

# Catapulting into the future

**B Salter\* BEng FIET CEng & G Bellamy\* BSc(Hons) MIET CEng**

*\* GE Energy Power Conversion UK Ltd, Rugby, UK \* GE Power Conversion, UK*

\* Corresponding Author. Email: [ben.salter@ge.com](mailto:ben.salter@ge.com)

## Synopsis

The world of combat aviation is changing rapidly, and the next generation of aviation technology is extending the boundary of mixed manned and unmanned air operations. Drones have moved far beyond their initial role as decoy units and have long been performing operational duties in the areas of surveillance and ground attack. In the near future, drones will be performing operational roles in air-to-air combat. These unmanned aircraft are not the highly expensive and heavy manned fighter aircraft of the present, but light, agile and relative cheap “loyal wingmen”. This opens up enormous potential for naval aviation as this technology acts as a force multiplier to existing aviation capability.

Low voltage electromagnetic catapult technology has the capability of being integrated with the power systems of a large number of existing platforms. Such catapults could add fixed wing fighter capability to such platforms and enabling the rapid launch of multiple combat drones. Advances in drone technology open up the possibility that the linear catapult track could also be used for recovery. This paper examines how advances in EM catapult technology allow it to be applied, not only to full aircraft carriers, but also to the wide range of large deck assault vessels that currently have limited or no fixed wing capability thereby massively increasing the options open to fleet commanders.

Keywords: Electromagnetic Catapult; Integration; Marine systems

## 1. Introduction: Why Loyal Wingmen?

Offensive air capability and specifically naval air capability faces a number of challenges in the coming decades. The world of air superiority leading to information dominance, that has been enjoyed by Western Powers for a generation, is increasingly being challenged by new doctrines and weapon systems, as illustrated by the 2020 wargame (name withheld) which “Failed miserably” according to the Chairman of the US Joint Chiefs of Staff Gen. John Hyten.

The key air assets of the Western Powers are very costly and are highly capable, but they are facing an environment of increasing numbers of capable opponents and consequently a higher risk of loss. Each loss is extremely painful, not only in terms of the very expensive platform but more particularly in terms of aircrew. This limits a commander’s flexibility to employ them in anything other than either low risk or very critical tasks. Furthermore, the manned nature of the platforms means that to achieve the necessary level of safety certification, development and entry into service is invariably a protracted process with cost/capability compromises along the way and, typically, late entry into service. This is far from the agile response to emerging threats that is desired.

It is in this context that a new generation of Unmanned Aerial Vehicles (UAVs) are seen as an emerging technology of enormous potential. These are not the “remote piloted”, loitering surveillance drones, equipped with a few missiles, of the last UAV generation. Rather these are high subsonic aircraft that may be “remote operated” (e.g. from a nearby aircraft) but are piloted onboard by advanced artificial intelligence. Conceptually, they fly alongside a manned fighter, with a high bandwidth data link to it and under the command of its pilot. Following the “dirty, dull, dangerous or difficult” principle of application for unmanned vehicles, they contain sensors and/or weapons and may be forward deployed by the pilot into areas that are dangerous, or for tasks that are dull where they can gather data on the battlespace, and could potentially be commanded to deploy their weapons. The key feature of these aircraft is that they are relatively cheap (a few millions rather than several tens of millions) and that they have no humans onboard. They are therefore “attributable” in the jargon, i.e. capable of being sacrificed for a mission objective. They could therefore plug the gap between low risk and critical missions, thus restoring flexibility to commanders and enabling a more calibrated response to emerging threats.

## 2. Naval Considerations – size matters

The loyal wingman concept is a rapidly developing area and one of the key decisions concerns the size of the wingman. In principle this could be as large as a de-manned fighter, though this does not satisfy the “low cost” requirement. The larger UAV sizes in the naval sphere tend to be around the 20T mark, with the X-47B being the

trailblazer, now superseded by the MQ 25 Stingray. However, these are large vehicles that take up a similar space in a carrier to an F18 fighter; and space on a carrier is a limited and valuable commodity. Their size effectively means that for each UAV added, a fighter must be removed from the ship – which rather defeats the object. Such large UAVs are therefore being considered more as drone re-fuelling tankers than combat UAVs. At the other end of the scale are very small drones, such as the AltiUS series, which have relatively low capability individually, but could be more effective in a swarm configuration. Such small drones could not, however, “keep up” with fighters and are not therefore a credible size for the loyal wingman concept.

