General Atomics Electromagnetic Systems Group

9 June 2016

High Efficiency Motor Optimized for UUV Applications

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Outline

1. **Background:**
   - Expeditionary Undersea Networks for Military Applications
   - Or, Why GA is in this area

2. **Contactless Power/Coms Connectors for AUV Recharge**

3. **Air-independent power/energy for…**
   - Extended range AUV's
   - Long endurance seafloor mission modules

4. **Other GA undersea technologies/initiatives that may be of interest**

Background

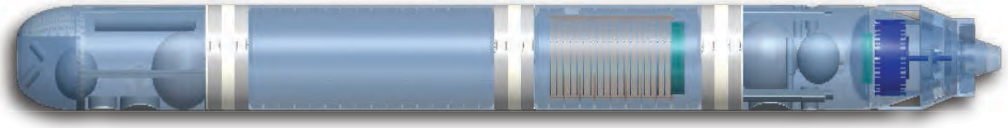
- **The Government has numerous initiatives to develop:**
  - Various classes of AUV's including LD-UUVs
  - Networked, multi-node, AUV-deployable undersea installations
    - To perform: AUV recharge, Communications, ISR, METOC, Payload deployment, etc.

- **General Atomics is developing several key technologies in support of these initiatives in the areas of:**
  - Air-independent power and energy
  - AUV-deployable cabled power & communications networks

- **Some of these technologies may be applicable to MBARI needs**

UUV/AUV Technologies

- Over $8M GA investment since 2005
- Developed UUV concept from UUV mission requirements, 2009



- Enabling power & powertrain technology development initiatives:

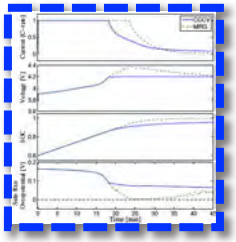
Program: ONR

LDUUV Al-H_2O/O_2 Fuel Cell

Program: NSWC Crane

Safe Li-Ion Batteries

Future IRaD



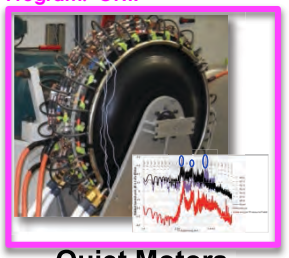
Model-based BMS

[collaboration w/UCSD]

Current IRaD

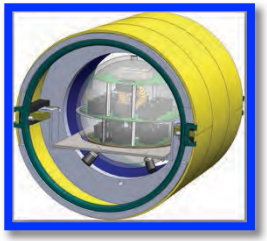
SiC Converters

Program: ONR



Quiet Motors

Current IRaD



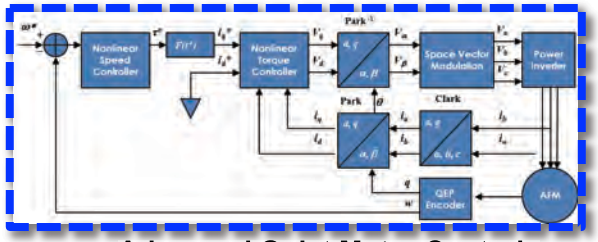
Wireless UUV Recharge

Current IRaD

Hi-BW Optical Data Xfr

[collaboration w/SSC-Pac]

