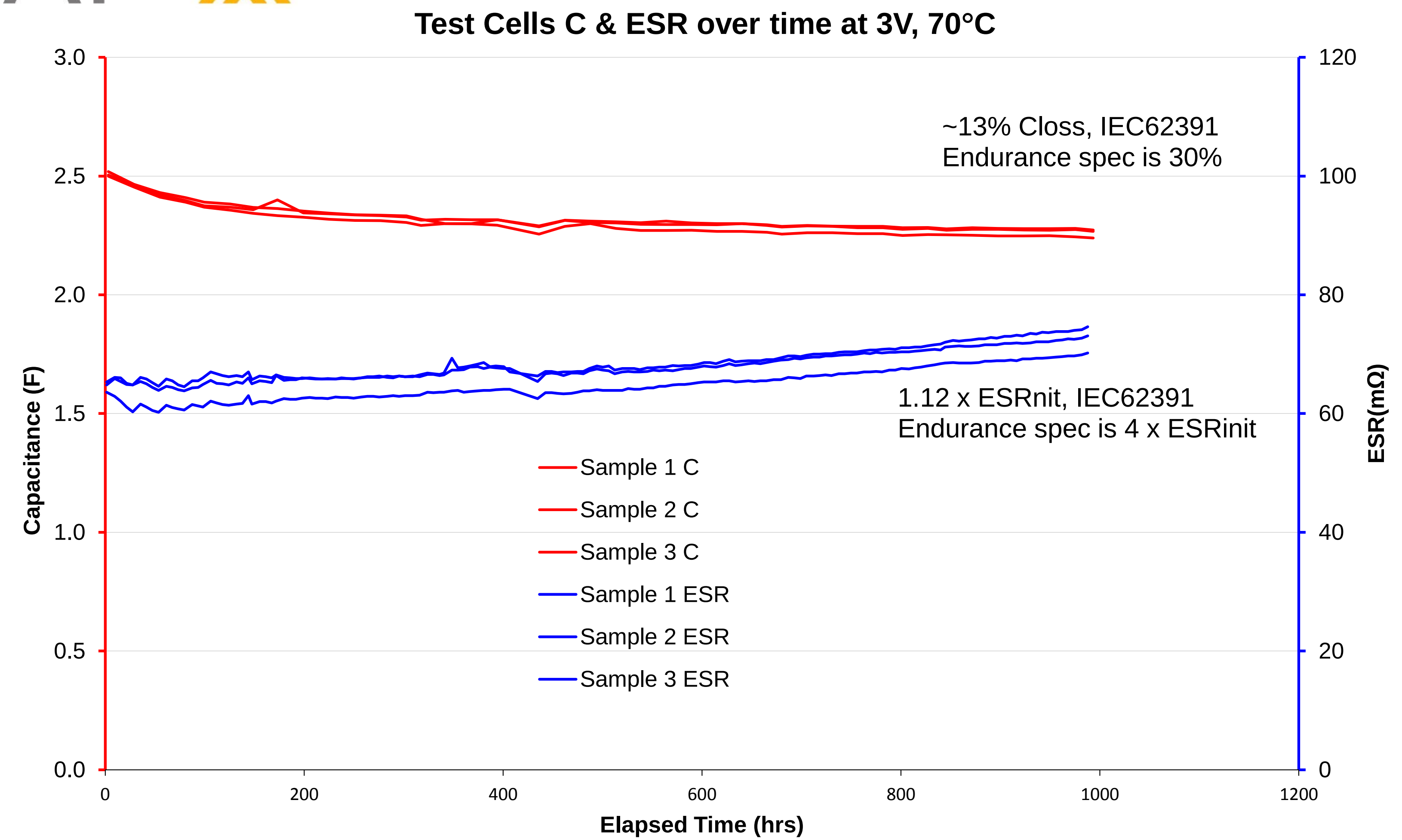
3V cells, excellent life: 3V, 70°C



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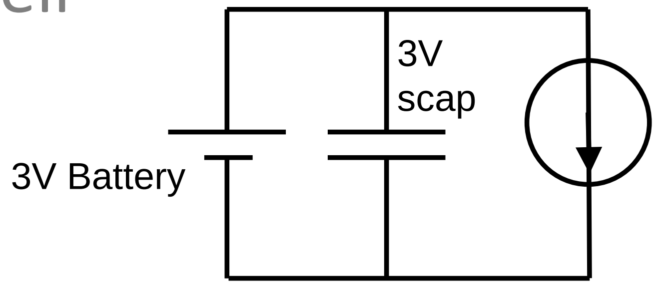
3V Supercapacitor Cell

- Target specs:
  - 3V, -20°C to +70°C
  - 500mF
  - ESR < 200mΩ
  - IL < 2µA

- HA130 size (20mm x 18mm x 1.7mm)
  - Fits over CR2032 coin cell
- Place directly across a 3V coin cell
  - No extra circuit required
- Higher energy for EH apps
  - 3V→ 2V 50% more energy than 2.7V → 2V



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Take Aways

- **Supercapacitors enable µPower energy harvesters to power wireless sensors with high power bursts**
- **Supercapacitors are ideal power buffers**
  - High C (enough energy to do the job)
  - Low ESR (high power delivery)
  - Wide temperature range of operation
  - Easy to charge (show me the current)
  - Low leakage current & Excellent round trip efficiency
- **Supercapacitor Charging**
  - Into a S/C, from 0V, O/V protection, cannot discharge into the source
- **Characterise your Energy Harvester**
- **Sizing the supercapacitor**
  - Allow for I.ESR voltage drop
  - Constant current or constant power?
  - Ceff for narrow pulse
  - Easy to charge (show me the current)
  - Low leakage current & Excellent round trip efficiency
  - Ageing (need real data, Arrhenius a gross approximation)
- **Case studies**
  - LoRa
  - Cellular IoT (LTE CAT M1)
  - WiFi IoT

Visit www.cap-xx.com for App Notes, EVBs. Visit us at booth 942

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www.cap-xx.com