Robust cell-level control of large battery packs

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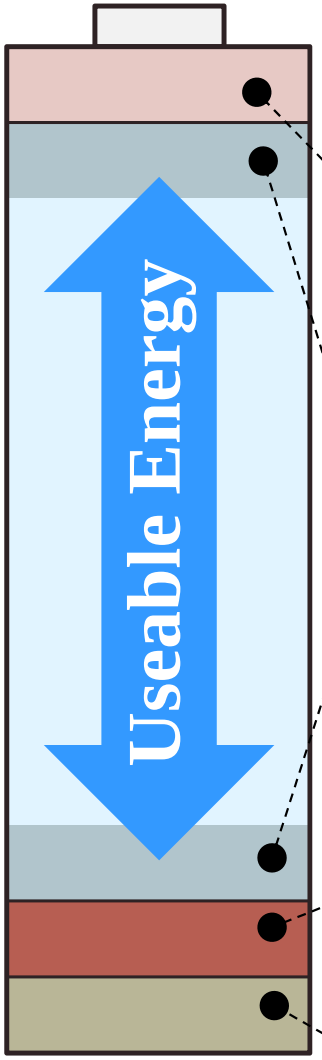
Today's battery systems



Passive cell balancing slow, wastes energy

Cell rate-capability voltage-limited with conservative safety margins

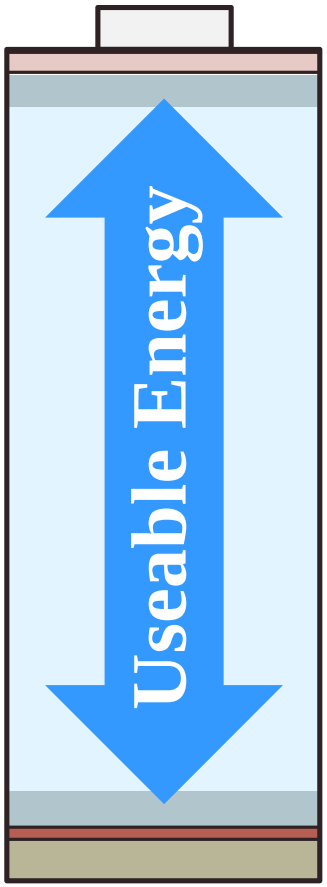
Cell inhomogeneity ***worsens* with age**, energy limited by lowest performing cell

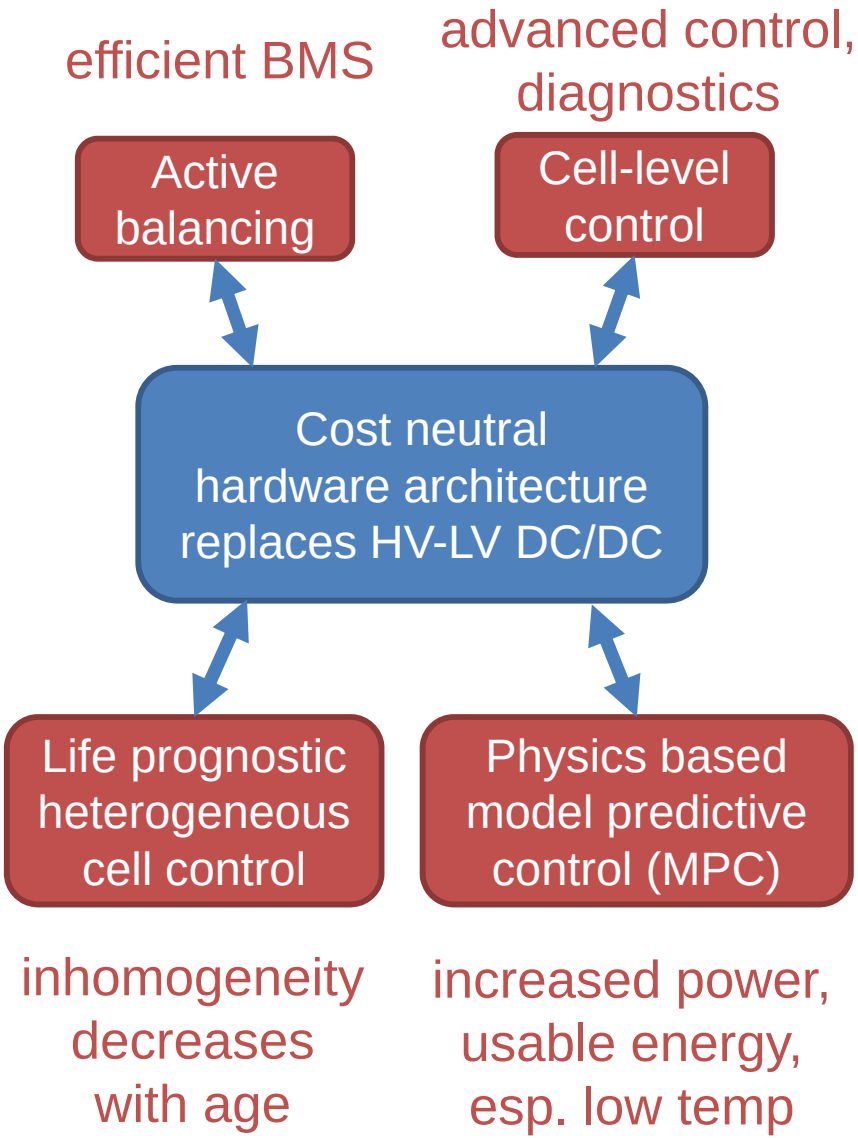
Uncertain battery state

Limitations

- Packs limited by worst case cell
- Lower performing cells degrade faster than stronger cells
- Usable energy of pack significantly lower than physical limits of cells
- Result in underutilized pack

