Flywheel Energy Storage
Williams Hybrid Power

- Subsidiary of Williams F1
- Established in 2007
- 45 employees
- £127M Turnover
- 600 employees

Imagery indicative only © 2013 Williams Hybrid Power
WHAT IS A FLYWHEEL?

“MECHANICAL BATTERY”, ELECTRICALLY COUPLED TO A HYBRID DRIVETRAIN

Mechanical Battery
Power in / out electrically
Stores energy mechanically

Replaces the battery in a conventional hybrid system
WHAT IS A FLYWHEEL?

“MECHANICAL BATTERY”, ELECTRICALLY COUPLED TO A HYBRID DRIVETRAIN

Max Speed 36,000 rpm – 45,000 rpm
Magnetic Loaded Composite
Allows continuous cycling
Very efficient electrical machine
(95% 1 way cycle efficiency)
SYSTEM SCHEMATIC

Vacuum Pump

Flywheel

Oil Cooling System

Inverter

Position Sensors

Interface with Customer System

DC Bus

CAN Interface

Additional Sensors
High Power Density
The flywheel can continuously cycle at high power with no loss of performance over life.

High Cycling Capability
Can cycle at up to 40% of max power continuously

Low Production Cost
The flywheel is a mechanical device, and is manufactured using mainly existing automotive supply chain.

Low Whole of Life Cost
Flywheel asset lasts 20 years – requires low cost yearly service, and 5 year bearing replacement
## STATE OF THE ART

**LIGHTER AND SMALLER THAN COMPETITION**

<table>
<thead>
<tr>
<th>System</th>
<th>Cont. input kW</th>
<th>Mass (kg)</th>
<th>Cycle Life</th>
<th>Energy Density (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A123Systems Li-ion</td>
<td>120</td>
<td>240</td>
<td>~1,000</td>
<td>390</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cycle life</td>
<td></td>
</tr>
<tr>
<td>Maxwell Boostcap</td>
<td>120</td>
<td>370</td>
<td>~1,000,000</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cycle life</td>
<td></td>
</tr>
<tr>
<td>WHP MK4</td>
<td>120</td>
<td>55</td>
<td>&gt;1,000,000</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cycle life</td>
<td></td>
</tr>
</tbody>
</table>
2 KEY FAILURE MODES

Burst – Catastrophic failure of carbon fibre in hoop due to exceeding tensile strength of material.

**Burst failure is mitigated by design.** Sufficient safety factor, backed by A basis materials testing, NDT inspection, and proof testing. Same philosophy to Type 4 (Fully Wrapped Composite with non metallic liner) Compressed Natural Gas tanks on vehicles. ISO 11439 States burst Safety factor of 2.35.

Intact Rotor Failure – Rotor is intact, but is spinning uncontrolled within containment. Eg Shaft failure, bearing failure.

**Intact rotor failure is mitigated by containment, verified by test**
Component Testing

• “Split-D” hoop pull test
• Load to Failure measurement
• Tests performed in oven at 80 degs C
Component Testing

• Typical post-failure component
• multiple component samples tested
SAFETY
HEXAPOD FAILURE TESTING TO VALIDATE INTACT ROTOR FAILURE
WHP is leading the development for a standard for the design and manufacture of composite flywheels for mobile transport applications.

The standard will be published by the British Standards Institute following independent peer review.

* British Standards Institute – Publicly Available Standard
SUCCESSFUL RACING PROGRAMMES WITH PORSCHE AND AUDI

Endurance racing success with Porsche in 2010 & 2011

Le Mans 24 Hours race wins with Audi
In 2012 & 2013
2010 Porsche Hybrid Endurance Racing Programme

- **Nürburgring, May 2010**  
  - Led race by 2 laps until hour 22.
  - Car retired with non hybrid failure

- **Road Atlanta, October 2010**  
  - 10 h race

- **Zhuhai, November 2010**  
  - 6 h race
  - 6th overall – fastest GT car in race