There may, however, be a “sweet spot” between these two extremes; for example, the XQ 58 Valkyrie has a declared maximum take-off weight of 2.7T with a speed of Mach 0.85 and an operational ceiling of 45,000 feet. Other, similar sized drones are under development, such as the “Team Mosquito” Lightweight Affordable Novel Combat Aircraft (LANCA) for the RAF. UAVs of this size could potentially be stored in a carrier in large numbers (note that the Storm Shadow missile has a weight of 1.3T), without seriously compromising the ability to accommodate the fighters, to whose wings they are designed to be “loyal”.

Furthermore, such lightweight aircraft do not necessarily require the full flight deck of a super-carrier in order to be launched and recovered. They therefore open up the possibility of loyal wingmen being launched from other platforms, such as Landing Helicopter Docks (LHDs) or Assault Ships (LHAs) in order to complement and multiply the capability of carrier borne fighters. This could provide a commander with different options, with fighter capability augmented from forward deployed platforms, making fixed wing operations more unpredictable and therefore more dangerous to an opponent.

However, a key consideration is that runway length on a naval platform is very limited. This requires aircraft either to have very high thrust to weight ratios and/or vectored thrust (both typically combined with a ramp) or assisted launch in the form of rocket boost or pneumatic/electromagnetic catapult. For the loyal wingman concept, pneumatic boost is insufficient and complex high-powered engines are hard to justify in an attritable aircraft. In any event, such an approach would be likely to require a large amount of deck space that could interfere with the fighter launches that would ideally be happening simultaneously. The electromagnetic (EM) catapult is therefore a very attractive technology to enable the rapid deployment of a loyal wingman capability that complements conventional fighter launch. It is for this reason that the technology is being considered by several navies, including the Royal Navy Vixen programme. This consideration covers not only the application of catapult technology to new, purpose-built platforms, but also to the retrofit of this capability to existing platforms that still have decades of service life ahead of them.

### **3. EM Catapult Power System Implications**

In order to assess the potential applicability of a loyal wingman EM catapult system for retrofit, it is first necessary to consider whether the ship’s existing engine fit and power system are capable of supporting the necessary power demand. This because, while deck modification for such a technology is an inevitable implication, the location of such modifications is at least highly accessible. The implications, however, of a change to the engine fit, and potentially the electric grid of a ship, are likely to be so significant as to make such a modification far less practical and affordable. The power demand on the grid is for the average power of the launch system, since the peaky nature of the launch itself requires that energy storage is an inherent part of the catapult. In order to calculate an average power demand, it is necessary to make some assumptions about the UAV itself.

#### **3.1. UAV Assumptions**

The characteristics of any given UAV selected for a platform are likely to vary from navy to navy and it is not possible to provide a universal data set to cover all possibilities. In order to gain an “order of magnitude” sense of the power requirement of the sort of system under consideration, it is necessary to make some fundamental assumptions. These are not based on any specific UAV but are intended to be in the correct “ballpark” for the sort of UAVs that maybe used in the loyal wingman role. Note that the UAV itself is launched by being connected to, and accelerated by, the catapult shuttle which runs in the track below deck. Once a UAV has been launched, the shuttle must be retracted to the start of the track to allow the connection of the next UAV, ready for its launch; and these factors have an impact on the overall efficiency of the system.

For the purposes of this analysis the following assumptions have been made.