Proposed approach and benefits

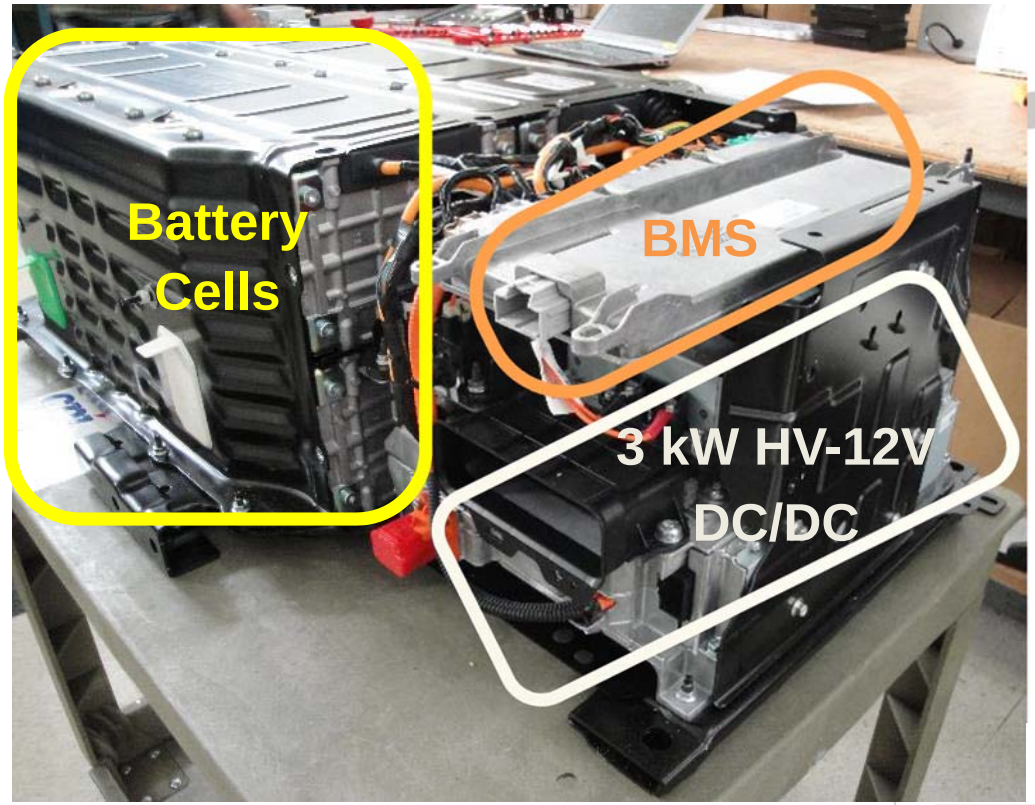




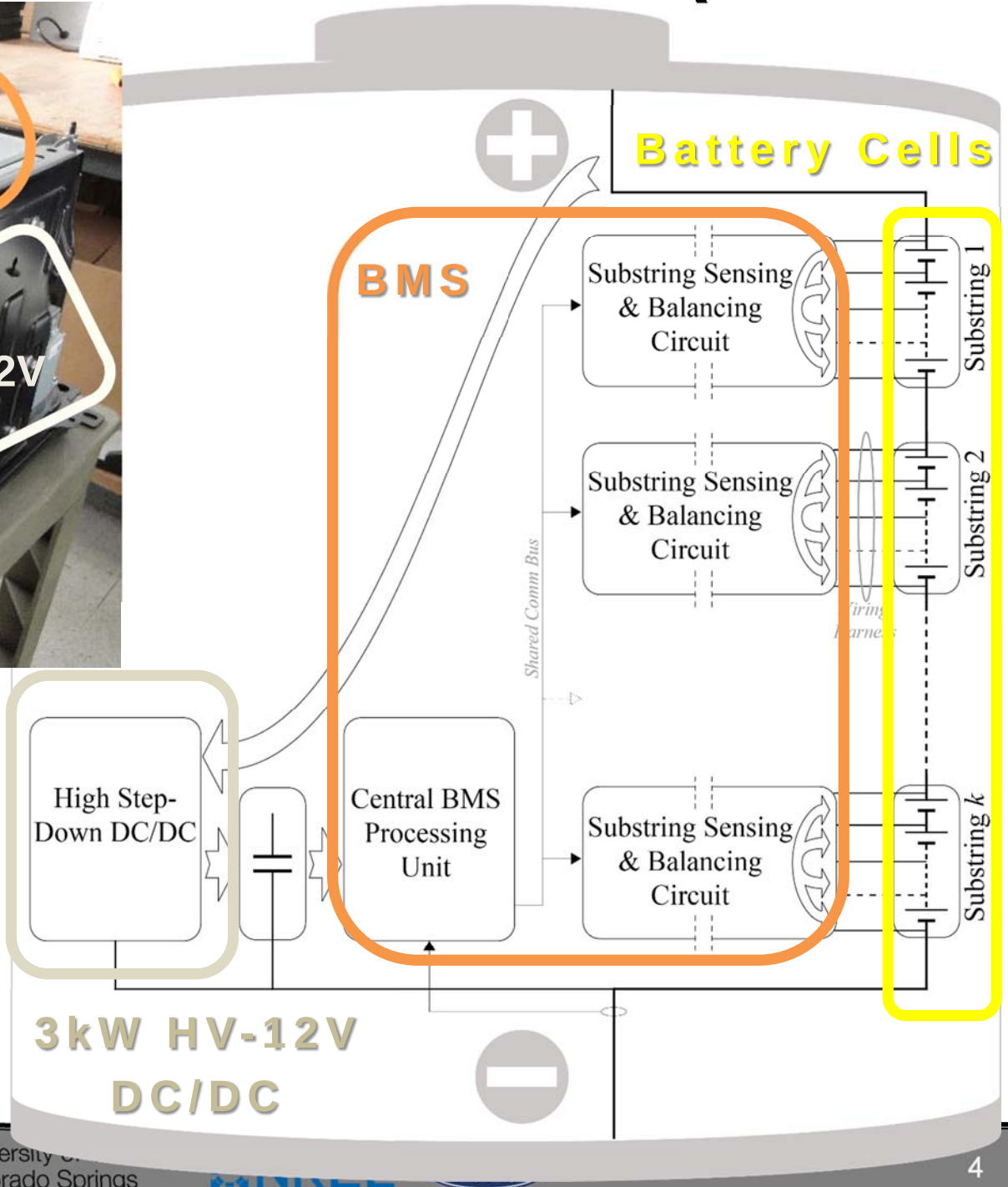
Benefits

- 20% greater usable energy at year 10
- 20% longer lifetime
- Improved power
- Simplified thermal design
- Reduced volume
- Improved 2nd use value

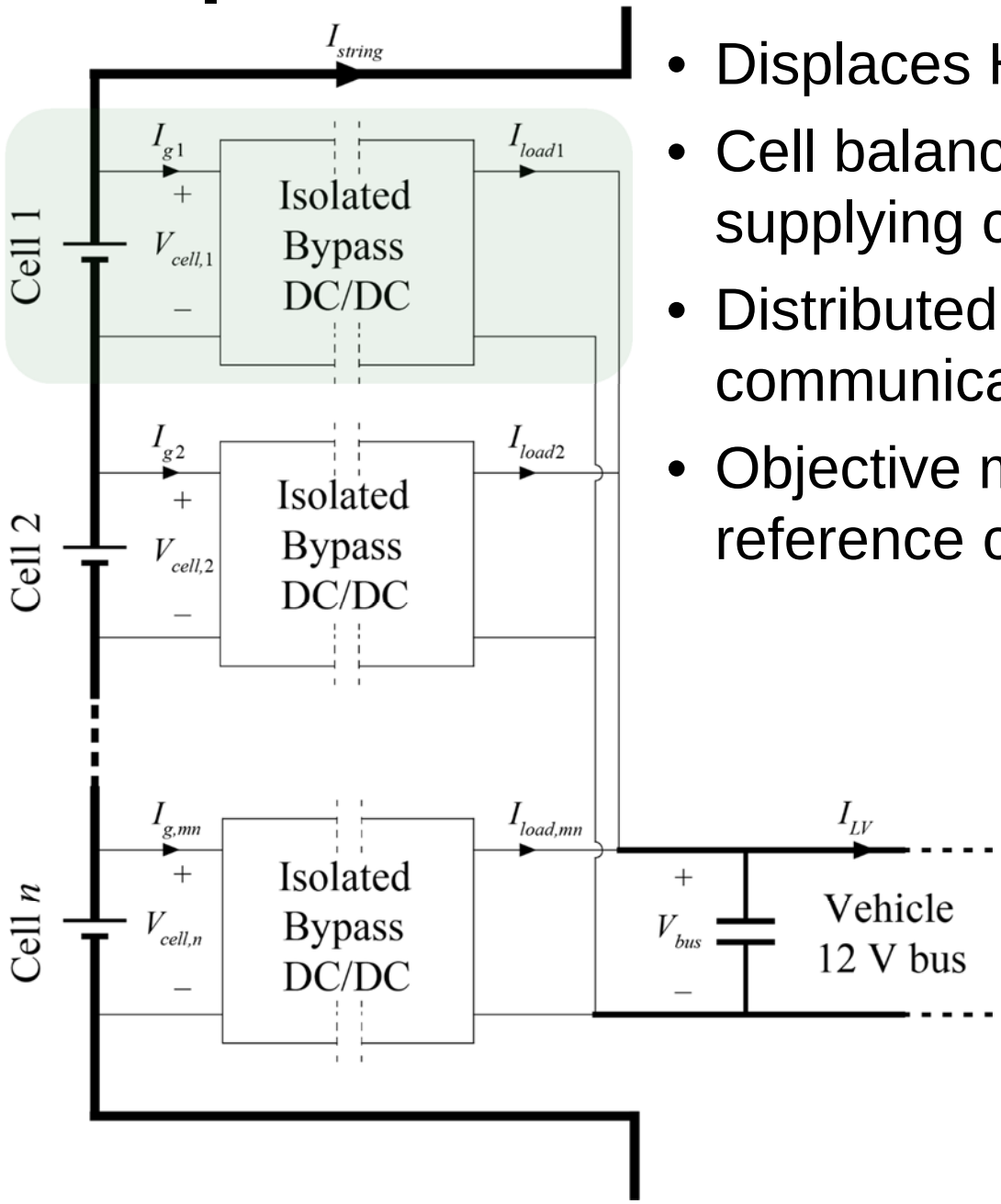
State-of-the-Art: Ford PHEV 7.6 kWh pack