Future IRaD

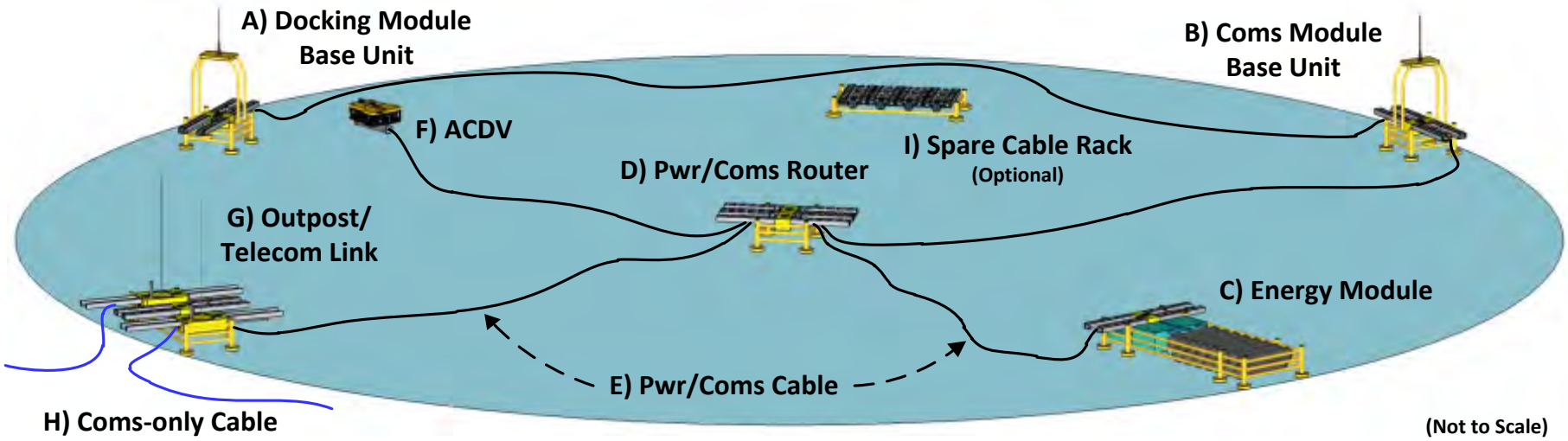


Advanced Quiet Motor Controls

Multi-mission, Undersea Outpost Technologies

ONR Forward Deployed Energy & Communications Outpost (FDECO)

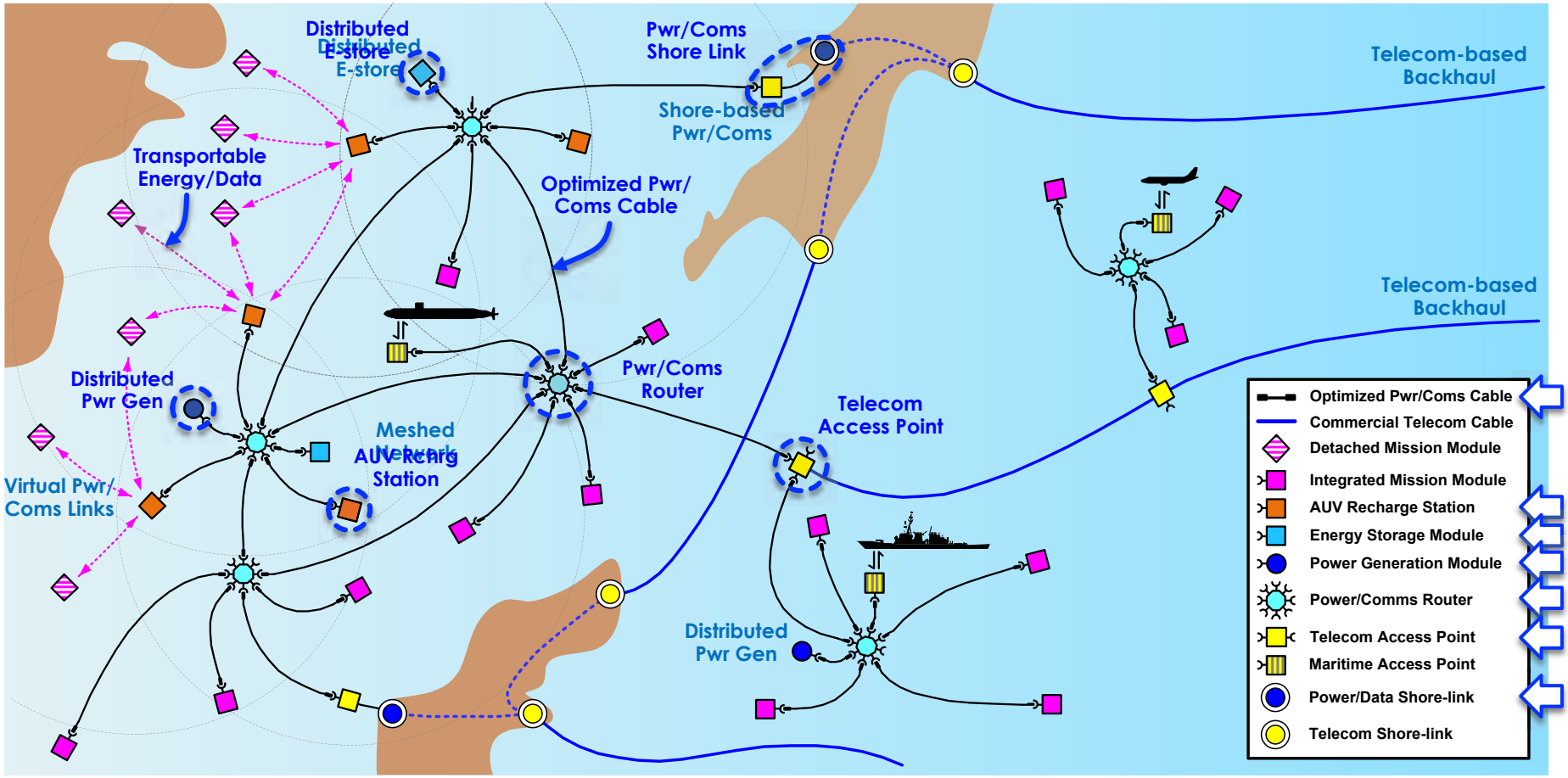
- **FDECO networks three core mission modules**
  - 1) AUV Recharge Node; 2) Coms Node; and 3) Power/Energy Node