1. Three nominal airframes are considered with Maximum Take-Off Weights (MTOW): 1500kg, 2700kg and 5000kg in “standard US Navy Day” operating conditions (up to 37.8°C/100°F)
2. The required catapult end speed for all 3 UAVs, including any necessary margins is up to 70ms<sup>-1</sup> (~140knots)

3. A nominal Wind over Deck (WoD) of 15knts is assumed i.e. true UAV airspeed is up to  $77\text{ms}^{-1}$  (150knts)
4. The maximum permitted acceleration is assumed the same for all the vehicles at  $3.8g$
5. The efficiency of the transfer of energy from electrical energy in the grid, for the entire launch process, to kinetic energy in the UAV is 50%
6. The launch rate of the fighter aircraft is 1 every 90 seconds
7. The number of UAVs that must be launched for each fighter is 2
8. The retract time of the catapult shuttle is 15 seconds
9. Power will be delivered to the catapult system from at least two sources

### 3.2. Energy Calculation

The following calculation is necessarily a crude simplification of the true calculation, but it is sufficient for illustrative purposes.

The kinetic energy that must be imparted to the 5000kg UAV is:

$$\begin{aligned} KE &= 0.5 \times \text{Mass} \times \text{Speed}^2 \\ KE &= 0.5 \times 5000 \times 70^2 && \text{(see assumption 2)} \\ KE &= 12.25\text{MJ} \end{aligned}$$

The electrical energy that must be supplied to the launch system is:

$$\begin{aligned} EE &= KE/\text{Efficiency} \\ EE &= 12.25/0.50 && \text{(see assumption 5)} \\ EE &= 24.5\text{MJ} \end{aligned}$$

Given that the catapult energy store cannot be recharged while the shuttle is being retracted, the time available to recharge the energy store is:

$$\begin{aligned} \text{RCT} &= \text{Launch interval for UAV minus the shuttle return time} \\ \text{RCT} &= (90/2) - 15 && \text{(see assumptions 6, 7 and 8)} \\ \text{RCT} &= 30\text{s} \end{aligned}$$

Average power requirement from each grid feeder is:

$$\begin{aligned} \text{AP} &= (EE/\text{RCT})/2 && \text{(see assumption 9)} \\ \text{AP} &= (24.5/30)/2 \\ \text{AP} &= \sim 408\text{kW} \end{aligned}$$

This means that to achieve a launch rate of a UAV every 45 seconds, to accompany fighters launched every 90 seconds and average power of less than 1MW needs to be taken from the ship's grid. For survivability and system integrity reasons, this power is likely to be drawn from a minimum of two feeders, each rated at less than 500kW. Powers of these magnitudes are capable of being supplied from a conventional LV power grid. A feeder of 500kW is certainly large but it must be borne in mind that this is not a direct online (DOL) load with a large inrush current requirement. The power will be drawn sinusoidally by the catapult converter at a rate of change that can be matched to the grid capability, to ensure that STANAG power quality requirements are met. Thus a catapult of this nature is unlikely to load the system more than an existing large LV load such as an aircraft lift or a large seawater pump and would be a fraction of the load of, for example, a hybrid electric drive motor.

With respect to losses, the cooling requirements for the equipment will be shared between the linear motors themselves and the converters feeding them. Even with a conservative efficiency assumption (see assumption 5), the total average losses are less than 500kW. Given that the converter efficiencies are  $>95\%$ , the vast majority of the losses are in the linear motors. These are air cooled, which is a practical solution given their surface area in a 70m track length. The only special provision may be forced ventilation for the shuttle when it is returned to its starting position. The converter losses should be capable of being absorbed by the existing seawater (or freshwater) cooling provision since the total flow requirement across all converters is likely to be less than  $500\text{lmin}^{-1}$ , which in turn is likely to be a very small proportion of the total system capacity on a vessel of an appropriate size.

### 3.3. Impact of Airframe and Sortie Rate Vs Recharge Power Requirements

The crude energy calculation above provides a good ballpark indicator of the power requirements based on a fixed nominal system efficiency number. However, like most electrical machines, catapults are designed to be more efficient at their key design operating points. In practice this makes the maximum peak power rating capability of the launcher relatively straight forward to define.

However, in terms of energy usage for both sizing and replenishment of the energy storage, the overall duty cycle for multiple conditions needs to be considered in more detail. EM catapults using Advanced Linear motors (Lewis E 2003), power electronic converters and energy storage provide a more complex efficiency and power factor profile which is directly impacted by the specific launch motor usage profile.

