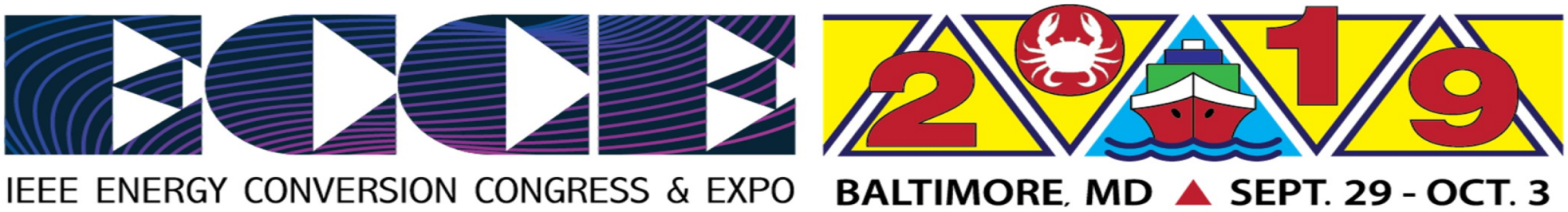



# A 13.56 MHz Multiport-Ac-Coupled (MAC) Battery Balancer with High Frequency Online Electrochemical Impedance Spectroscopy

Ming Liu, Ping Wang, Yueshi Guan, Minjie Chen

Princeton University


# Battery pack and cells balancer



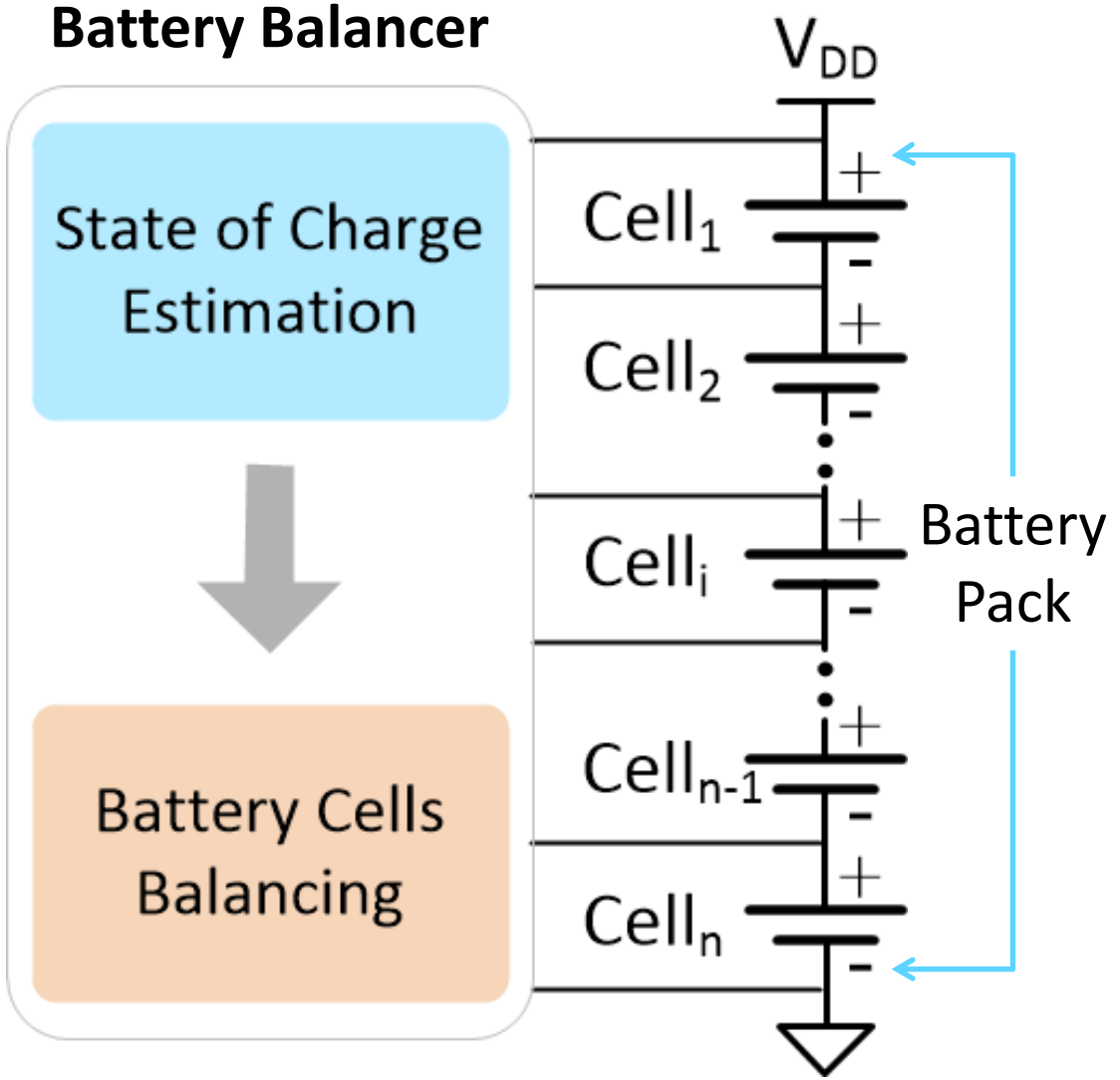
## Battery pack

- High output voltage and power capacity
- Different state of health (SOH) of cells
- Imbalanced state of charge (SOC) of cells

**Shorter life-cycle and reduced capacity**

**Battery pack**

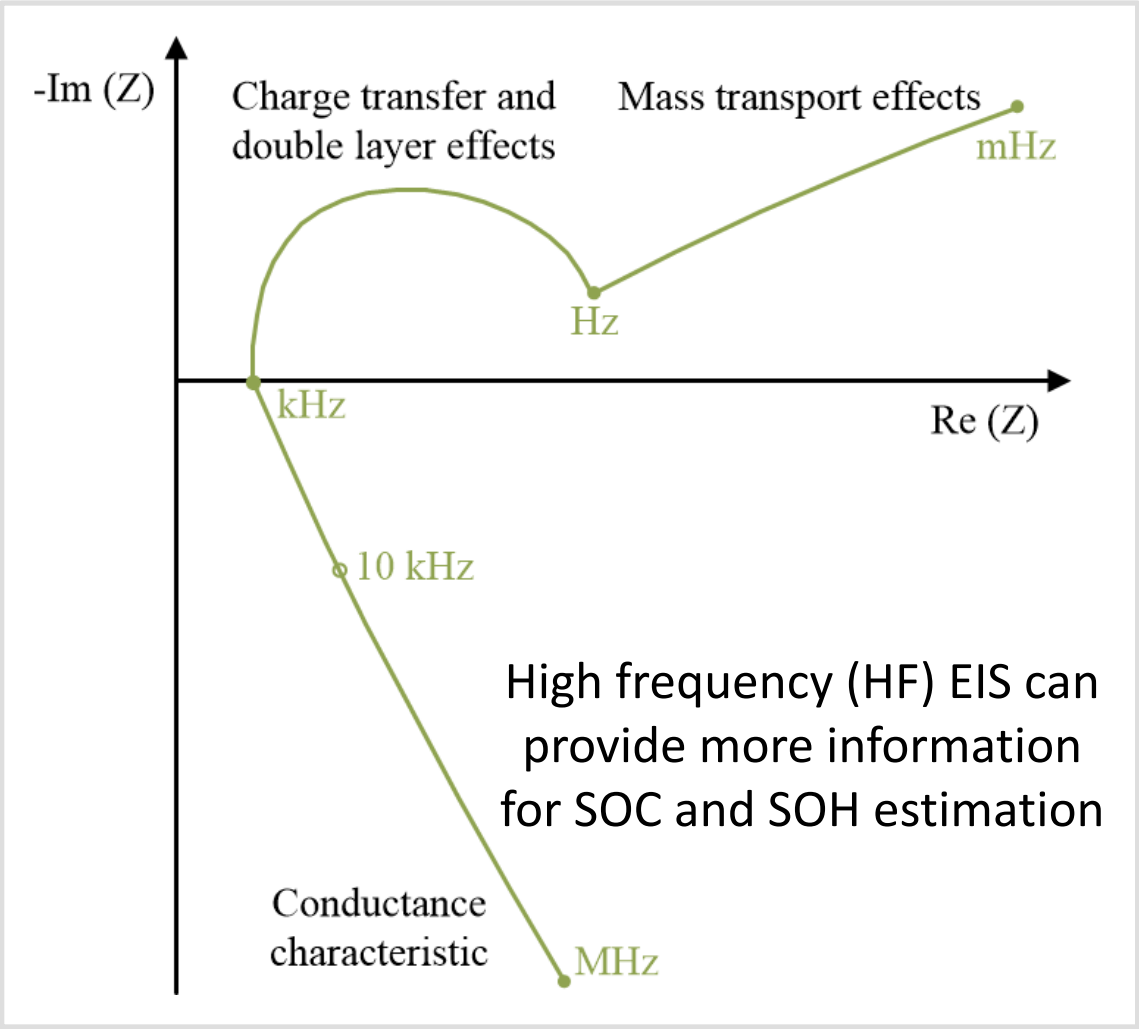
## Battery Balancer



# Electrochemical Impedance Spectroscopy (EIS)



## An example EIS Nyquist plot



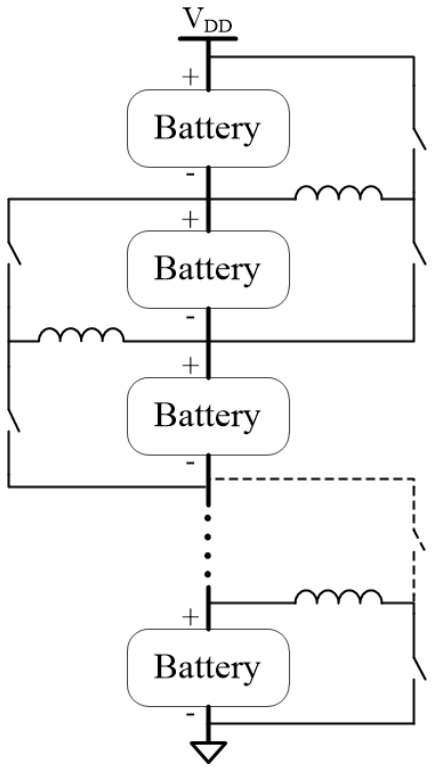

## Electrochemical Impedance Spectroscopy

- Battery state of charge (SOC) estimation
- Battery state of health (SOH) estimation
- Extra perturbation generation circuitry