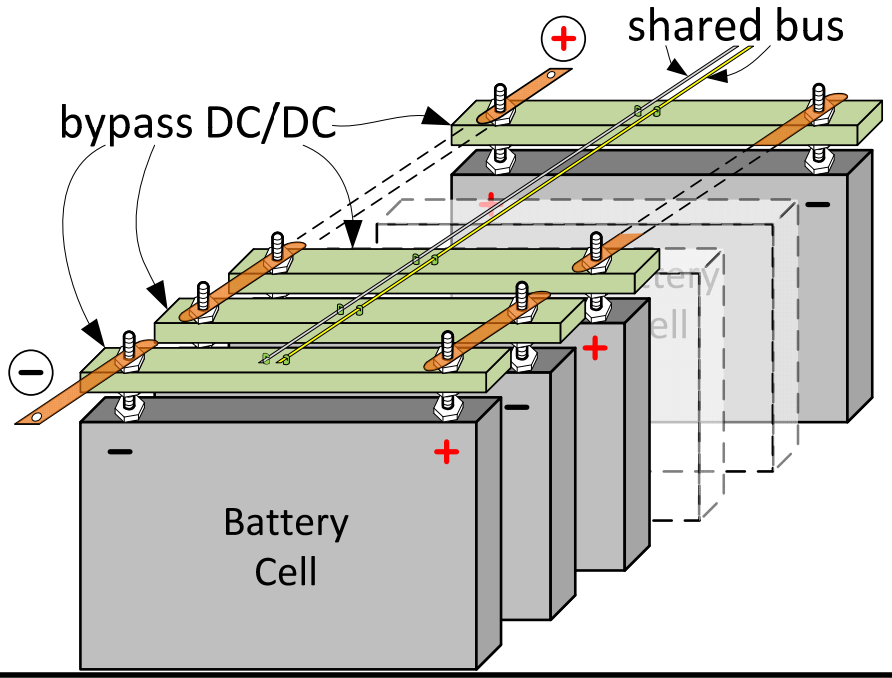
Wiring harnesses to BMS



Proposed hardware architecture



- Displaces HV-to-12V DC/DC converter
- Cell balancing achieved by differentially supplying current to the 12V bus
- Distributed control uses 12V bus voltage to communicate shared reference
- Objective map relates bus voltage to reference cell state

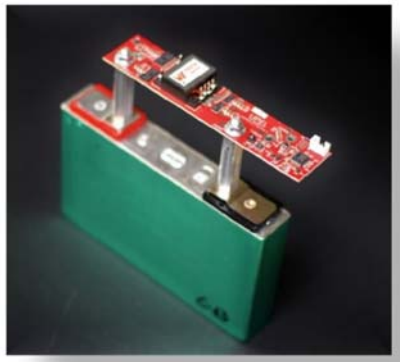


Hardware integration status

- Developed integrated BMS + DC/DC
- Built and tested > 100 DC/DC modules
- Integrated on 42 out of 84 cells for A/B comparison on 7.6 kWh battery pack

Battery Cell	
Capacity	25 Ah
Series Resistance	~ 1 mΩ

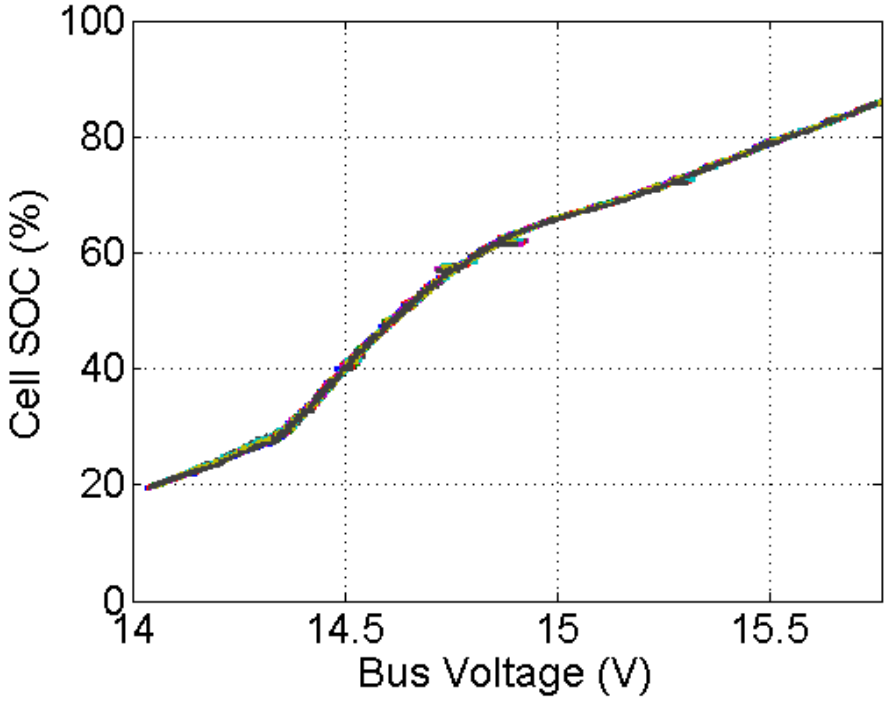
DC/DC Converter	
Power Rating	40 W
Peak Efficiency	>93 %