- **Multi-node undersea outpost**
  - AUV docking module
  - Coms module
  - Power/Energy module
  - Power/Coms Router
  - Outpost-to-Outpost coms-only link
- **Autonomous Cable Deployment system**
  - Autonomous cable deployment vehicle (ACDV)
  - Lightweight power/coms cable
  - Contactless power/coms connectors

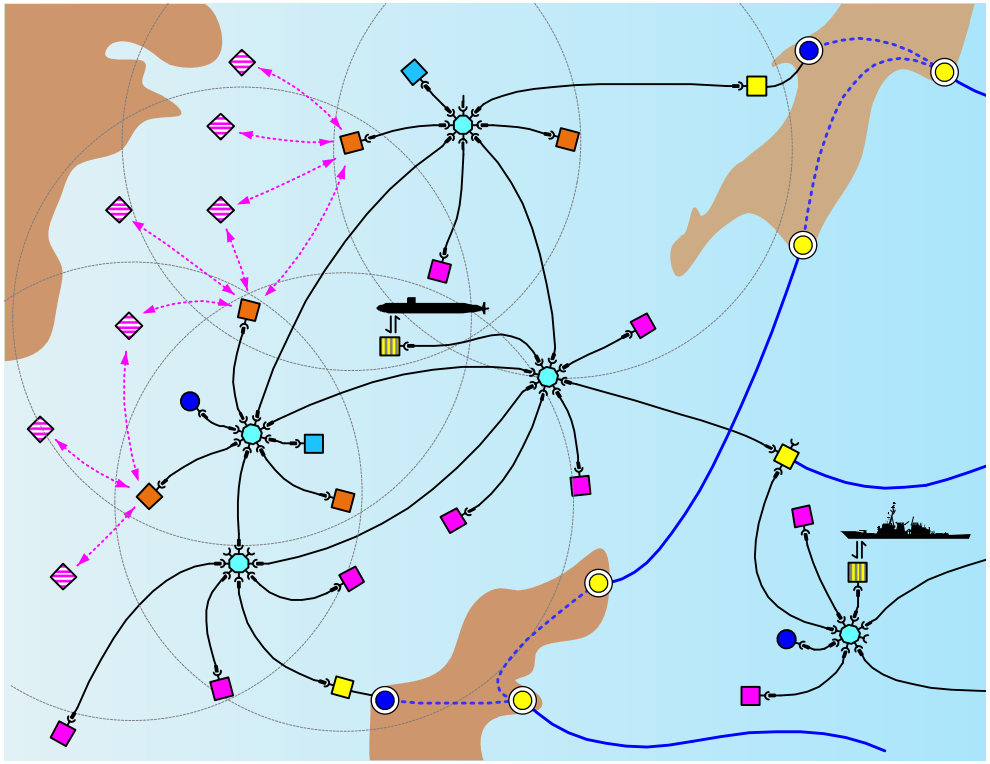
Expeditionary SmartGrid for Regional Coverage; Telecom-based Backhaul for Global Reach

- Expeditionary SmartGrid deploys when/where needed; supports variety of ops
- Telecom-based Backhaul provides long-distance, high-capacity, secure coms

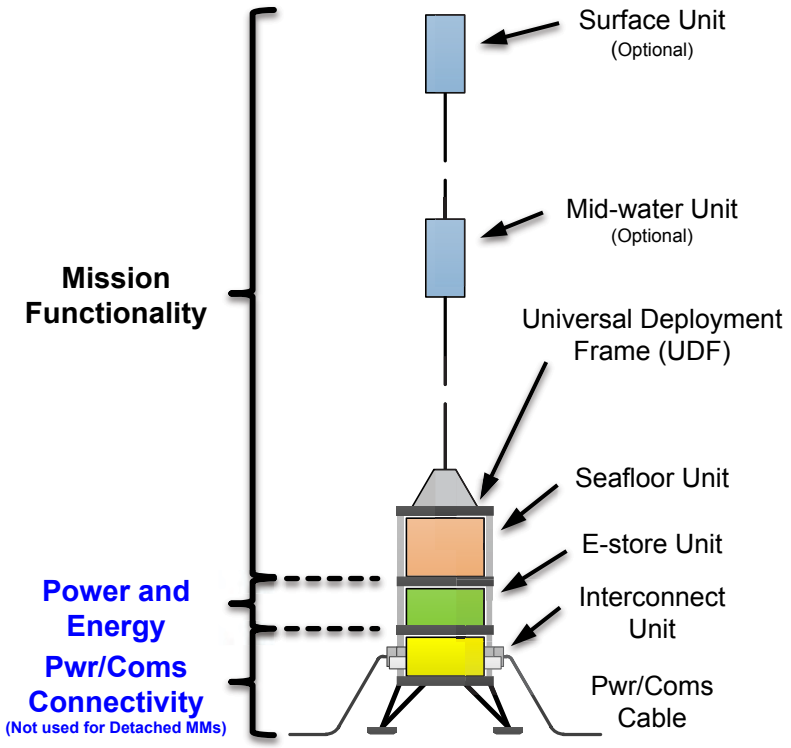


Modularity Maximizes Flexibility, Scalability, Enables Spiral Insertions of New Capabilities