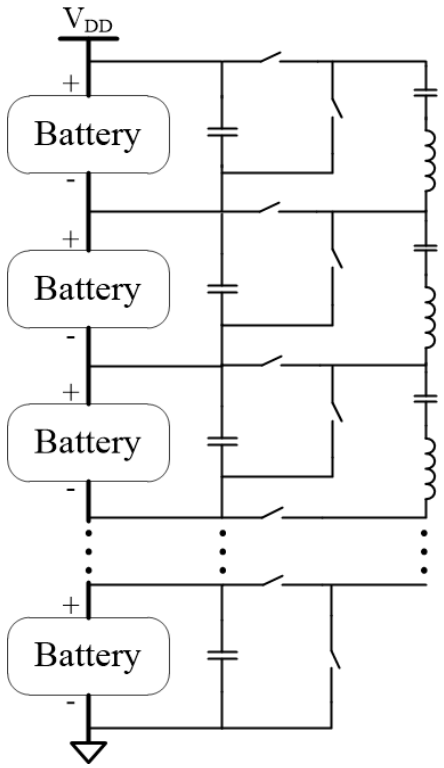
# Existing battery balancer topologies



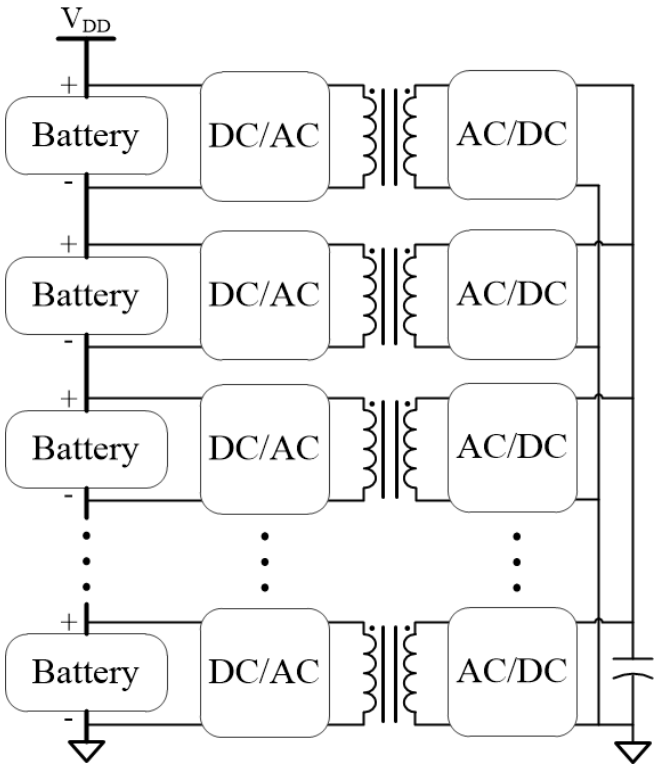
## Load to load



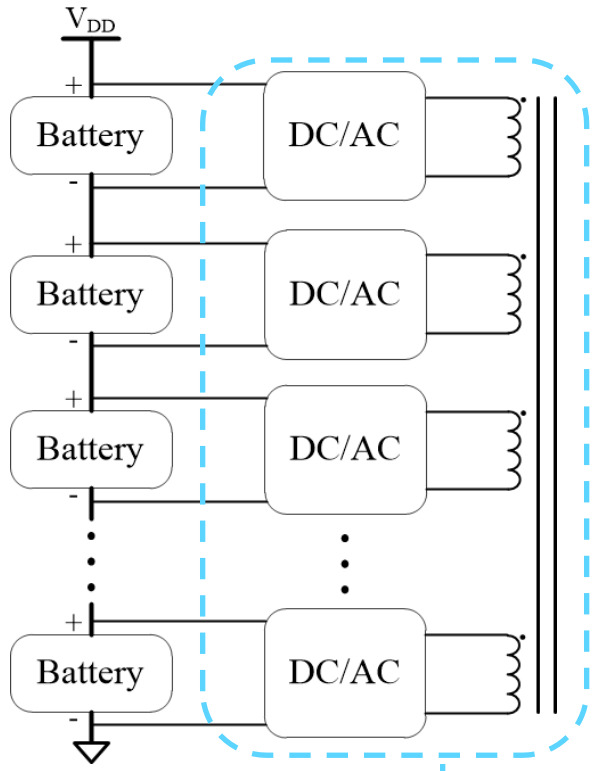

## Switched-capacitor




## Dc-coupled




## Multiport ac-coupled (MAC)

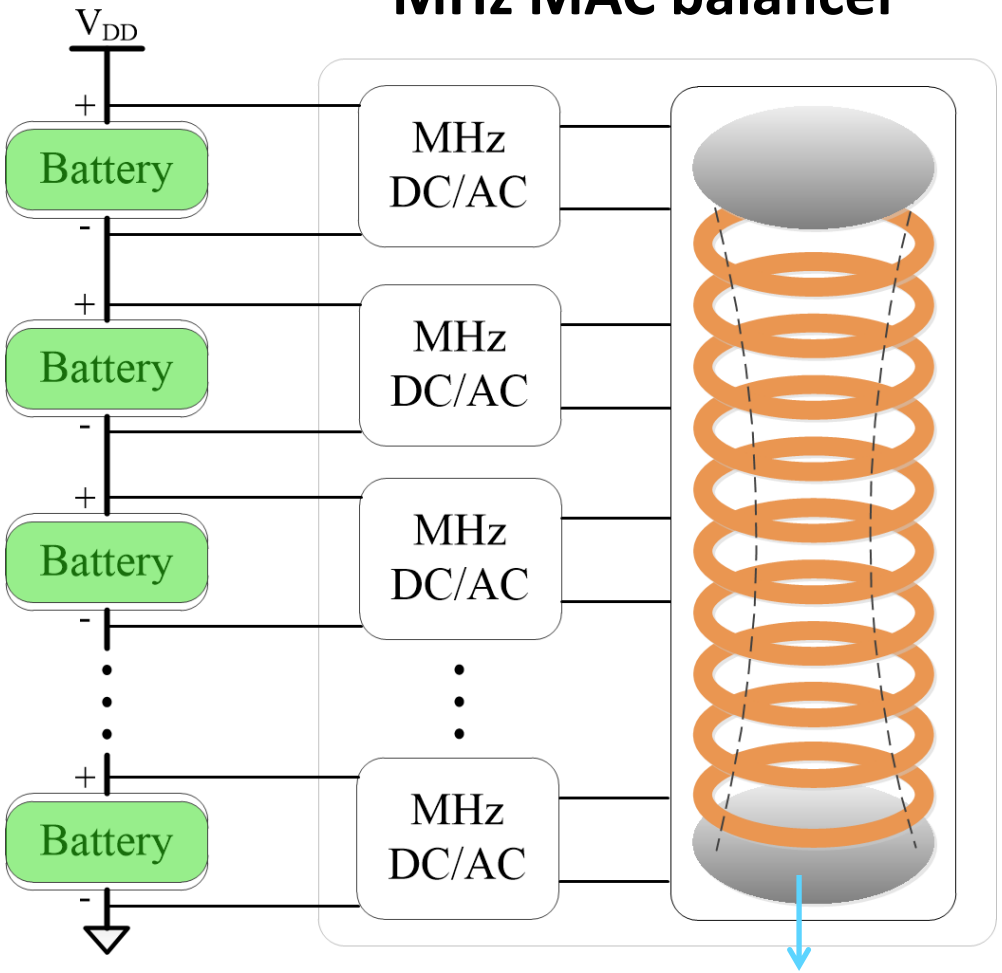



- Balance any two cells only through one dc-ac-dc conversion stage
- Offer reduced power conversion stress and low component count