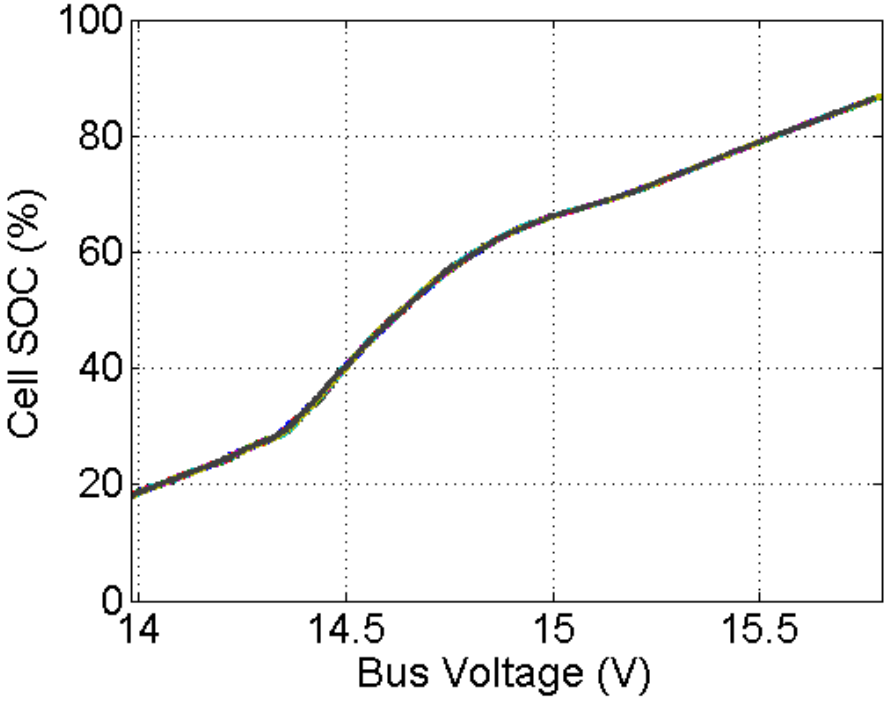
Hardware results SOC balancing

- Control Objective: SOC Balancing
  - Bus voltage mapped to internal cell Voc to improve DC/DC efficiency
- DC-DC converters supply 25 A to 12V load
- Results shown for 21 cells in series

Discharge Cycle (NREL US06 drive cycles)

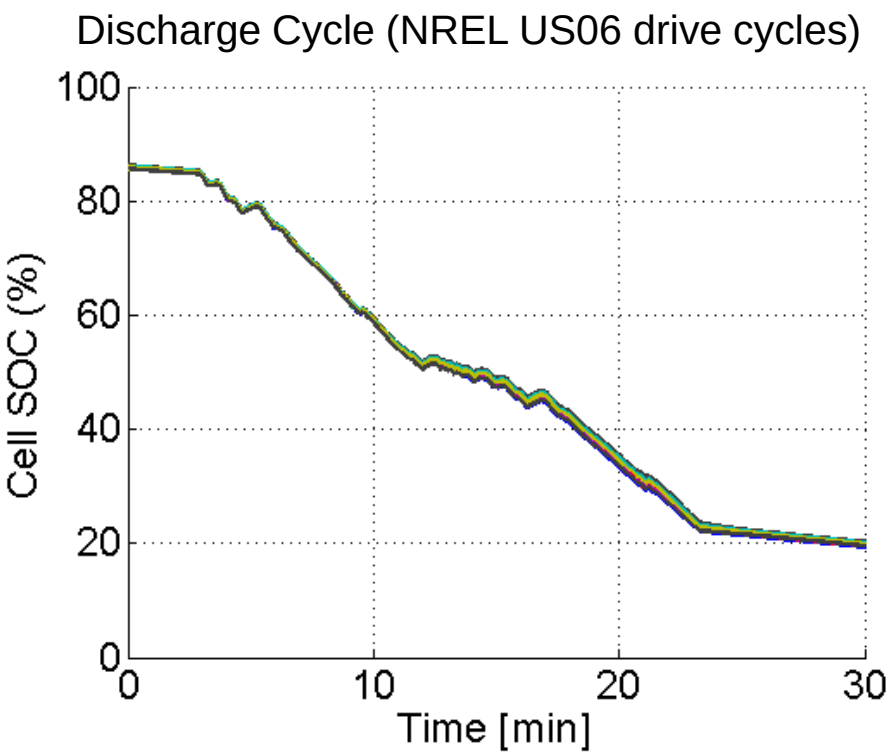


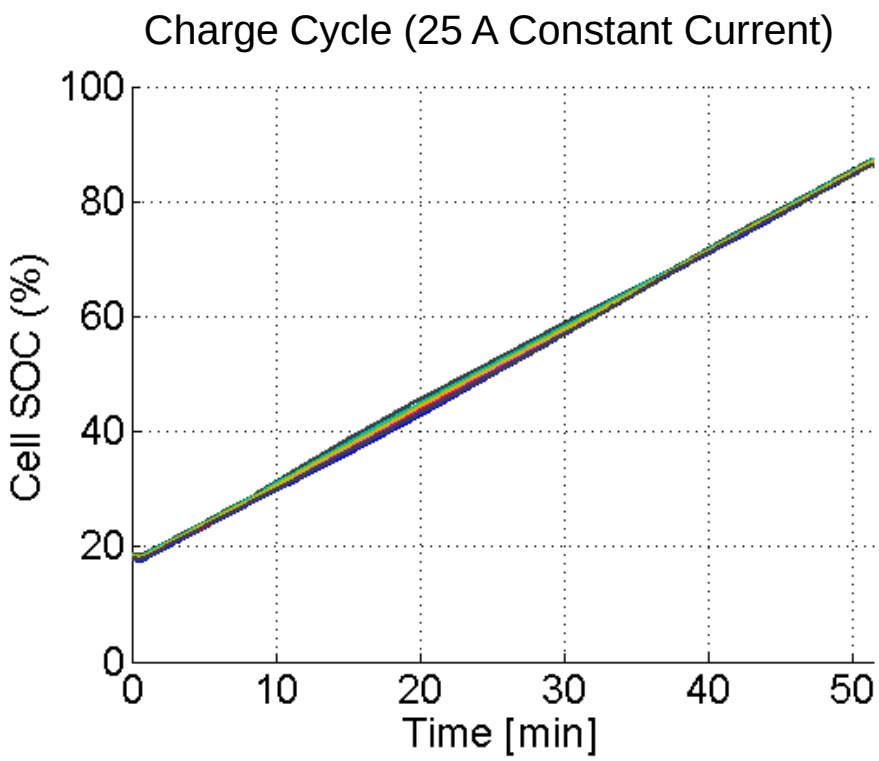
Charge Cycle (25 A charge current)



Hardware results SOC balancing (time)