Modular Architecture



Modular Mission Module



- **Key Architectural Elements:**
  1. Lightweight Cable
  2. Contactless Connectors
  3. Power/Coms Router
  4. Covert/Clandestine Deployment

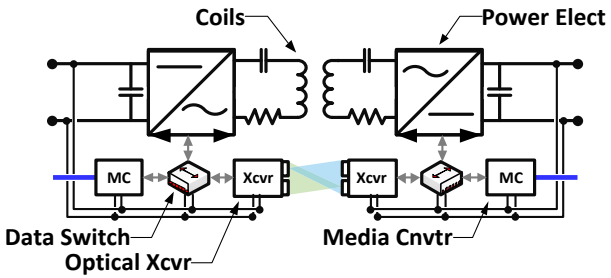
- **Key Module Elements:**
  1. Mission Element
  2. Universal Deployment Frame
  3. Energy Unit
  4. Interconnect Unit, Optional

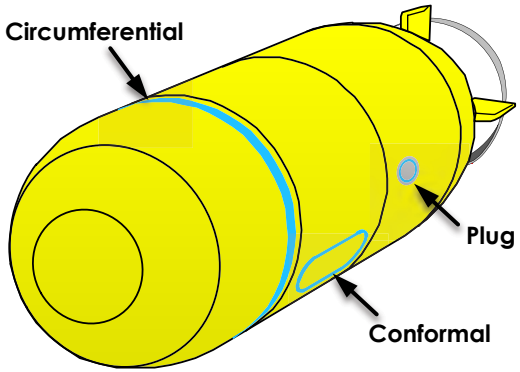
Contactless Power & Data Transfer for UUV Recharge & Data Exfil/Infil

Contactless Undersea Power & Communications Connector

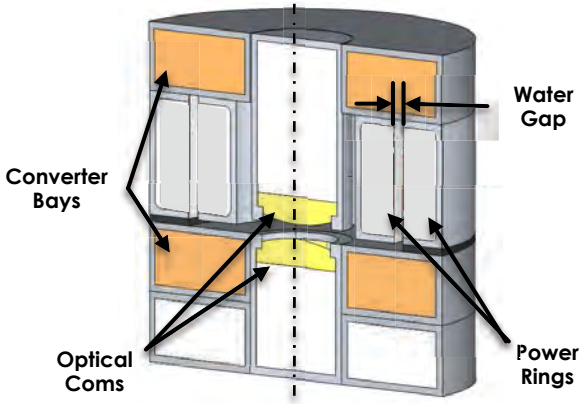
- **Contactless Power & Communications Connectors**
  - High-efficiency / High-rate power & data transfer
  - Low mate/de-mate forces, Low precision alignment
- **Enables Simple Reliable pwr/coms connections for…**
  - Contactless connector for AUV recharge & data transfer
  - Power/data "slip-rings" for winches & mooring lines
  - AUV-deployable power/coms cables
  - Multi-port power/coms Routers
  - AUV-deployable Transportable Energy & Data (TED) Units