# Multi-MHz MAC battery balancer

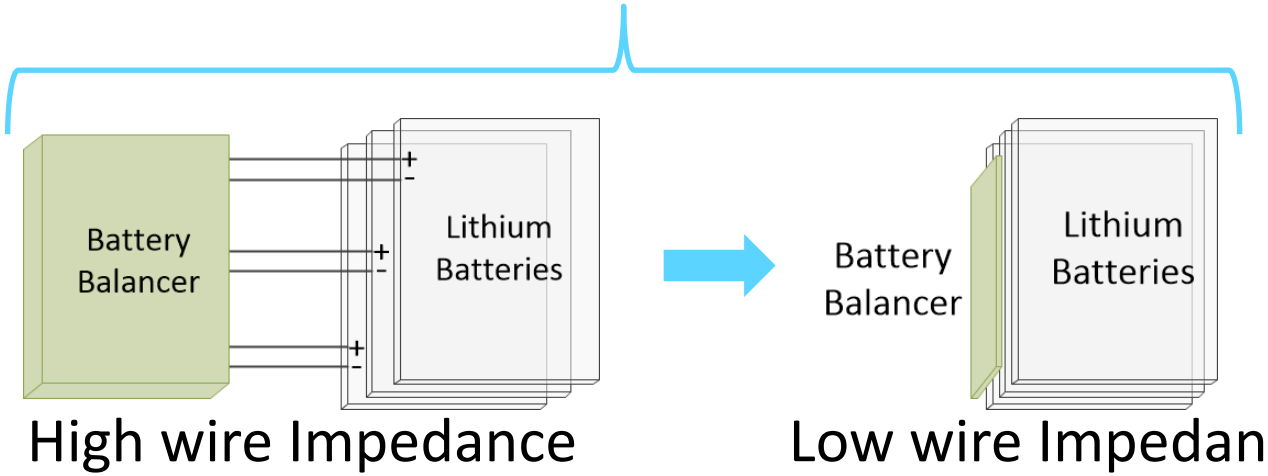


## MHz MAC balancer



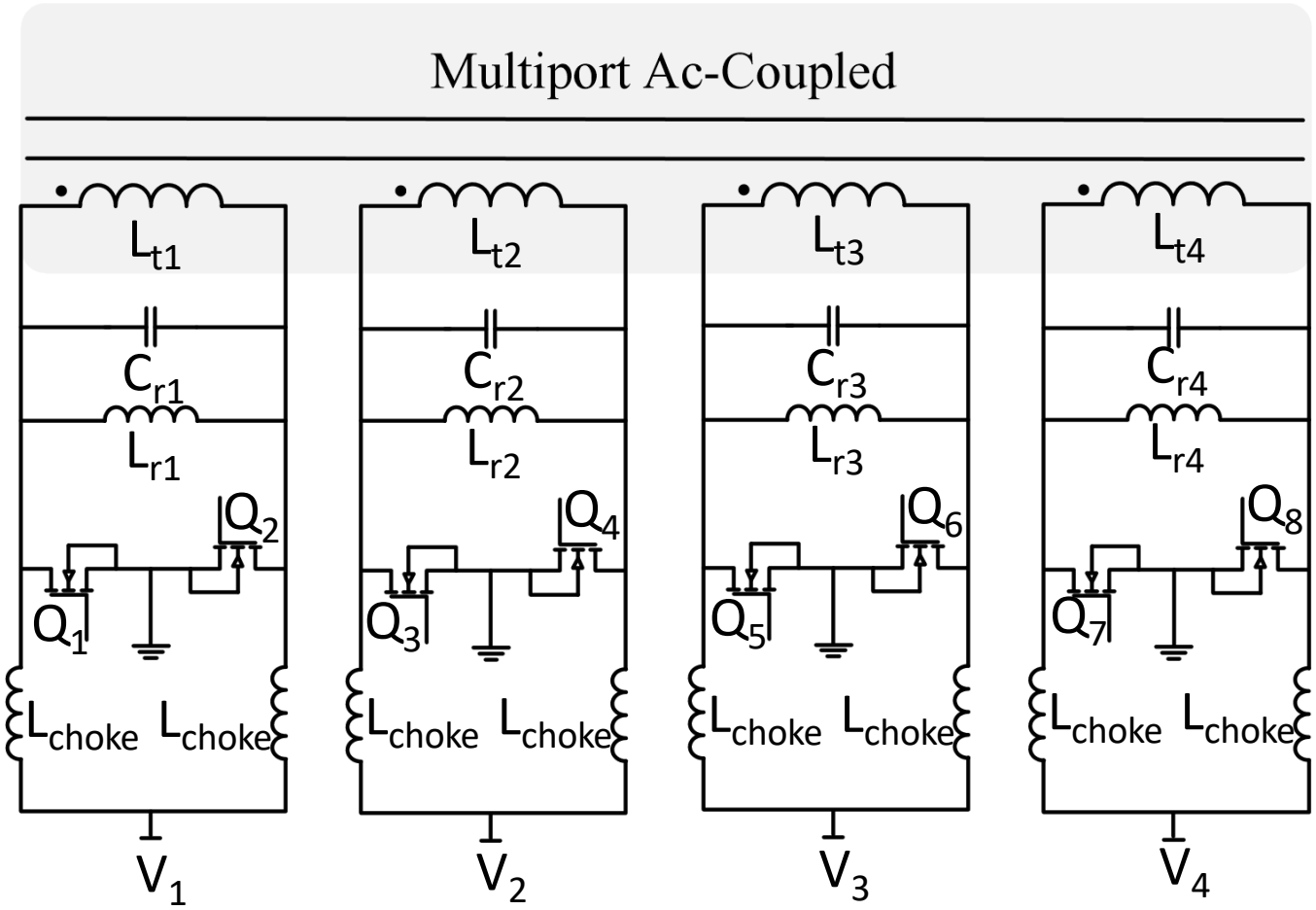

## Benefits of the MHz MAC balancer

- Implement HF EIS without extra perturbation circuitry
- Reduce coil size and eliminate bulky magnetic core
- Easily integrated with cells to reduce wire impedance and achieve high frequency battery EIS measurement



# Multi-active Class D MHz MAC converter

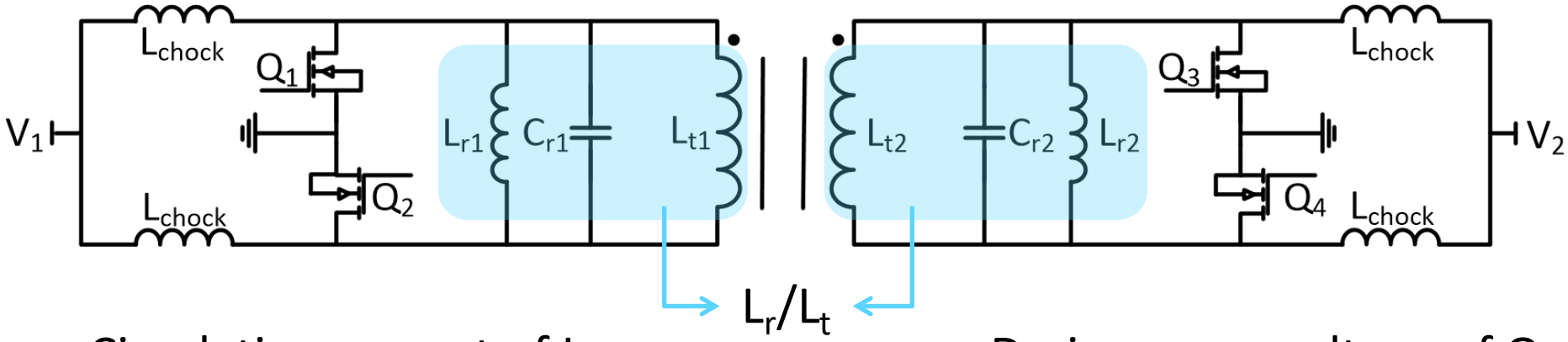




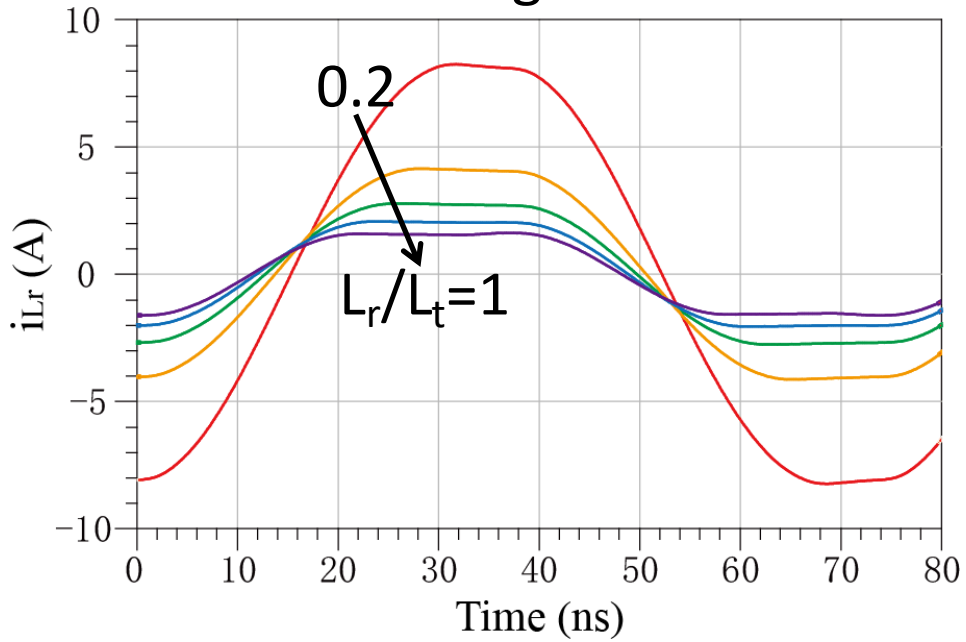

- High performance at multi-MHz
- Easy to drive and control at MHz
- Current-mode phase shift modulation