EM catapults comprise of many linear machine stator segments along the launch track (Bellamy G 2006). Net efficiency figures are driven by the number of linear motors on load vs offload, the ratio of time of onload to offload as the shuttle moves along the track, alongside the initial thrust build up profile, frequency/voltage launch profile, electromagnetic braking to name a few key parameters, and finally a retract period.

As an example of this net system efficiency nonlinearity, low speed retraction at say  $5\text{ms}^{-1}$  and very low thrust levels can be significantly less efficient than launching at  $70\text{ms}^{-1}$  and maximum thrust, in a machine optimised to operate at this rating. In terms of energy, this can mean for low speed, low power retraction lasting 10s of seconds at hundreds of kW the energy to be recovered and associated load is still non-trivial compared at the energy used over a few seconds and multi MW peak launch; as such the net energy consumed from this part of the duty can also be up to a MJ or more. This can significantly impact the whole duty efficiency, particularly on smaller launchers, if not coming from a continuous supply and must be included in a single complete cycle discharge profile from an e-store, as must be accordingly accounted for.

The detailed calculation and recharge rating function such as retraction and electromagnetic braking (including energy salvaging) is beyond the scope of this paper, but the output from a range of typical rating calculations for the 3 UCAV sizes along with various complete duty cycles is shown below in Figure 1.

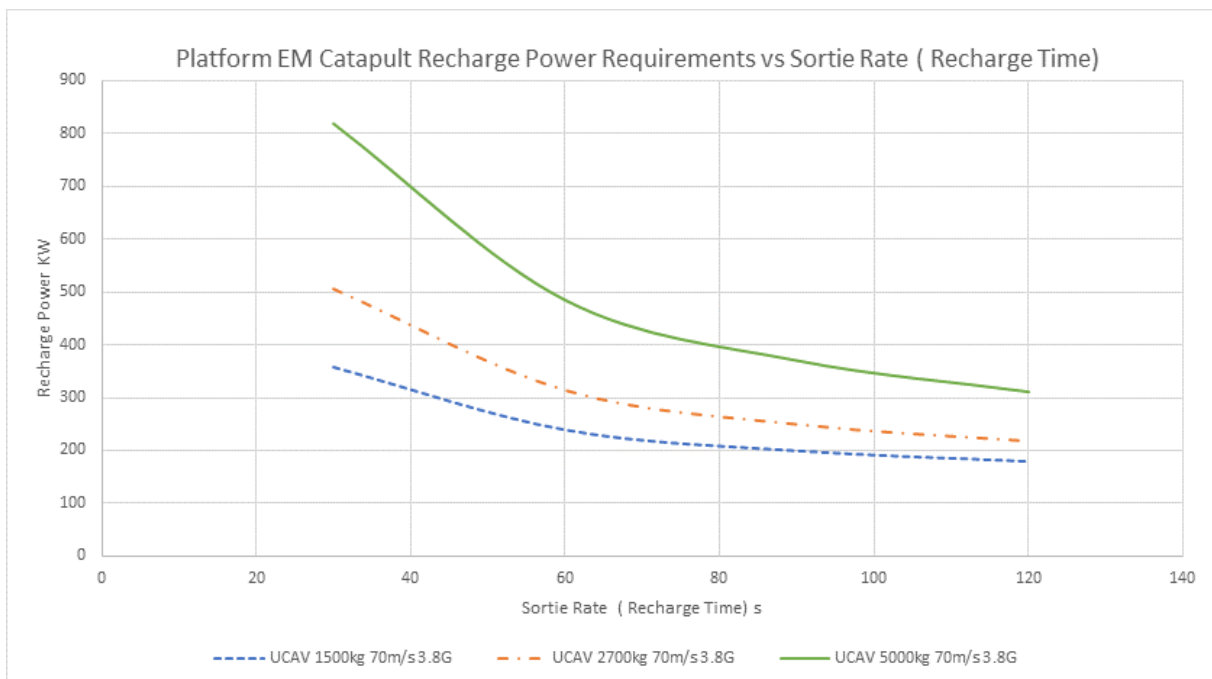


Figure 1 Total Recharge Power Requirements vs Sortie Rate

The more detailed analysis shows to still be aligned well with the earlier broad assumption of <1MW requirement from the platform recharge needs for a broad potential range of conditions.