- Same results shown in time
- 21 cells in series, SOC balancing

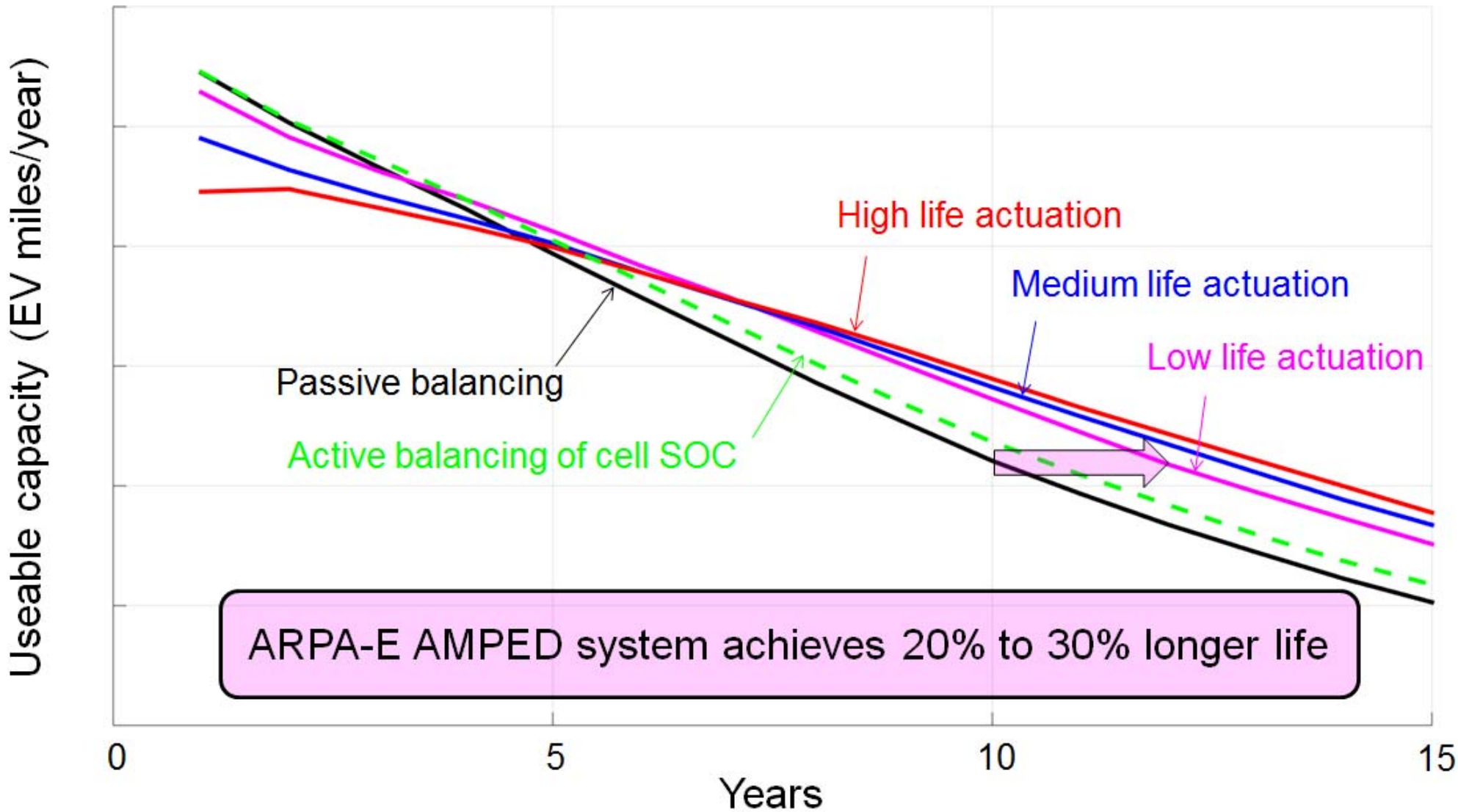




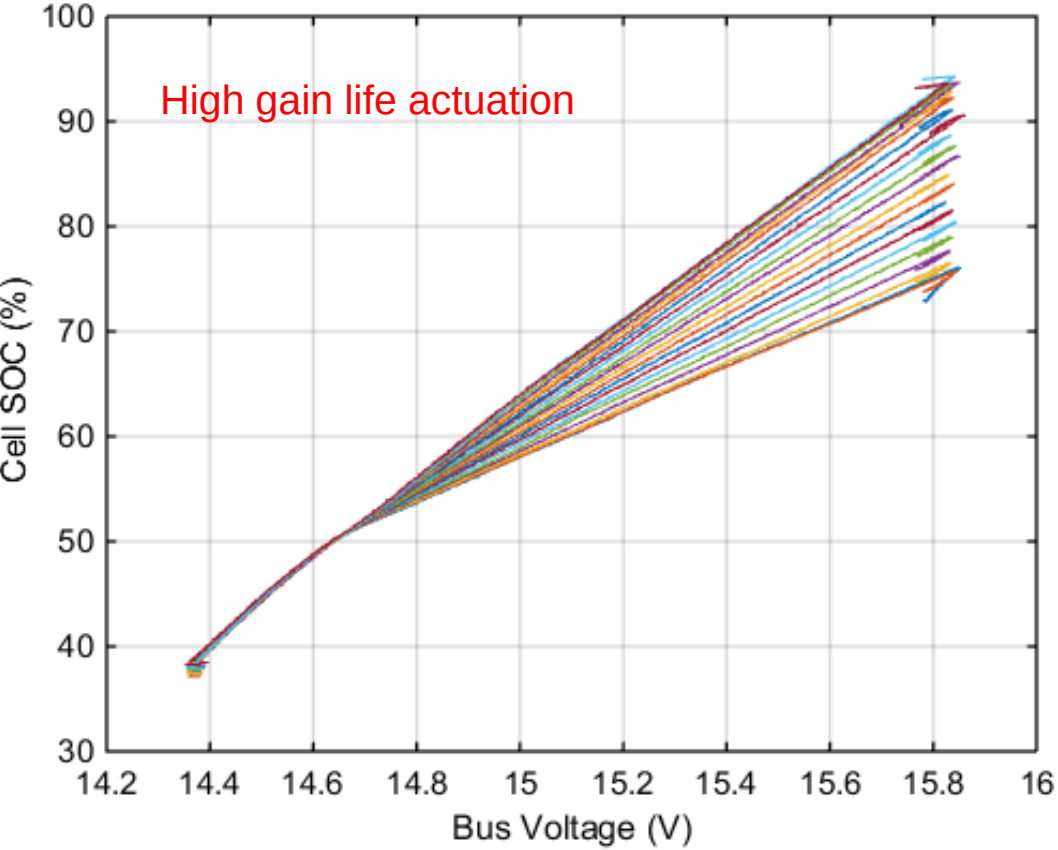
Life prognostic heterogeneous cell control

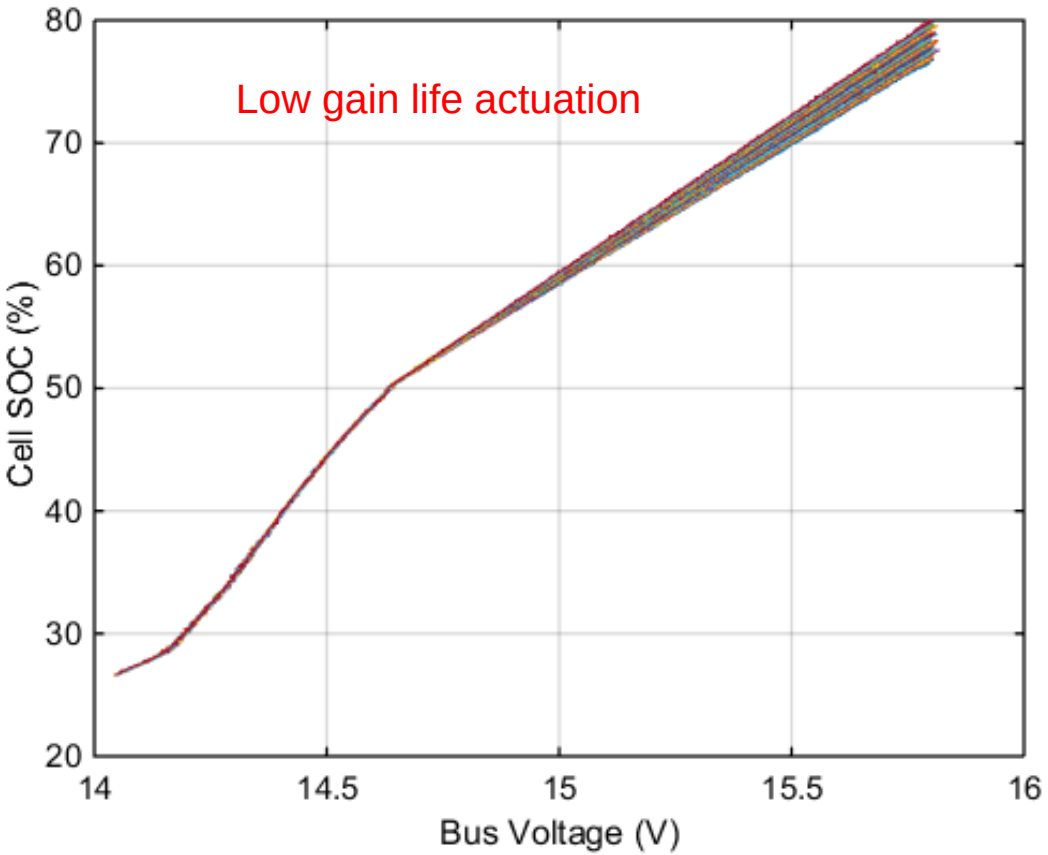
- Concept: strong cells are pushed harder, weak cells are treated better
- Life prognostic models show strong correlation between capacity fade and max SOC
- Objective map developed to drive high capacity cells to higher max SOC and low capacity cells to lower max SOC
  - Map defines relationship between shared bus voltage and cell Voc
  - Evaluated with “high” “medium” and “low” life actuation gains
- Cell power capabilities are matched at min SOC based on series resistance