# Design of Active CM Class D converter

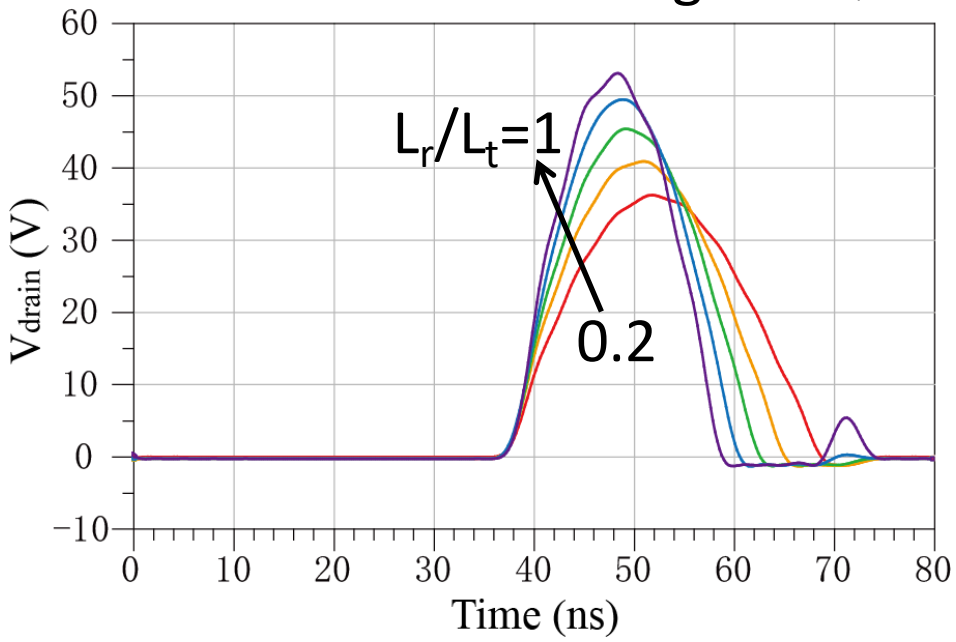





Circulating current of Lr




Drain source voltage of Q

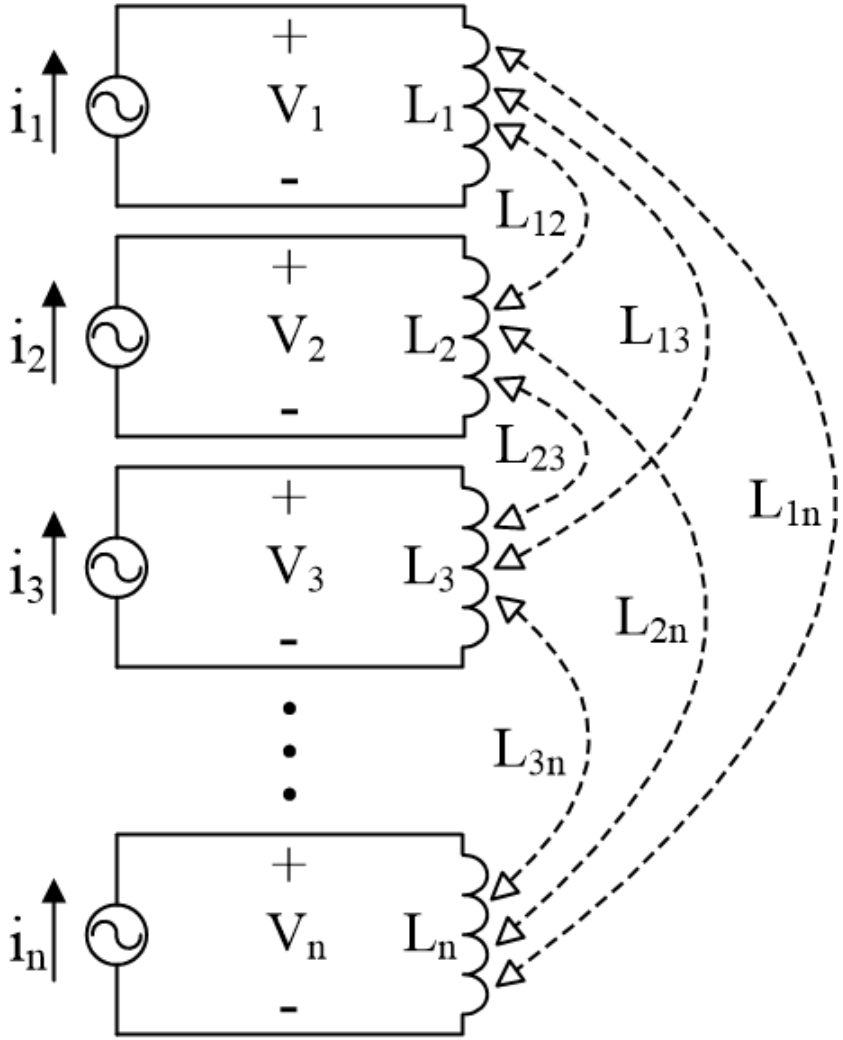



- Low $L_r/L_t$, high circulating current
- High $L_r/L_t$, high switch voltage stress

# Control of the multi-way power flow



## Simplified lumped circuit model




The impedance matrix of the MAC transformer is

$$\begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ V_n \end{bmatrix} = \begin{bmatrix} j\omega L_{1,1} & j\omega L_{1,2} & \cdots & j\omega L_{1,n} \\ j\omega L_{2,1} & j\omega L_{2,2} & \cdots & j\omega L_{2,n} \\ \cdot & \cdot & \cdots & \cdot \\ j\omega L_{n,1} & j\omega L_{n,2} & \cdots & j\omega L_{n,n} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \cdot \\ i_n \end{bmatrix}$$

The active power feeding into port *k* is

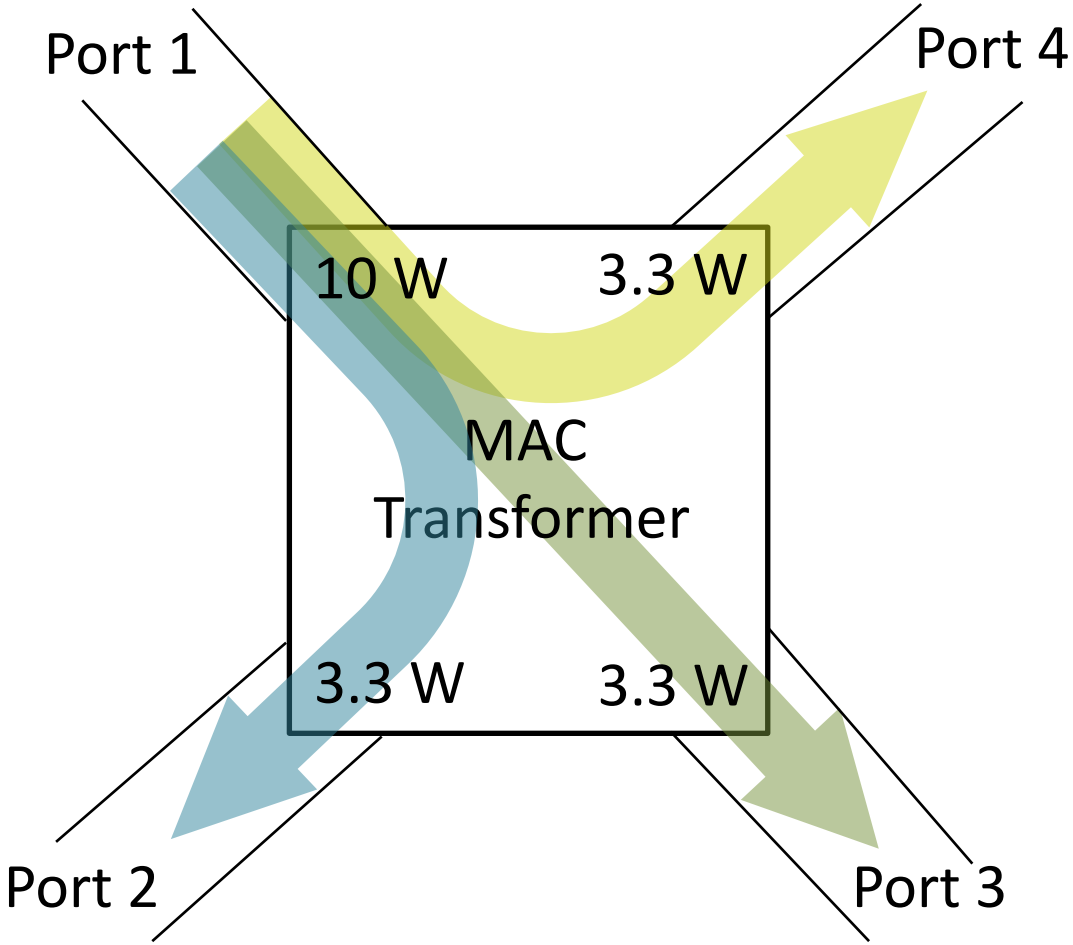
$$P_k = V_k \times i_k^* = \frac{1}{2} \sum_{q=1, q \neq k}^{n} \omega L_{k,q} I_k I_q sin\theta_{qk}$$