A final consideration in determining the practicality of such a power demand is to consider the size of ship that would be likely to need to provide it. For the purpose of this basic example fixing the G limit and max end speed for all 3 variants effectively fixes the minimum catapult launch stroke as the same for each airframe. The G limit is often the limiting factor on minimum viable catapult length vs potential thrust and energy that could be derived from a range of electromagnetic catapult topologies and thrust capabilities.

The acceleration limit and maximum speed given in assumptions 4 and 2 above imply that the track length would need to be at least 70m. Conventionally, this track is likely to be at the front of the flight deck. The recovery system, which is likely to be located towards the rear of the flight deck, would require similar distance to bring a landing aircraft to a halt. If overlap between the two systems is to be avoided (which is a probable requirement) then a minimum deck length of the order 200m is likely to be required. This sort of deck size is available on vessels ranging from Landing Helicopter Docks (LHDs) and Assault Ships (LHAs) up to full scale super-carriers.

### 3.4. Comparison to existing power systems

There are a number of classes of ship with the sort of deck sizes that could be suitable for loyal wingman operations. These not only include aircraft carriers such as the QE class carriers and the Cavour class but also a range of LHDs and LHAs. For the purpose of comparison, only public source data has been used. It has been assumed that the efficiency of the electric propulsion equipment is 90% in order to calculate the approximate maximum electric propulsion demand. Note that for Integrated Full Electric (IFEP) power and propulsion systems and for Hybrid (combined mechanical and electric) power and propulsion systems, additional power is available by simply reducing the electric propulsion demand slightly; but this is not taken into account in the table below. The comparison is summarised in Table 1 below:

Class	Installed Electrical Power (MW)	Estimated Electrical Propulsion Demand (MW)	Power Available for Service, Sensor and Weapon Loads (MW)	Propulsion Type	Length (m)
Queen Elizabeth	109	88	~21	IFEP	280
Cavour	13.2	-	13.2	Mech	244
Trieste	21	5	~16	Hybrid	245
Mistral	21.6	15.4	~6.2	IFEP	199
Makin Island (America)	24	8.2	~15.8	Hybrid	257
Juan Carlos / Canberra	33.9	24.4	~9.5	IFEP	231

Table 1: Vessel Power System Comparison

As can be readily deduced from Table 1 the power systems of all the potential vessels are well able to accommodate a load of the order of magnitude of a megawatt. In virtually all cases this represents less than 10% of the available service capacity of the power system and where it does not, the additional power could readily be made available if the vessel were moving at a little less than its maximum speed, since for an IFEP ship the cube law (power demand is proportional to the cube of speed) means that a large amount of power is released to the system by running at even a single knot below top speed.

### 4. Development challenge

One of the key development challenges for manned aircraft is the time required to qualify the safety integrity of the components and software on the platform. A similar challenge exists for the catapult required to launch such an aircraft, with the time and cost associated with qualifying the catapult being a significant contributor to the overall programme time and cost. The design of a catapult exclusively used for UAVs is therefore released, in the same way as the UAV, from a key constraint on its rapid development and deployment. For such a catapult it is therefore possible to consider an agile deployment strategy built on industrial integrity levels, suitable for protecting the valuable aircraft, but not at the levels required for manned flight. This opens up the ability to pull through proven power conversion technology from, for example, the naval propulsion domain and use it for EM catapult applications. This has obvious benefits both for training and spares holding. The risk here is that the only standards for catapults are those legacy standards that were developed when catapults were used exclusively for manned launch. If the potential cost savings and developmental agility improvements are to be realised, then the application of these legacy standards must be reviewed for unmanned catapults to ensure that an appropriate balance is struck.

It is therefore likely that an EM catapult, suitable to launch up to a ~5000kg loyal wingman UAV could be deployed, at a credible pace and cost over a number of potential naval platforms and could be integrated, relatively straightforwardly into their electrical infrastructure. The next consideration is: what form would such a catapult take?