Life model results with life actuation gains



Hardware results with life actuation gains



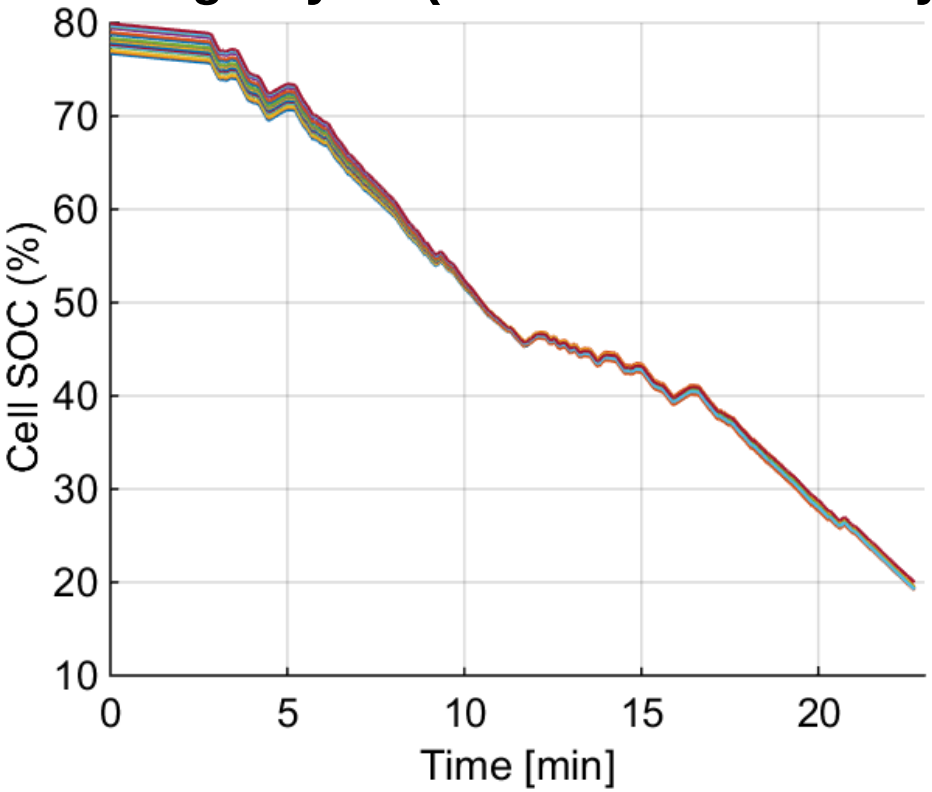


- DC/DC converters regulate objective map, differentially supply 12 V load
- Demonstrated on 21 series cells, 25 A charge current
- LV load: 350 W constant power
- Cell capacities: 23.6 to 25.2 Ah
- Plan to use “high” gain for validation; “low” gain likely for vehicle use

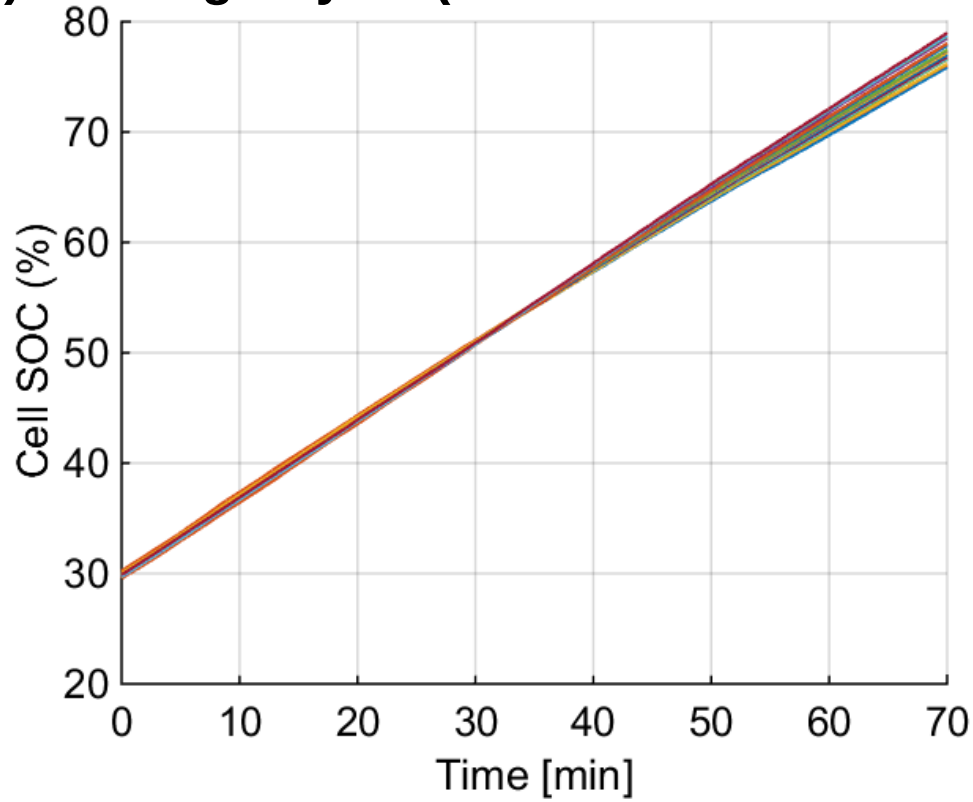
Charge/discharge hardware results (time)

- Operated over US06-based drive cycles
- DC/DC converters supply a load of 25 A on the DC bus
- Low life actuation gain

Discharge Cycle (NREL US06 drive cycles)