- Power flow control by current phase modulation

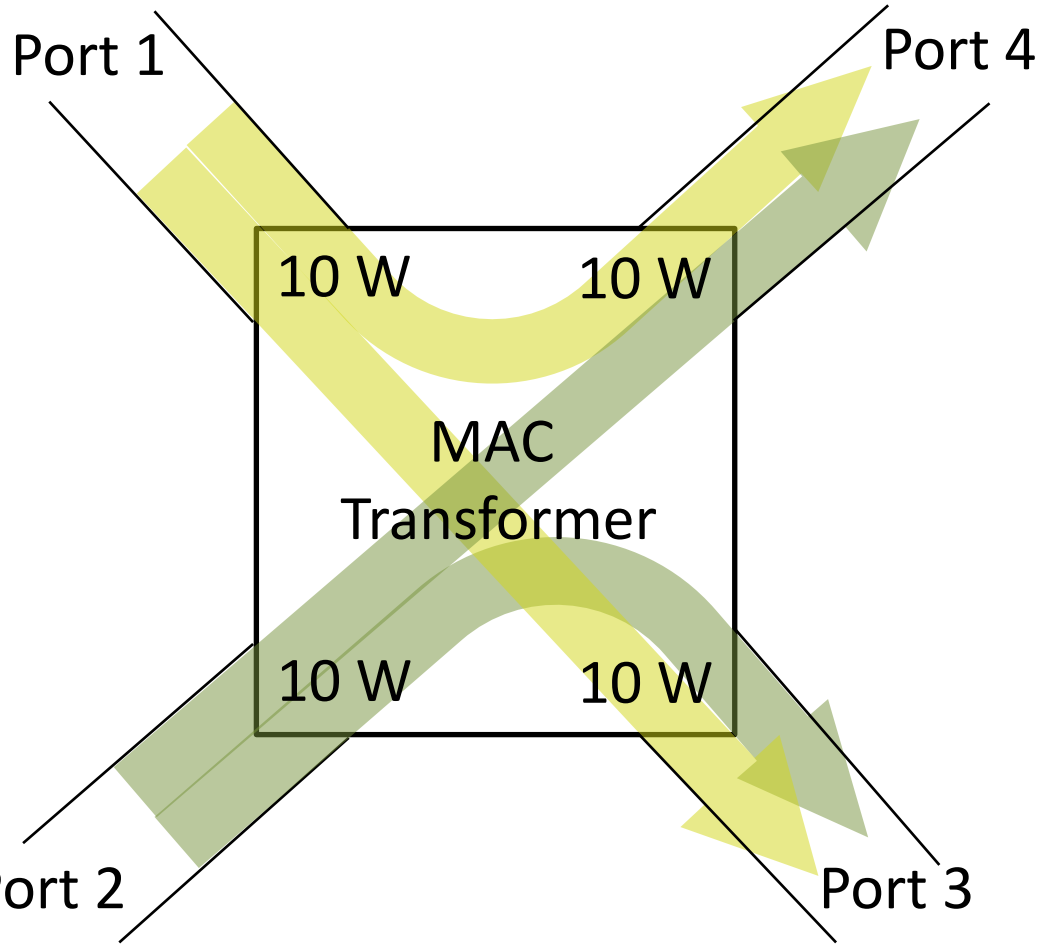
# Examples of Power Flow Control



**Case I:** $\phi_1$=0°, $\phi_2$=90°, $\phi_3$=90°, $\phi_4$=90°




**Case II:** $\phi_1$=0°, $\phi_2$=0°, $\phi_3$=90°, $\phi_4$=90°

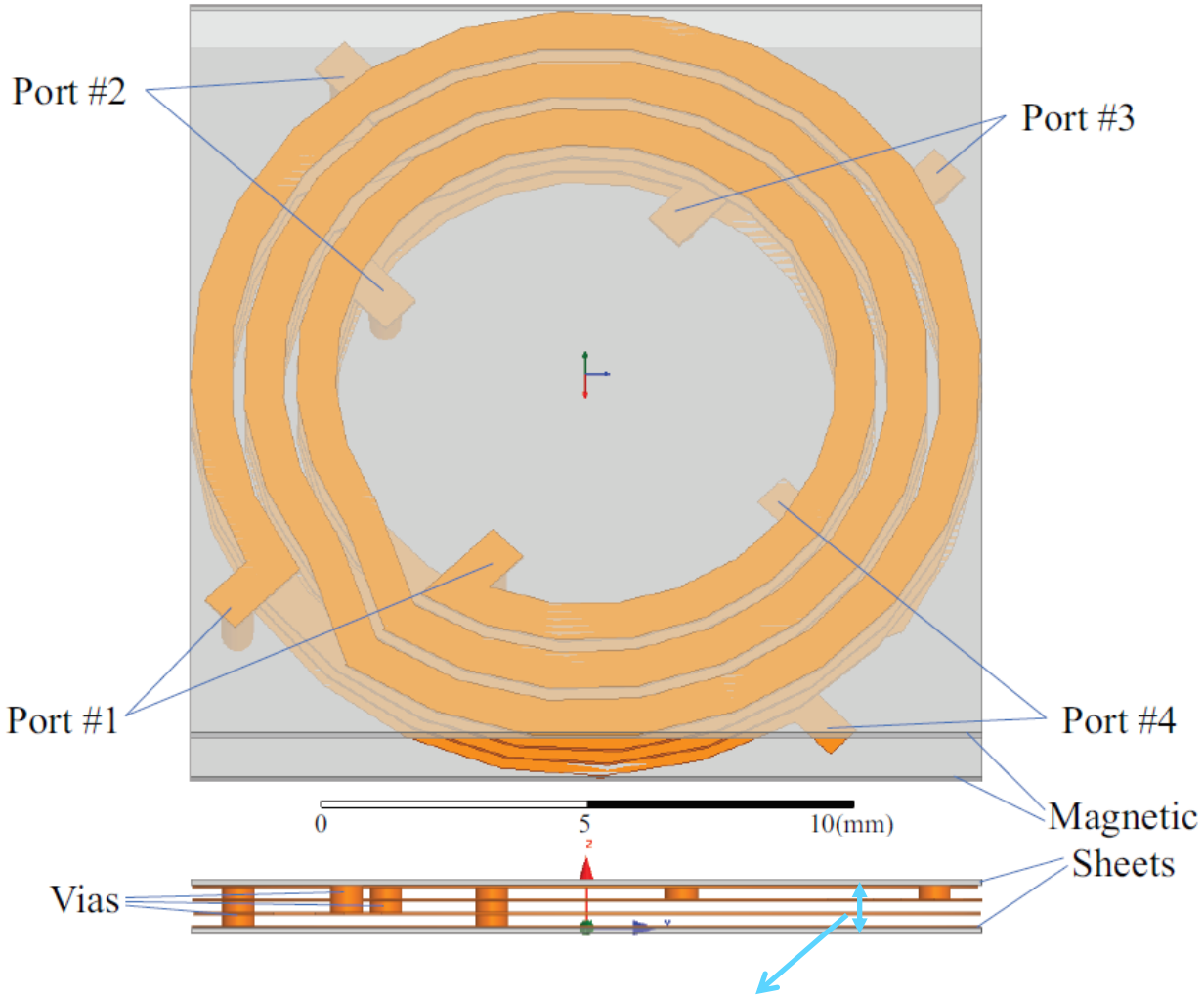



- Case I: Power is transferred from Port 1 to Port 2, Port 3, and Port 4
- Case II: Power is transferred from Port 1 and Port 2 to Port 3 and Port 4