### 5. Modularity vs Requirements

The first question to address is the electrical technology required for the catapult launch of the loyal wingman UAVs under consideration in this paper. The peak power that is required for the 70ms<sup>-1</sup> launch of a 5000kg UAV is <15MW (see Table 2). However this power is likely to be delivered from multiple independent converters and machines, in order to achieve the necessary level of integrity for a launch system. Thus, at this peak power, low voltage technology provides a good solution without the need to deal with the additional factors associated with

HV power electronics and motors. Furthermore, an LV system is much more easily integrated with a static, “supercapacitor” energy store and with the ship’s existing LV grid (Southall M. 2017). The next consideration is the detailed requirements of the launch itself.

Identifying all the specific UAV launch requirements to allow an EM launch solution, tailored to specific needs, early on in programs can be challenging. Often at the time of considering a future operational capability or requirement for a UAV, the airframe is not fully defined or matured sufficiently to allow an EM launch system to be fully designed in parallel and tailored exactly to the specific needs of the target airframe. Requirements such as minimum take off speed, MTOW, maximum tow load and G limits are key to arriving at the optimal compatibility fit and solution. These requirement interactions between airframe and catapult are closely coupled; however, the availability of detailed design information from both airframe and catapult may not fully merge with respect to the aspirations of the end capability timeline.

Of course, one approach is to fit the biggest catapult energy and thrust capability that fits and hope that it is capable of covering all possible duties in the ship’s future service life. In practice this will likely result in unnecessary costs, size, weight, risk and unused capability programs cannot afford or justify.

A conventional steam catapult capability is effectively defined and fixed from the outset. However, an EM catapult can be designed more flexibly. One approach to managing potential capability growth through life utilises the modular LV EMCAT arrangement. This approach utilises only few variables to be defined and others to be more flexible to allow through life growth in capability.

For example, with a nominal maximum G limit and maximum end speed fixed, the track length is inherently defined. However, with these parameters fixed, it is then the mass of the UAV to be launched that defines the required thrust, the required energy and the maximum launch power. A modular approach to the power conditioning equipment and launch motors in the catapult allows additional modules to be added through life to enable higher mass UAVs to be launched from an upgraded system, without major surgery to the track.

In practice this means the launch track and number of motors is fixed for all applications, but the configuration of these machines, and the power conditioning and energy storage is what is adjusted by the addition of pre-engineered modules (Bellamy G. 2006 and Lewis E.2003). This enables the system to be tailored, through life, to suit new airframes as they come into service since the modules can increase through life the capability of the launch thrust and energy up to a predefined thrust limit.

Using the previous example of the range of UAVs from earlier of 1500kg, 2700kg and 5000kg MTOW. These can all be achieved with a Low Voltage EMCAT with additional EMCAT power conditioning and storage modules that are added to the launcher as required for further thrust and energy capability. See Figure 2. This approach lends itself particularly well to smaller systems or retrofits where the capability can also be tailored to available platform space. The power conditioning modules can be integrated into the platform or potentially deployed as mission modules, as needs arise, relative to the embarked UAV.