Resonant Inductive Power xfr
Optical Data xfr

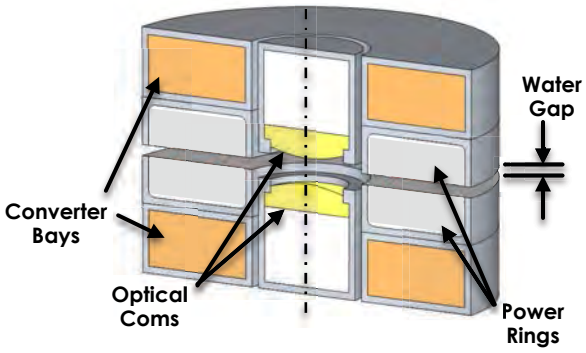




Concentric



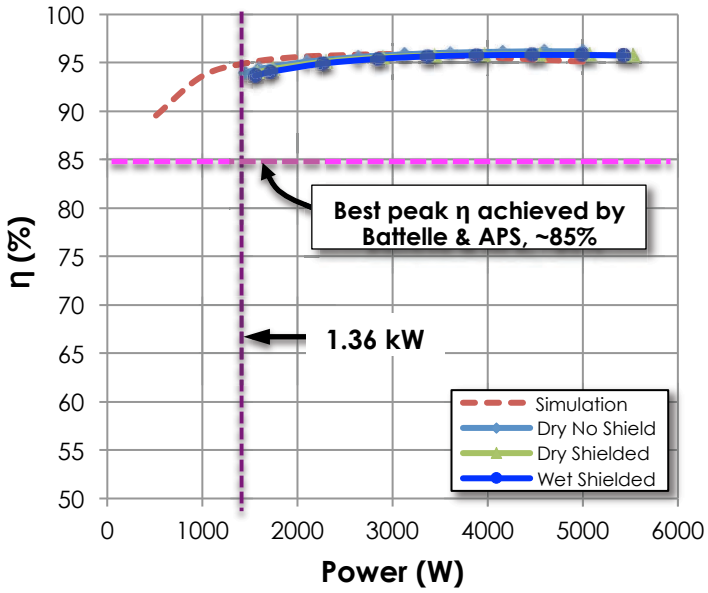
Parallel



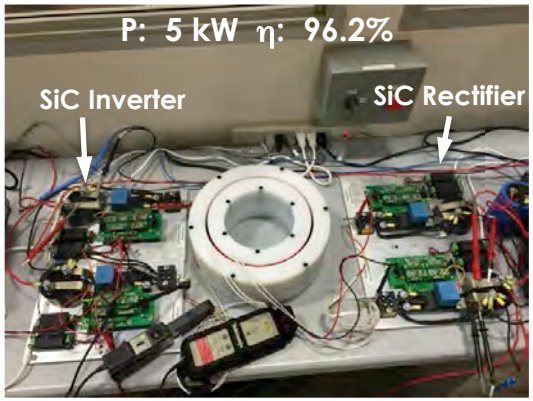
GA's Contactless Power Connector Prototype
High-power, High-efficiency, High Cycle-life

- **High Efficiency Power Transfer/Small Water Gap (~1 cm)**
  - >93% from 20% to full-rated power
  - Resonant inductive
  - Magnetically shielded, no EMI
  - Impervious to misalignment, ~±1 cm radial & axial
- **Scalable w/Multiple Form-factors**
  - From 10's W to MW's
  - Concentric
  - Parallel
  - Conformal