# Modeling of the multiport transformer

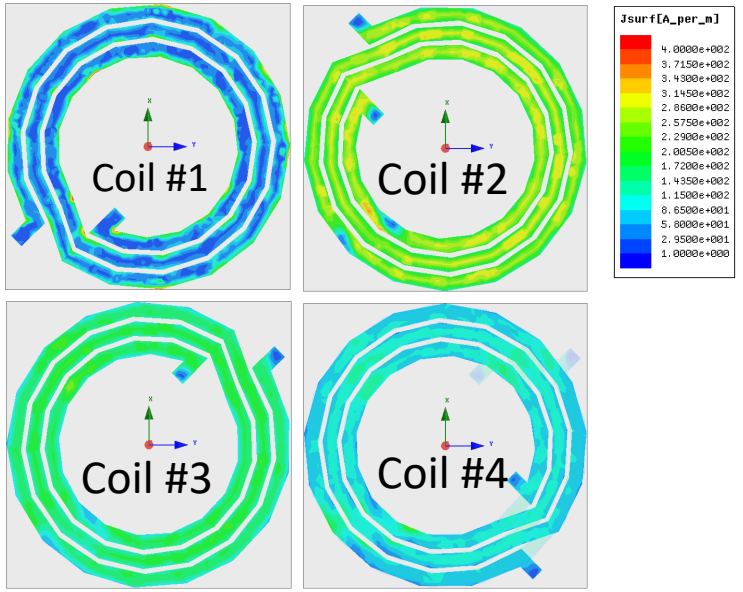


## 3D finite element model




Overall thickness < 1mm

## Current distribution



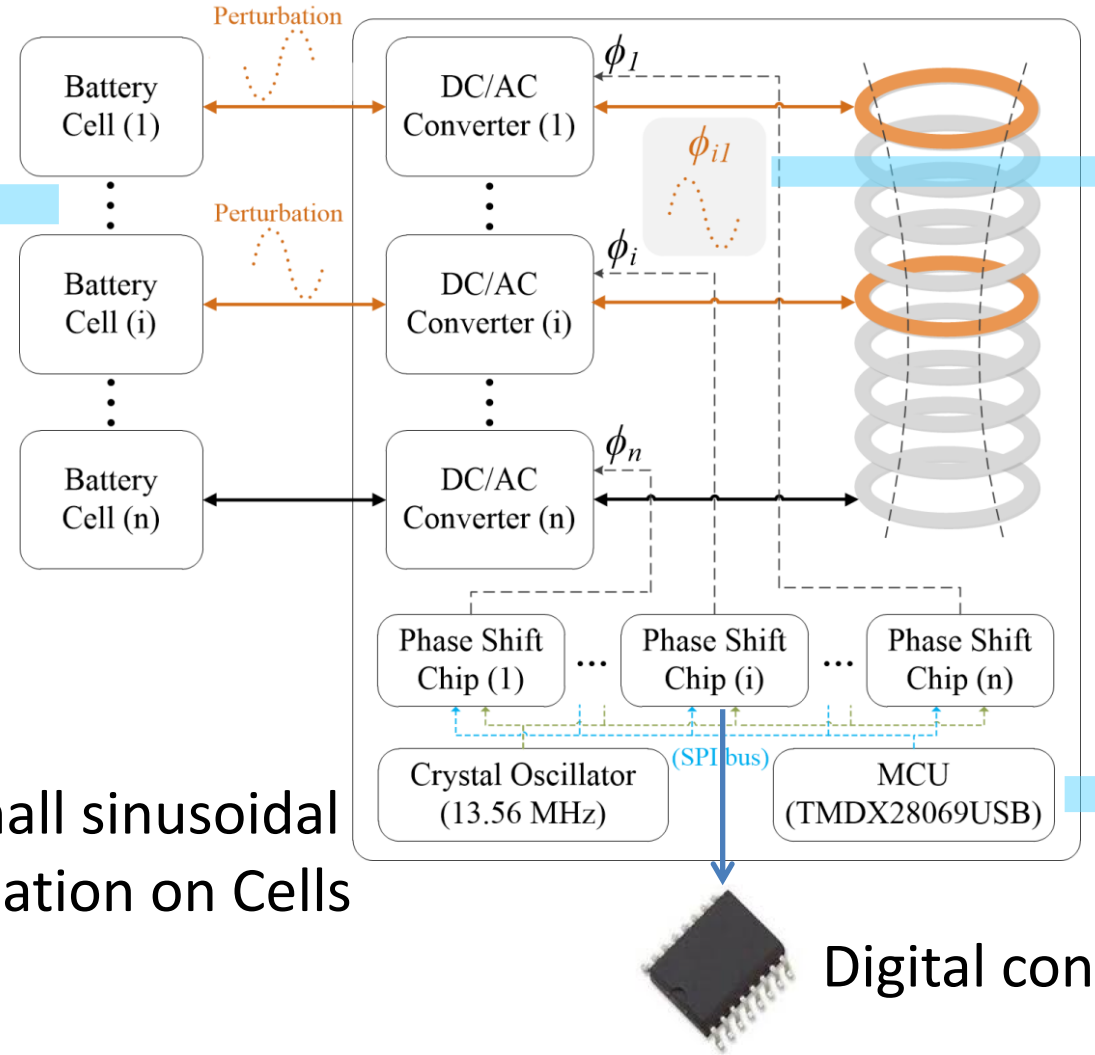

## Impedance matrix

$$Z_{air} = \begin{bmatrix} 12.5\ j\Omega & 10.9\ j\Omega & 9.92\ j\Omega & 9.11\ j\Omega \\ 10.9\ j\Omega & 12.3\ j\Omega & 10.9\ j\Omega & 9.92\ j\Omega \\ 9.92\ j\Omega & 10.9\ j\Omega & 12.3\ j\Omega & 10.9\ j\Omega \\ 9.11\ j\Omega & 9.92\ j\Omega & 10.9\ j\Omega & 12.3\ j\Omega \end{bmatrix}$$

$$Z_{sheet} = \begin{bmatrix} 29.5\ j\Omega & 27.4\ j\Omega & 26.2\ j\Omega & 25.4\ j\Omega \\ 27.4\ j\Omega & 28.4\ j\Omega & 26.9\ j\Omega & 26.7\ j\Omega \\ 26.2\ j\Omega & 26.9\ j\Omega & 28.3\ j\Omega & 27.2\ j\Omega \\ 25.4\ j\Omega & 26.7\ j\Omega & 27.2\ j\Omega & 28.9\ j\Omega \end{bmatrix}$$

# High frequency EIS measurement circuitry





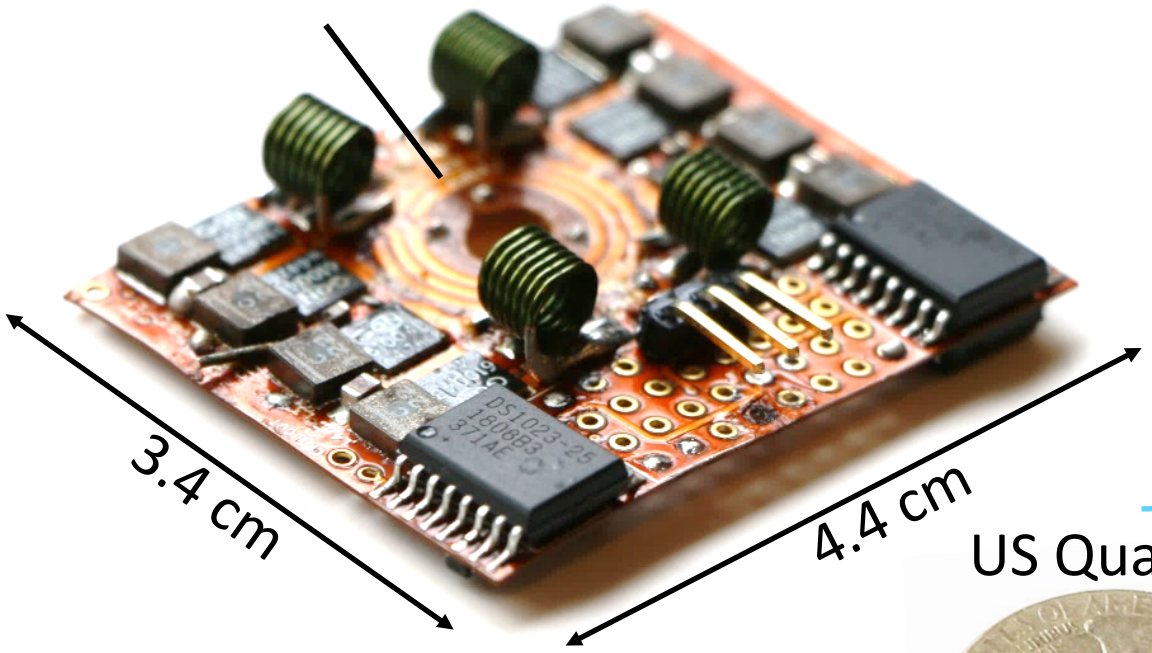

- Sweeping phase difference between two ports ($\phi_1$ and $\phi_i$)
- Phase-shift look up table for perturbation generation
- Synthesize a small sinusoidal current perturbation on Cells



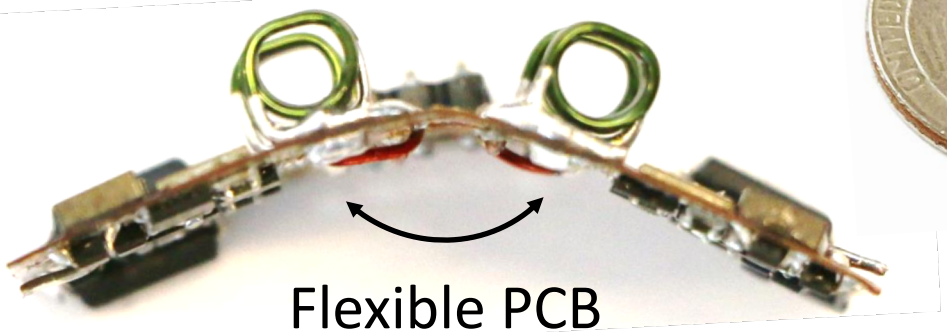
Digital control phase shift chip

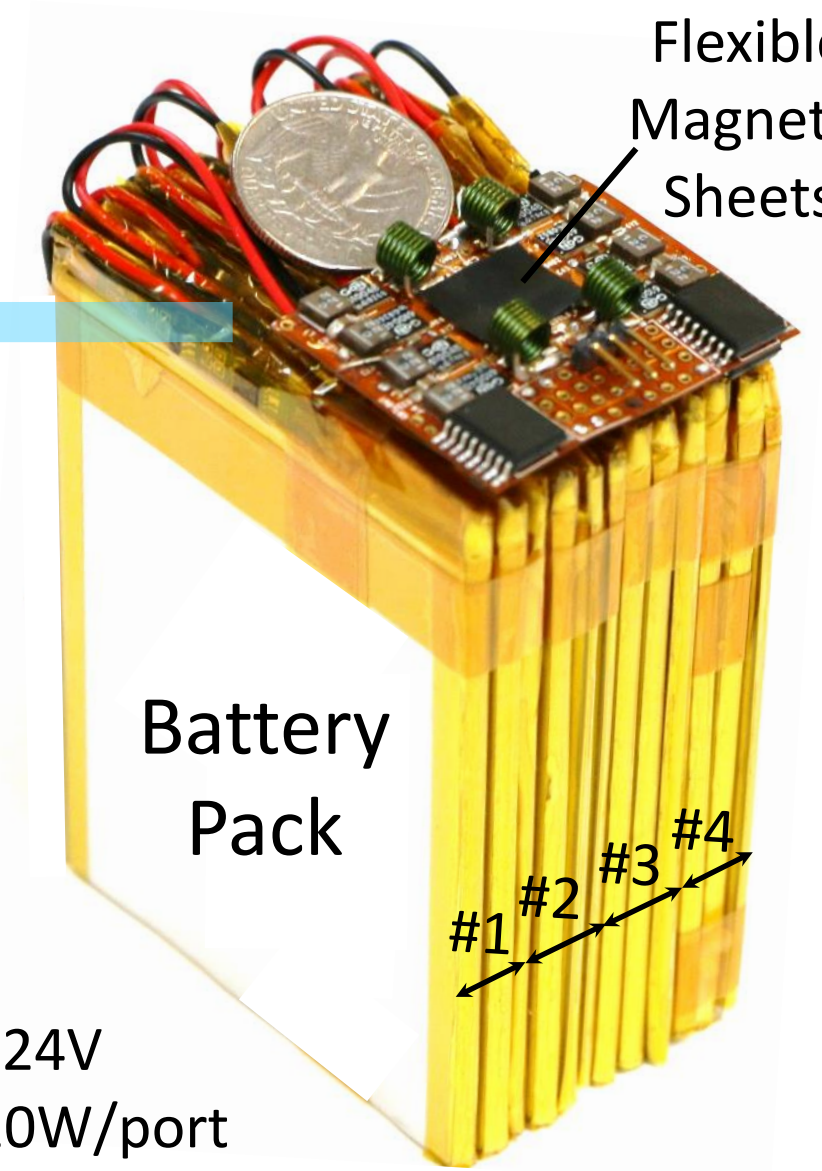
# A prototype 4-port 13.56MHz MAC balancer