- **120 kW peak Continuous cycling**
  - @ 40% duty cycle
2011 Porsche Hybrid Endurance Racing Programme

• Nürburgring, May 2011
  ◦ Won Race

• Nürburgring June 2011
  ◦ Leading race after 6 hours
  ◦ Then gearbox problem
  ◦ Finished 29th position

• 180 kW peak Continuous cycling
  @ 40% duty cycle
AUDI e-tron

Le Mans 2012  
1st & 2nd

Le Mans 2013  
1st & 3rd

• 150 kW peak Continuous cycling  
  @ 25% duty cycle
# Flywheel Comparison

## Is Power or Energy Density More Important?

### Porsche GT3R Flywheel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Energy</td>
<td>1350 kJ</td>
</tr>
<tr>
<td>Peak Power</td>
<td>180 kW</td>
</tr>
<tr>
<td>Flywheel Mass</td>
<td>47 kg</td>
</tr>
<tr>
<td>Power Electronics Mass</td>
<td>10 kg</td>
</tr>
<tr>
<td>Power Density</td>
<td>3.15 kW / kg</td>
</tr>
<tr>
<td>Energy Density</td>
<td>23 kJ / kg</td>
</tr>
</tbody>
</table>

### Audi e-tron 2013 Flywheel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Energy</td>
<td>350 kJ</td>
</tr>
<tr>
<td>Peak Power</td>
<td>150 kW</td>
</tr>
<tr>
<td>Flywheel Mass</td>
<td>19 kg</td>
</tr>
<tr>
<td>Power Electronics Mass</td>
<td>8 kg</td>
</tr>
<tr>
<td>Power Density</td>
<td>5.55 kW / kg</td>
</tr>
<tr>
<td>Energy Density</td>
<td>12.5 kJ / kg</td>
</tr>
</tbody>
</table>
2 Energy Recovery Systems allowed

Options

2 axles
1 axle + electric turbocharger for heat energy recovery

Maximum 8 MJ per lap released energy (no power limit)

Fuel flow is limited

Minimum weight limit 870kg – likely to limit the size of the systems.
LE MANS 2014  
POWER RATING

2013 Le Mans Pole 3.22 (202 seconds)

<table>
<thead>
<tr>
<th>Energy Cycle per lap (MJ)</th>
<th>4 (2)</th>
<th>8 (4)</th>
<th>12 (6)</th>
<th>16 (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assume 70% round trip efficiency</td>
<td>5.7</td>
<td>11</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>Average power for energy store (assuming 100% KERS) kW</td>
<td>28</td>
<td>54</td>
<td>84</td>
<td>109</td>
</tr>
</tbody>
</table>

2013 F1 Kers 800kJ in 90 seconds = 9kW average

Energy store requirement may be reduced if using Exhaust recovery
LE MANS
TOTAL FRONT & REAR POWER & ENERGY

Total Braking Energy 24 MJ
Peak Power 1900kW
LE MANS
TOTAL FRONT & REAR POWER AND ENERGY

Limit Power 500kW

Limit Braking Energy 13 MJ
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EFFECT OF MOTOR POWER ON BRAKING ENERGY

Braking Energy vs Braking Power

Braking Energy (MJ)

0 5 10 15 20 25 30

Braking Power (kW)

0 500 1000 1500 2000 2500
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FRONT ONLY POWER AND ENERGY

Peak Power 1100kW
Total Braking Energy 14 MJ
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FRONT ONLY POWER AND ENERGY

Limit Power 250kW

Limit Braking Energy 7 MJ
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EFFECT OF STATIC BRAKE BALANCE

Limit Braking Energy 2 MJ
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ENERGY STORAGE REQUIREMENT

Single Braking event 1.8MJ
Thank You

www.williamshybridpower.com

Ian Foley
Managing Director
ian.foley@williamshybridpower.com
Williams F1, Grove, Oxfordshire, OX12 0DQ
T. +44 (0) 1235 777954, M. +44 (0) 77 6840 5001

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