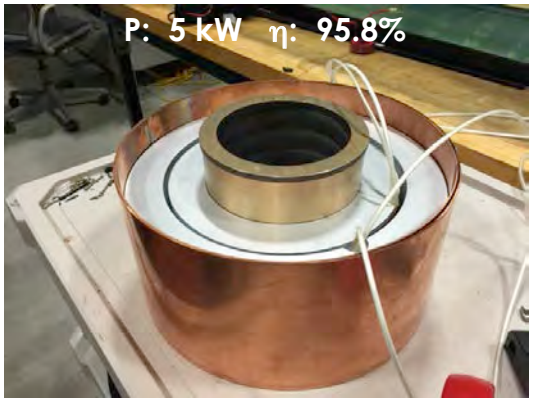
5 kW Proof-of-Concept Prototype



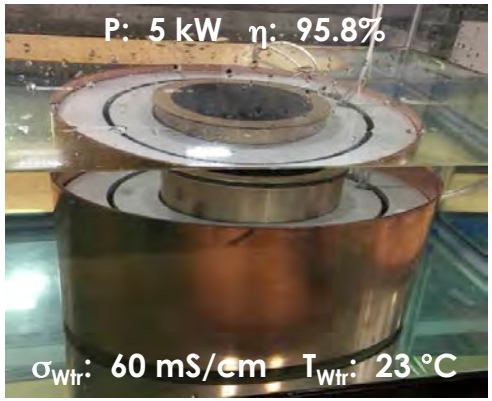
Dry, Unshielded



Dry, Shielded

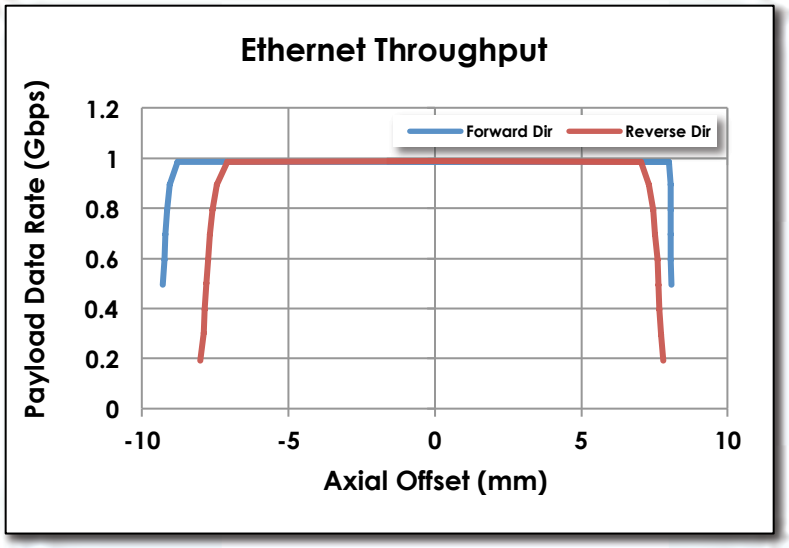


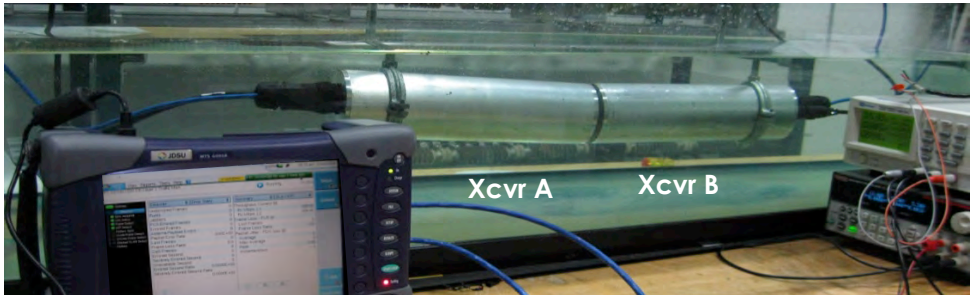
Wet, Shielded

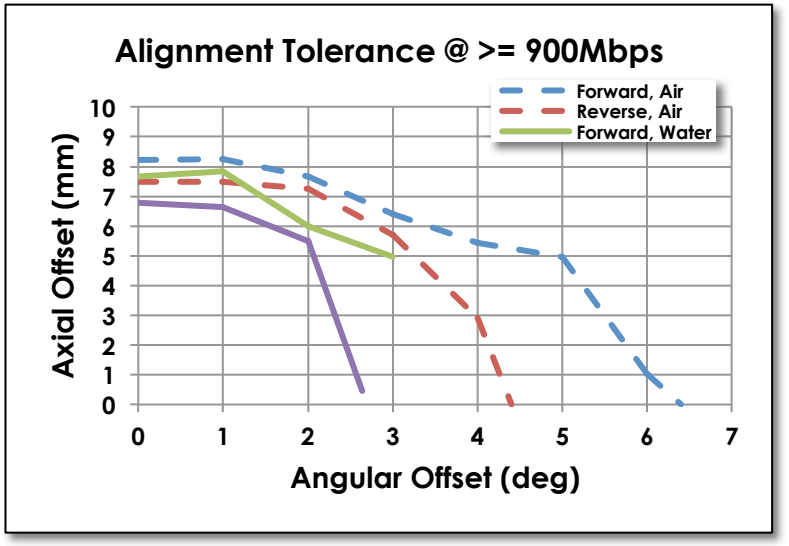


GA's Contactless Coms Connector Prototype
High date-rate, High reliability, High cycle-life

- **Small Water Gap, High Data Rate Optical Data Link**
  - 1 Gbps Ethernet throughput
  - 1 cm gap, Jerlov 9 coastal water
  - ± 1 cm axial / ± 2-3° angular offset
  - 780/850 nm, dual-channel, full-duplex
  - UV mitigation of bio-fouling
  - 3" OD enclosure, mounts in bore of power transfer rings