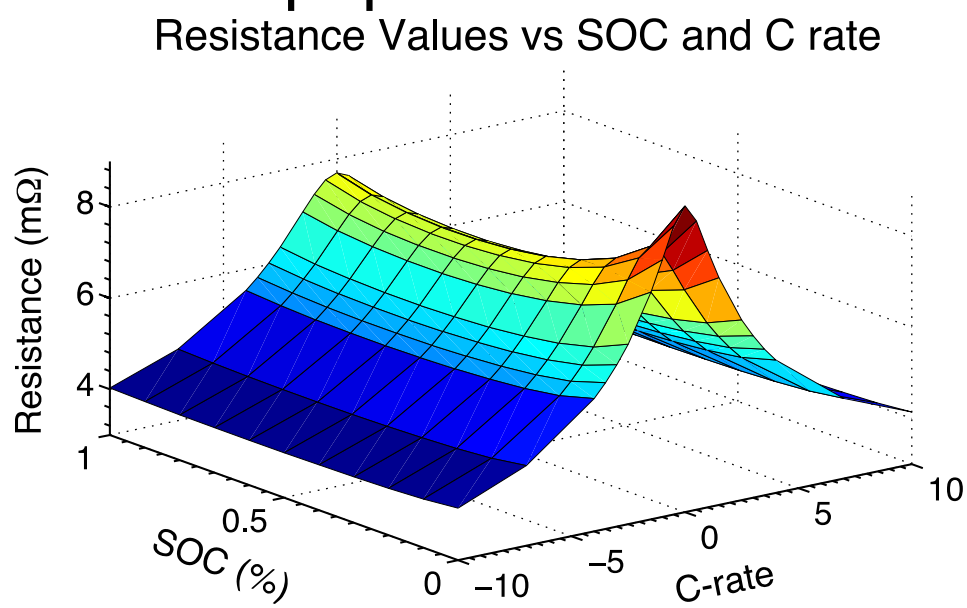


Charge Cycle (15 A Constant Current)



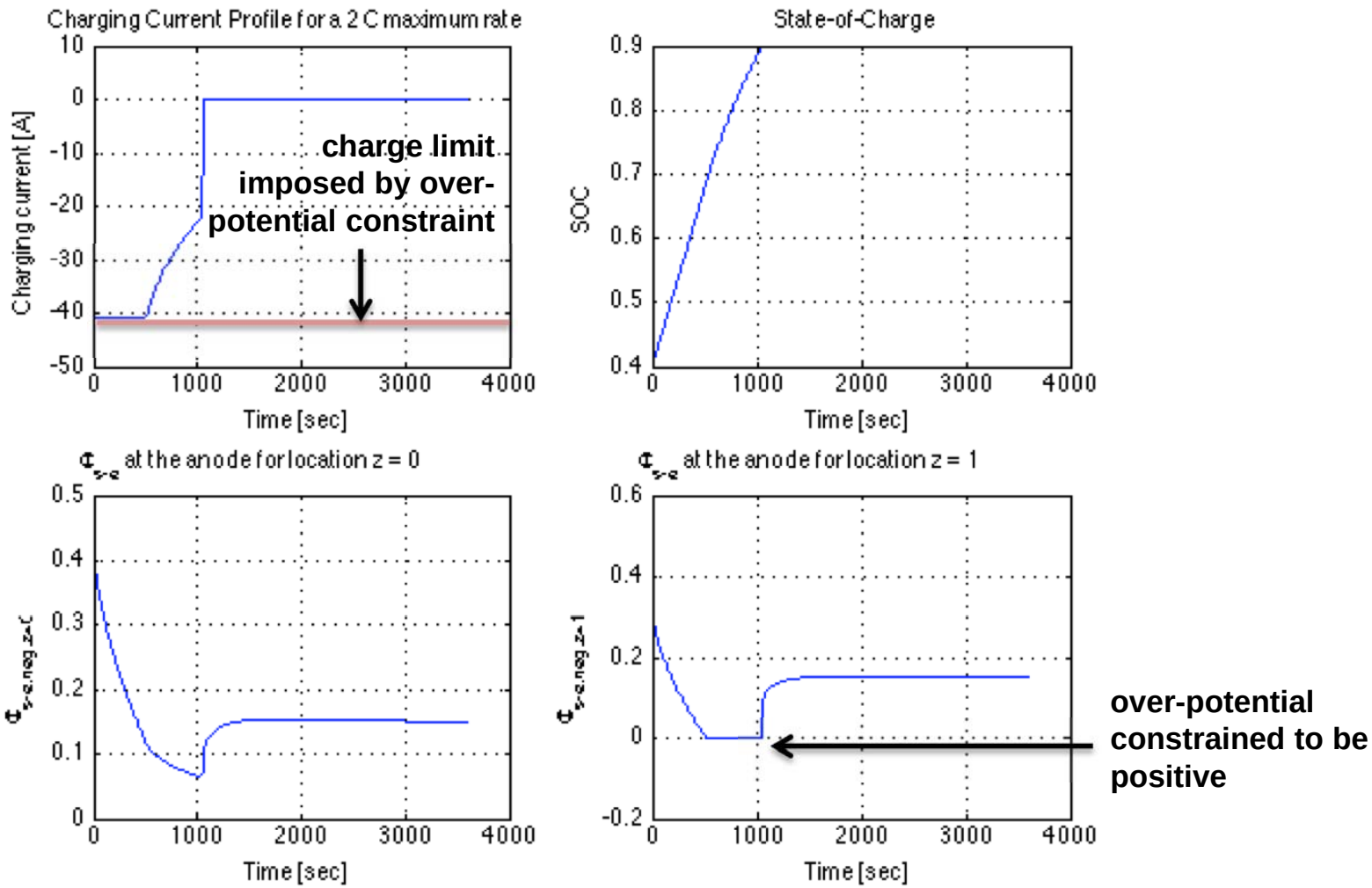
Physics based Model Predictive Control

- Improve lithium ion battery performance with model predictive control (MPC) using physics-based electrochemical models to achieve battery performance closer to theoretical limits
- Generate simple yet highly accurate reduced-order cell models amenable to fast computation
- Identify internal physical and electrochemical parameters via experimentation to populate models