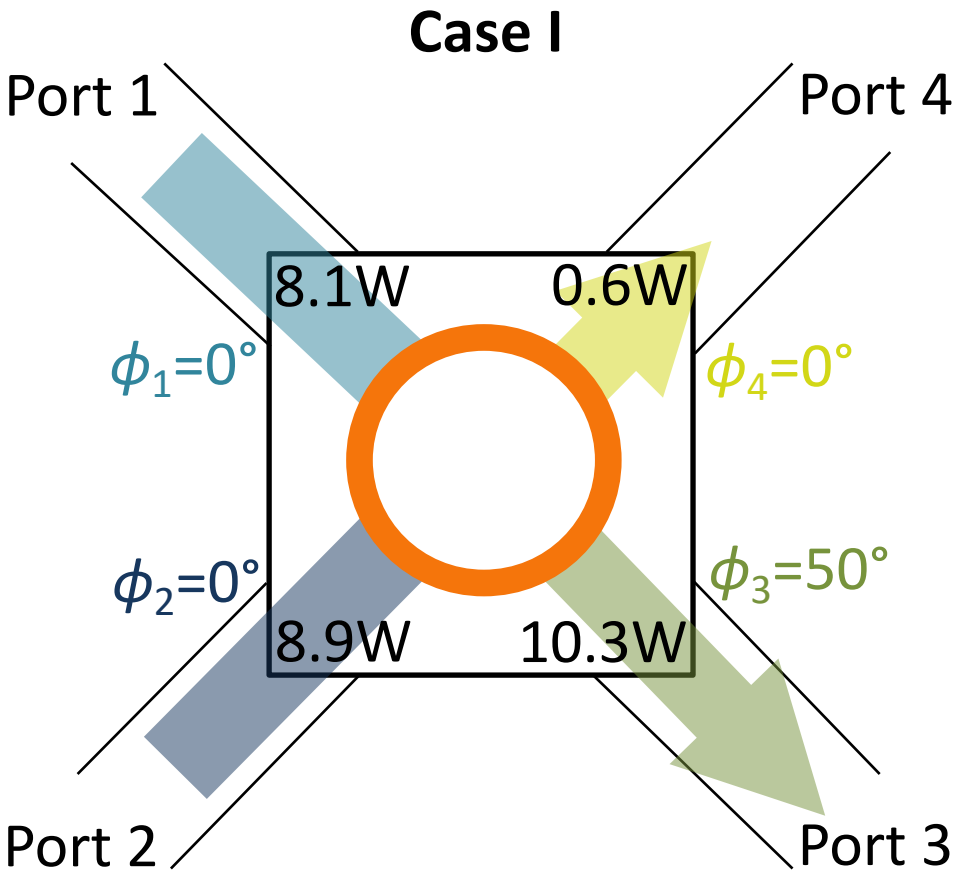



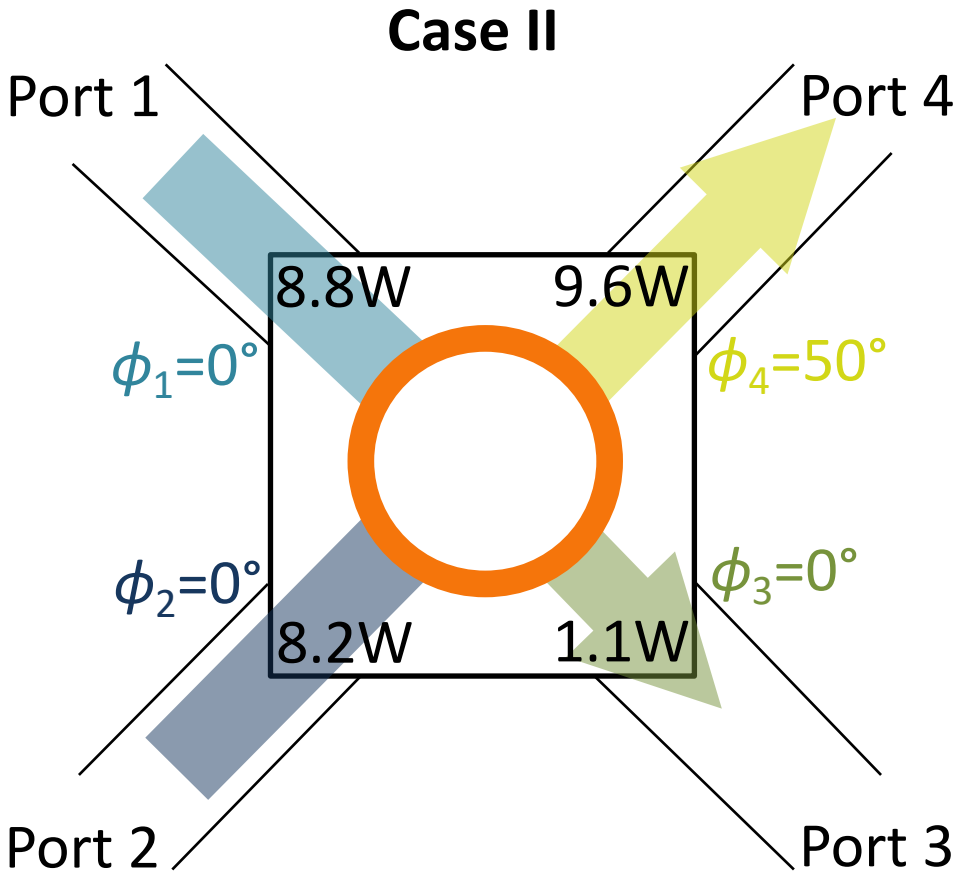

Voltage rating: 24V

Power rating: 10W/port

# Experimental results of power flow control






Port #1 and Port #2 are configured as sources by phase shift control

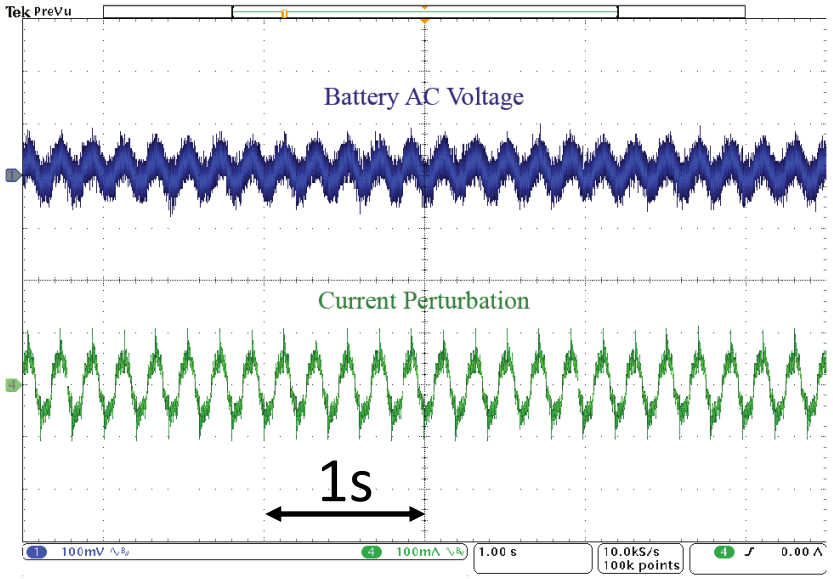
Port #3 and Port #4 are configured as loads by phase shift control

- The peak end to end efficiency is about 70%

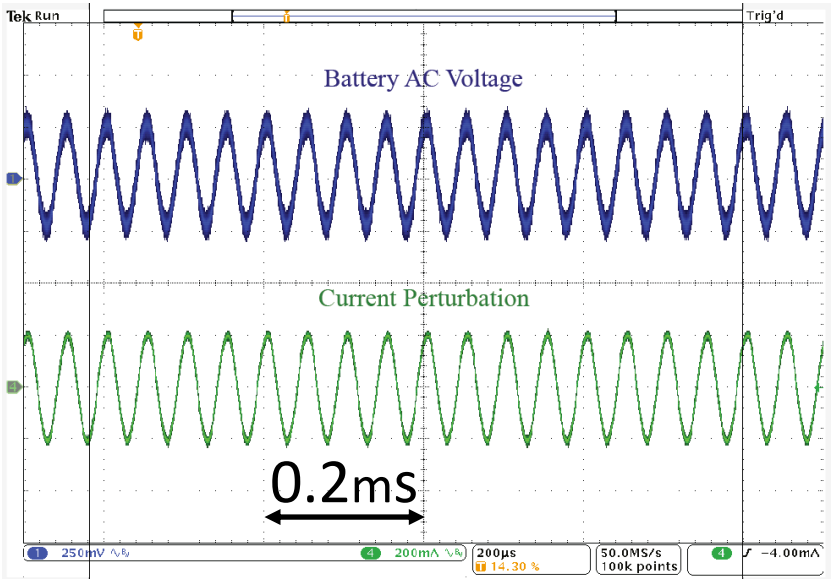
# Current perturbation and battery voltage for EIS