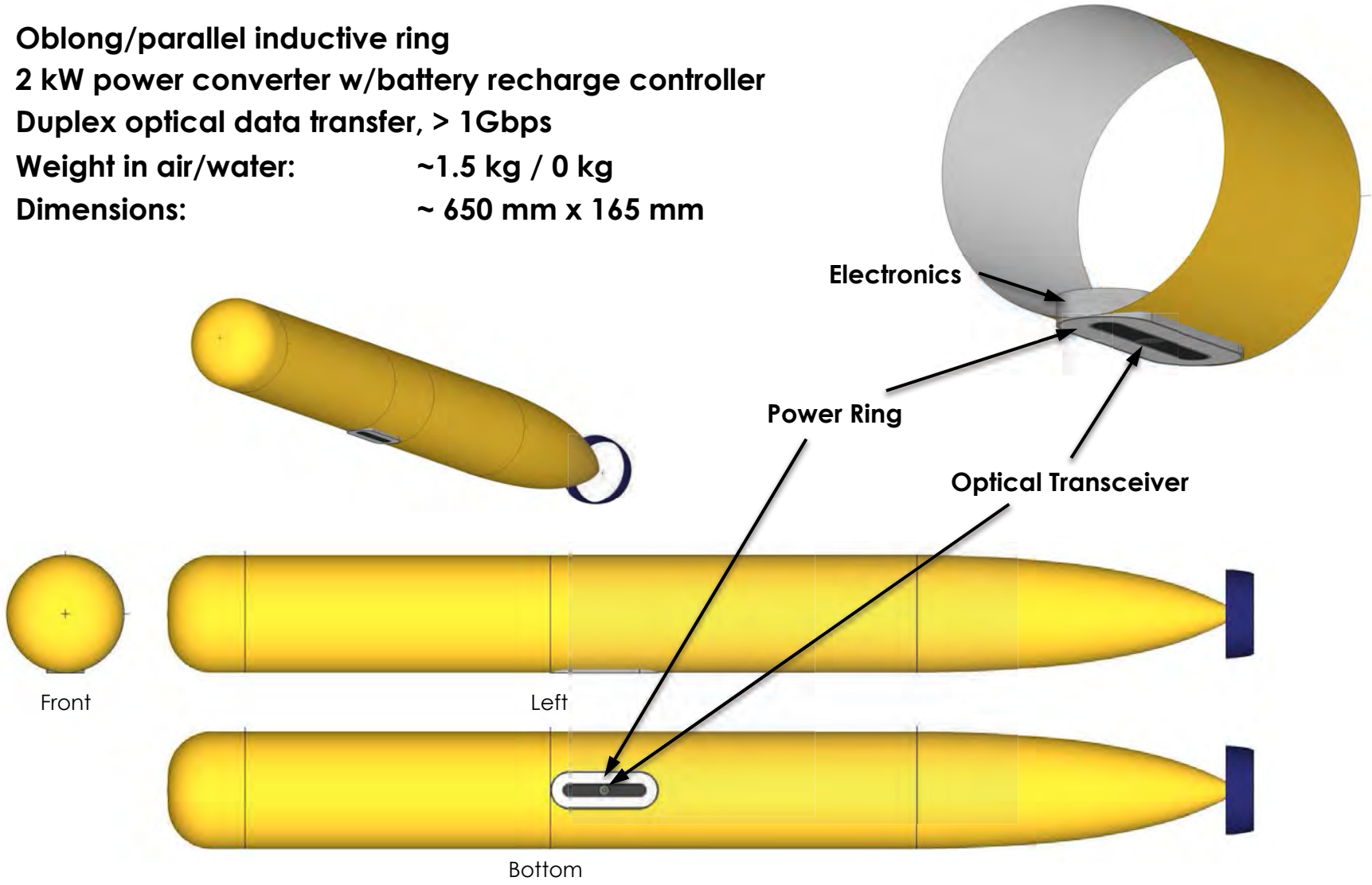




GENERAL ATOMICS ELECTROMAGNETICS

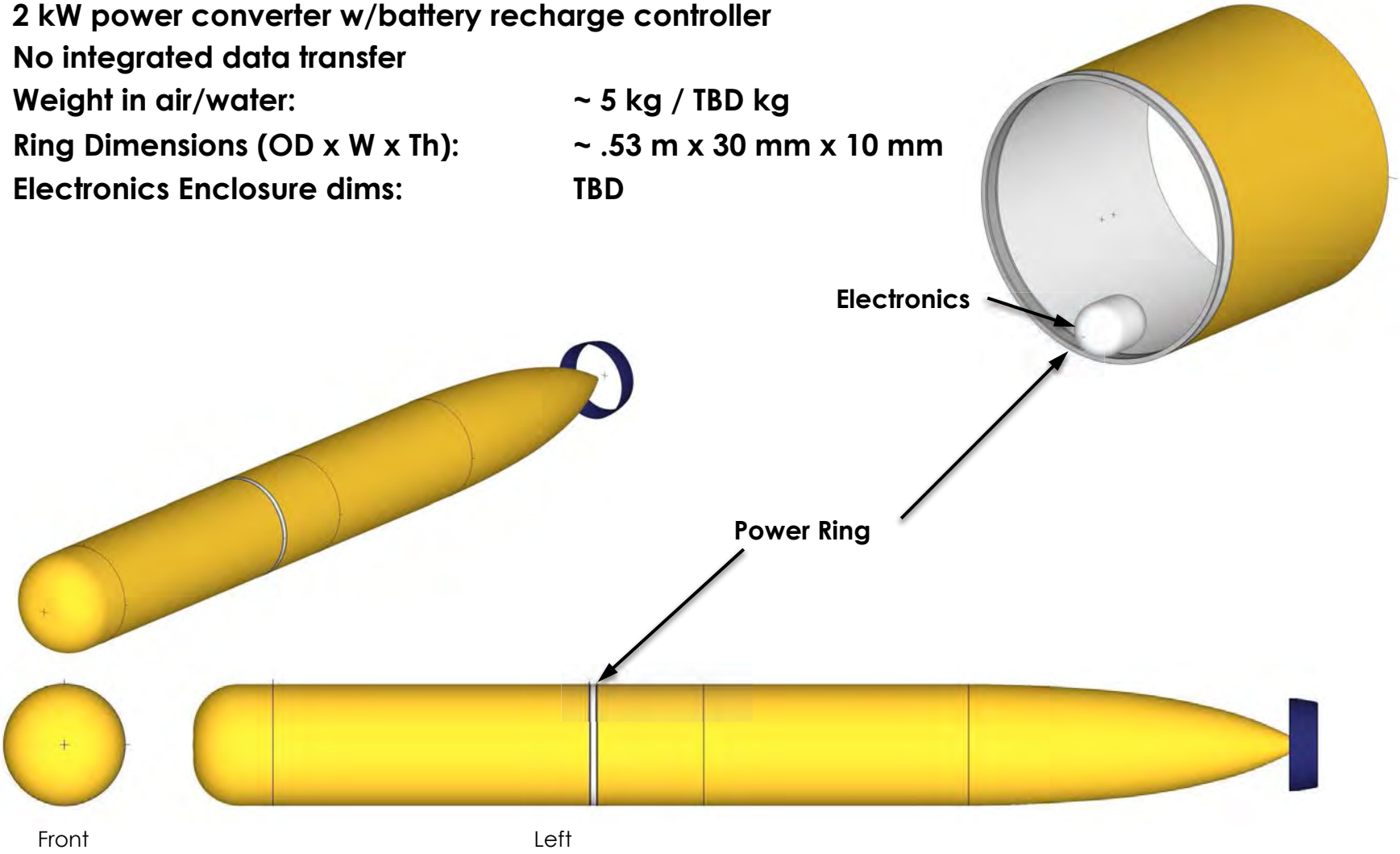
Power/Data Port for 21” UUV

- Oblong/parallel inductive ring
- 2 kW power converter w/battery recharge controller
- Duplex optical data transfer, > 1Gbps
- Weight in air/water: ~1.5 kg / 0 kg
- Dimensions: ~ 650 mm x 165 mm



Power-only Port for 21” UUV

- 2 kW power converter w/battery recharge controller