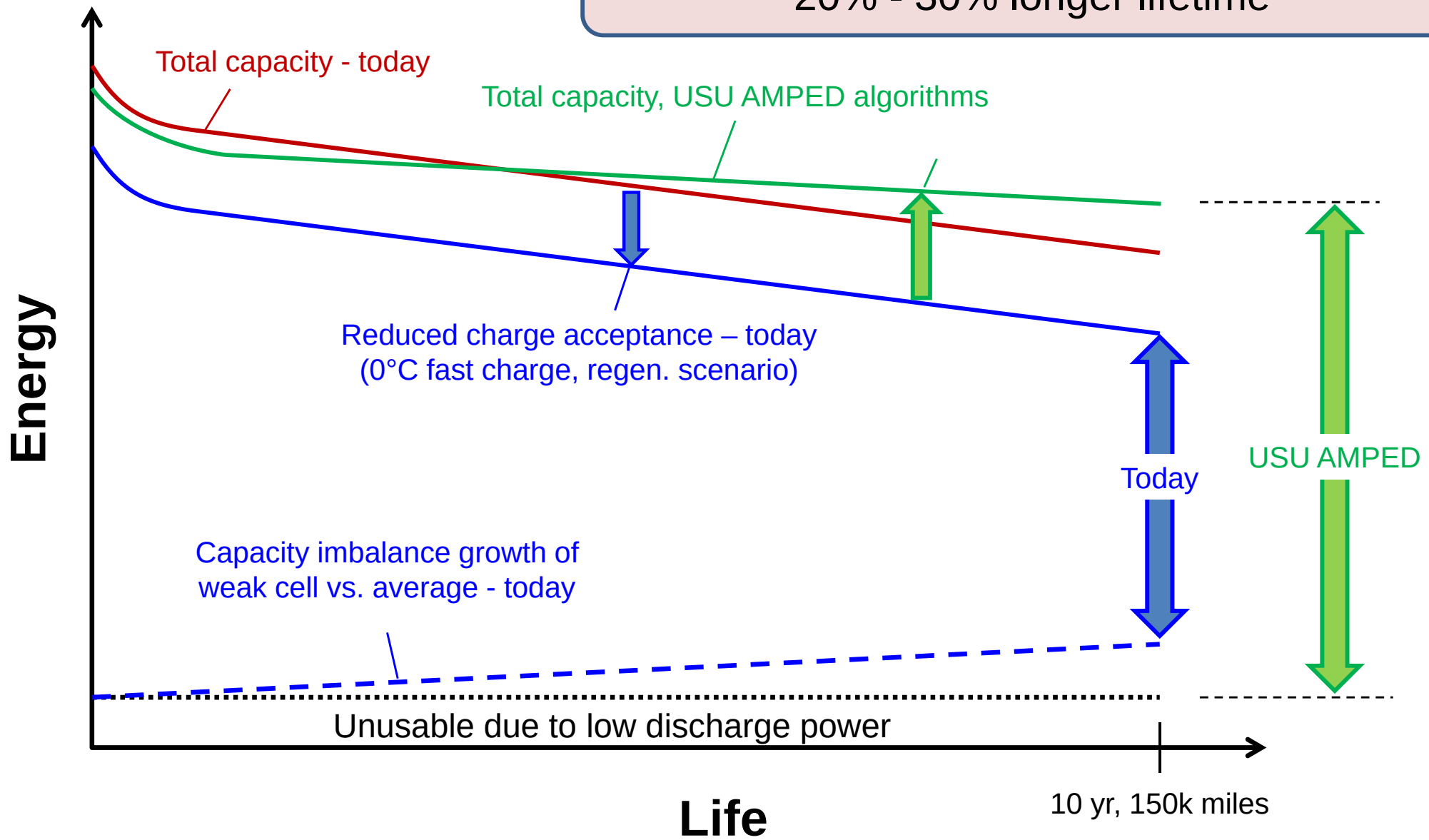
Fast charge with physics based MPC

- *Apply constrained model predictive control on a physics-based reduced-order cell model*



Combined Life and MPC improvement

~20% increased useable capacity in year 10
~20% - 30% longer lifetime



Validation plan

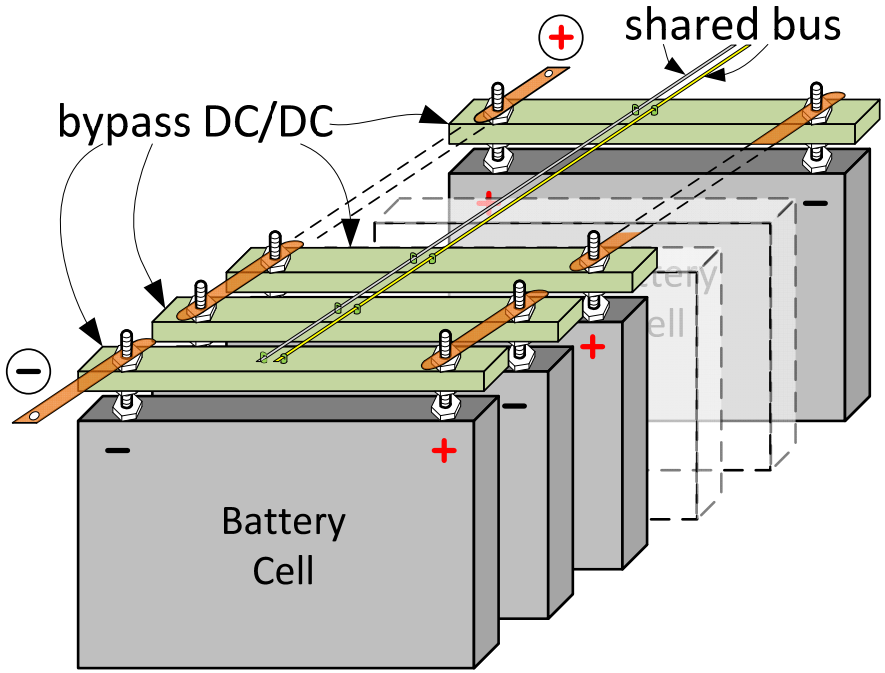
- Long term aging, A/B comparison, 42 of 84 cells integrated with USU AMPED DC/DC BMS, 7.6 kWh battery pack
  - NREL US06 drive cycles, >93% DC/DC efficiency, 1.5 kW 12V load
  - High life actuation gain
  - 3% greater usable capacity at month 0 (active balancing)
  - 5% greater usable capacity at month 12 (heterogeneous control)
  - 1% less capacity imbalance at month 12 (than passive)
- Model predictive control (MPC)
  - Validation on 3 cells in series, A/B comparison, US06 drive cycle
  - Short term validation
  - Demonstrate increased power over wider SOC range at 0°C
- System cost-benefit modeling
  - Predict 20% greater usable energy at year 10
  - Develop tool for evaluating cost-benefit of various system designs, chemistries, requirements

Next stage development

- Validation
  - Continue long term testing and evaluation (Heterogeneous + MPC)
  - Maintain platform to evaluate updated algorithms and sensors
- Leverage bypass cell-control platform
  - Cell level characterization and diagnostics
  - Safety and reliability
  - Next generation hardware for size, cost and energy loss reduction
- Systems and application integration
  - Expand optimization horizon and high level functionality through integration with system controllers (vehicle controller)
  - Methods to adapt models and algorithms to new chemistries
  - Algorithms for stationary energy storage and 2nd use
  - Demonstration at the application level

Technology status at end of program

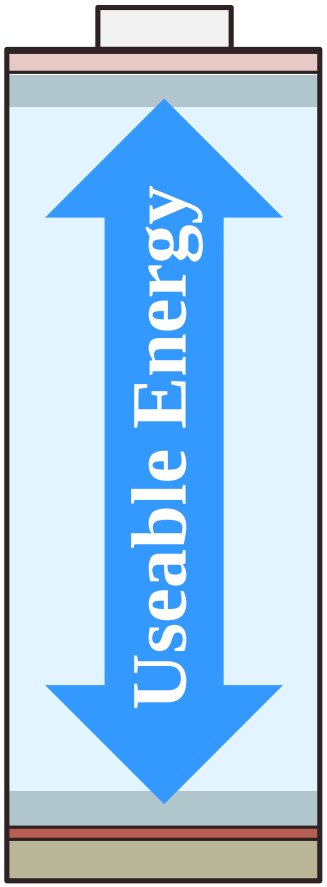
- Risks retired
  - Heterogeneous control for long life operation, improved energy utilization
  - MPC relaxes conservative limits
  - Cost-neutral active BMS displaces HV-to-12V DC/DC, provides cell-level control
  - Cost-benefit analysis and T2M industry feedback
  - System validation: 12-month aging on heterogeneous control, short term MPC evaluation
  - Cost constrained hardware and software considerations



Attendee battery challenges addressed

- Innovative, flexible BMS architecture, cost reduction
- Cost-effective active cell balancing
- Controlling battery packs to extract maximal capacity while also giving long cycle life
- Higher utilization of cell capacity in a long-lived pack
- Cell SOC and SOH estimation
- Simplified thermal management requirements
- Electrochemical model parameter and state estimation
- Accurate physics-based models
- System level integration of innovative technology
- Commercialization pathway

Summary



efficient BMS

advanced control, diagnostics

Active balancing

Cell-level control

Cost neutral hardware architecture replaces HV-LV DC/DC

Life prognostic heterogeneous cell control

Physics based model predictive control (MPC)

inhomogeneity decreases with age

increased power, usable energy, esp. low temp

Benefits

- 20% greater usable energy at year 10
- 20% longer lifetime
- Improved power
- Simplified thermal design
- Reduced volume
- Improved 2nd use value