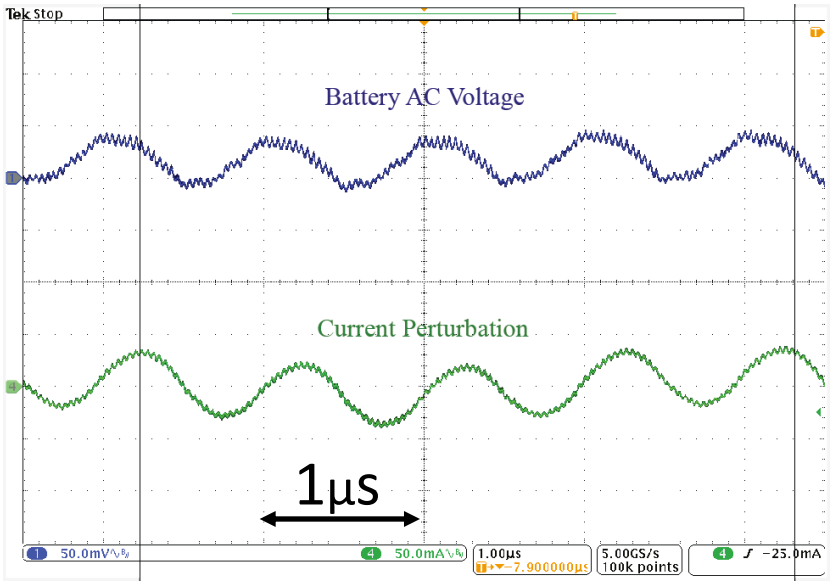
## Current perturbation at 2.5Hz




## Current perturbation at 10kHz



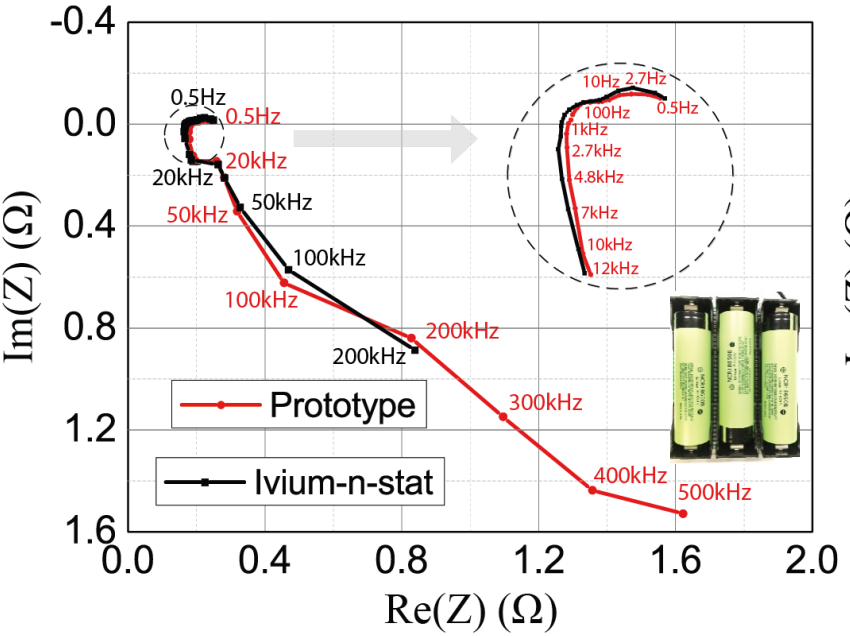

## Current perturbation at 500kHz



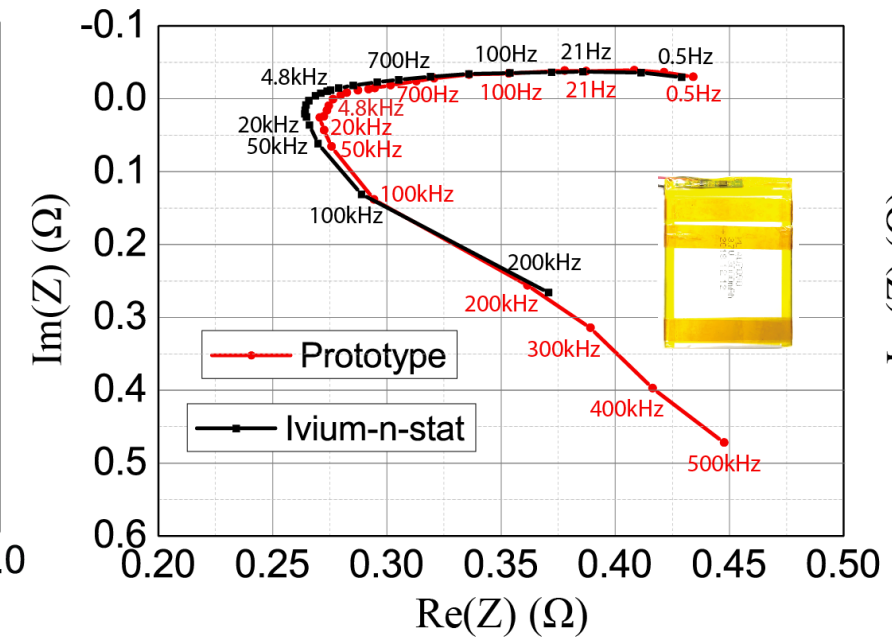
# EIS measurement results

IEEE ENERGY CONVERSION CONGRESS & EXPO

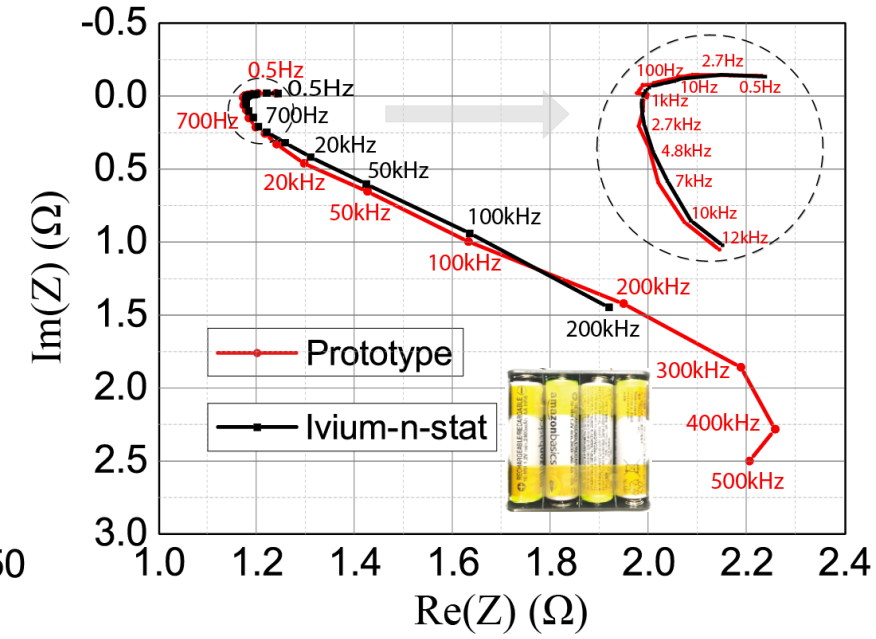
## 12 V Lithium-ion battery




## 12 V Lithium-polymer battery




## 10V AA-NIMH battery



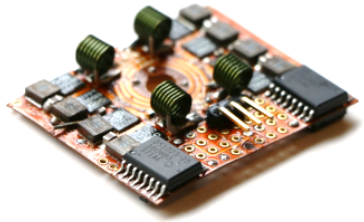

- 13.56 MHz MAC balancer with wide bandwidth online EIS
- Good match between prototype and commercial instrument

PRINCETON UNIVERSITY

# Specification of MHz MAC balancer



## MHz MAC Balancer



Operating frequency: 10μHz - 500kHz
Volume: < 5cm x 4cm x 1cm
Perturbation Current: 20mA – 200mA
Channel for EIS Measurement : 4
Prototype cost: < 100 USD

## Ivium-n-Stat


Operating frequency: 10μHz - 250kHz
Volume: > 70cm x 50cm x 15cm
Perturbation Current: 1mA - 1A
Channel for EIS Measurement : 32
Product price: >10000 USD

# Comparison with existing online EIS works



| Publication | [6] | [7] | [9] | [10] | [11] | This work |
|---|---|---|---|---|---|---|
| Cell Level Perturbation | No | No | No | No | Yes | Yes |
| Test Cell Capacity | 2.6Ah | N/A | 3Ah | 2.3Ah | 3.4Ah | 3.4Ah/3Ah/2.4Ah |
| Perturbation Source | Load | Battery Charger | Battery Charger | Motor Controller | Active Balancer | Active Balancer |
| Perturbation Type | Sinusoid | Sinusoid | Sawtooth | Noise/Multisine | Sinusoid | Sinusoid/Pulse |
| Perturbation Current | 72-750 mA | 1 A | 2 A | 130 mA | 160 mA | 20-200 mA |
| Perturbation Bandwidth | 10 kHz | 100 Hz | 5 kHz | 2 kHz | 8 kHz | 500 kHz |

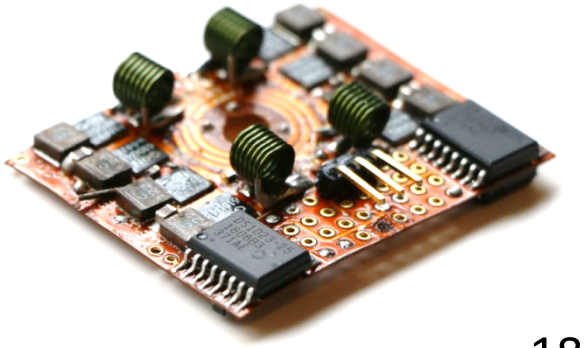
- Most works require external power supplies for perturbation generation
- Bandwidth of the existing EIS works is usually limited to 10 kHz or lower
- The proposed MAC balancer can perform a wide bandwidth EIS measurement due to the multi-MHz operating frequency

# Summary



- A MHz MAC balancer is proposed with the circuits and MHz transformer design
- Enable HF EIS measurement without extra perturbation generation circuitry
- Compact MAC transformer with reduced coil size and thin magnetic sheet
- Integrate with cells to reduce wire impedance and achieve high frequency EIS
- The MHz MAC balancer with HF EIS is applicable to different dc/ac topologies
- A prototype 4-port 13.56 MHz flexible battery balancer with 500 kHz EIS capability

# Thank You



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