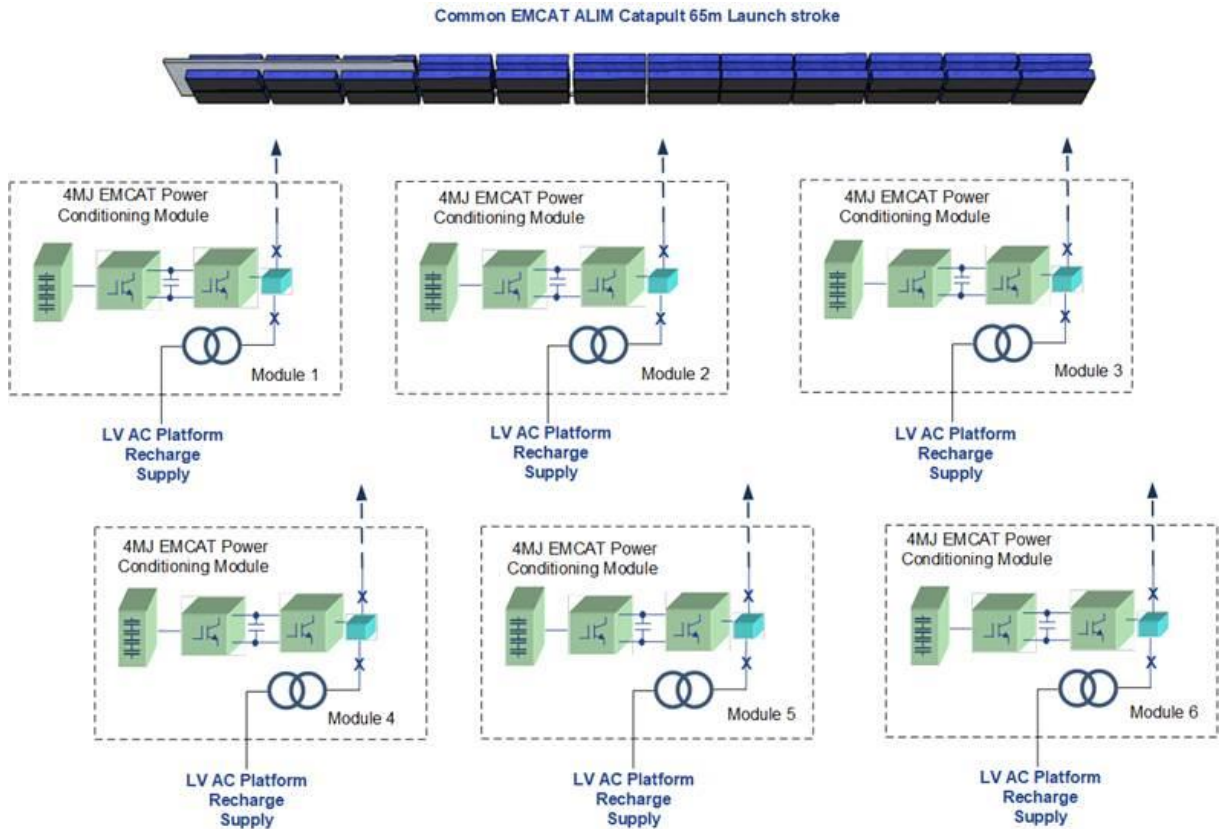


Figure 2 LV EMCAT Module Topology

EMCAT Modules vs Catapult Requirements			
UCAV Mass	1500kg	2700kg	5000kg
End Speed	70m/s	70m/s	70m/s
G Limit	3.8G	3.8G	3.8G
Launch Stroke	65m	65m	65m
Launch Energy Required MJ	4.5	7.5	13.5
Energy In MJ	6.8	11.1	19.4
Thrust Required	72kN	117kN	209kN
Peak Catapult Power MW	5MW	8.1MW	14.6MW
Number of EMCAT Modules Required	2	4	6

Table 2 EMCAT Modules vs Catapult Requirements

The ultimate in configurability would be the addition of an additional track, at the aft end of the deck, with the shuttle movement coordinated with the UAV flight management in order to achieve “active catching” of a UAV rather than using a traditional arrestor wire base approach. Such an approach would require considerable advances in the real-time control of the UAV and the data linkage between the two systems, but in terms of the modular equipment, the same converters that are used to deliver the launch energy on the forward track could be switched to return energy to the stores while recovering on the aft track. Such an approach would lead to higher overall system efficiencies and potentially a lower arresting force profile for the UAV airframe.

## 6. Conclusion

The “Loyal Wingman” UAV concept is becoming increasingly attractive to Western Navies as a force multiplier. An effective way of launching these aircraft is to use EM catapult technology. This paper has shown that a low voltage catapult can, in principle, be fitted to a range of potential vessels thereby increasing the tactical choices available for naval commanders, making their fleets both more powerful and less predictable. It has also shown that a low voltage catapult, suitable for loyal wingman UAVs can be made both flexible and modular, allowing for cost effective installation and growing capability through life.

## 7. References

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