- No integrated data transfer
- Weight in air/water: ~ 5 kg / TBD kg
- Ring Dimensions (OD x W x Th): ~ .53 m x 30 mm x 10 mm
- Electronics Enclosure dims: TBD

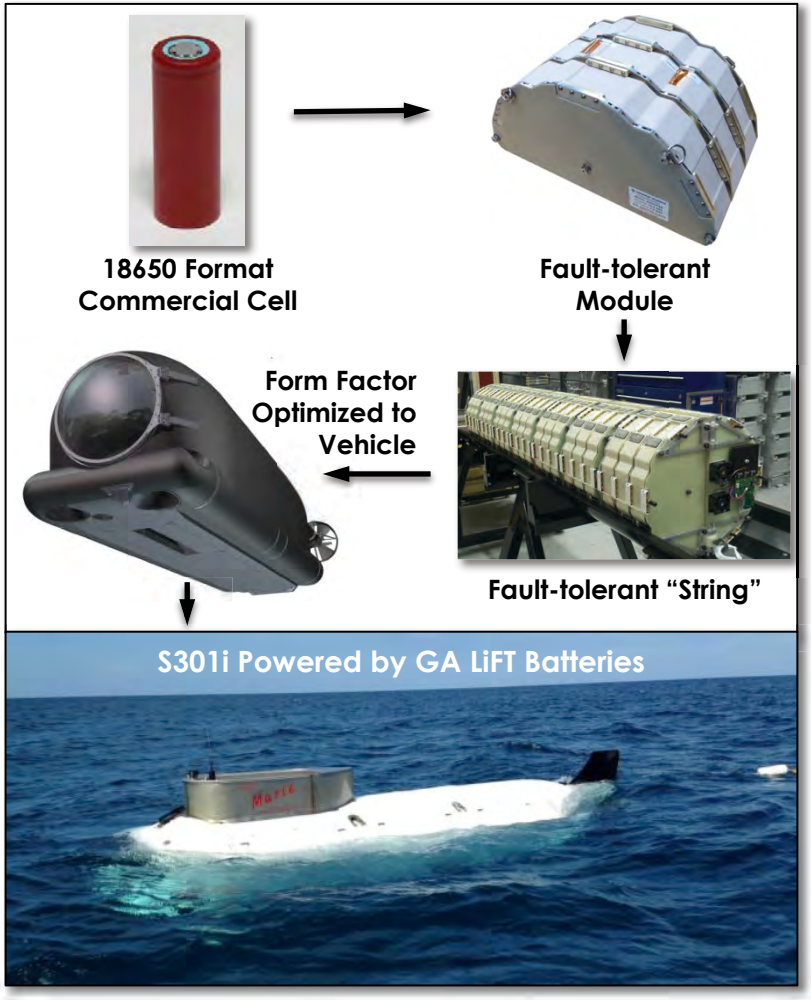


Undersea Power/Energy for Vehicle and Seafloor-mounted Mission Modules

GA's Lithium-ion Fault Tolerant (LiFT) Batteries
Highest Energy Density "safe" Lithium-ion Battery Available

- **Employs robust commercial cells**
  - Leverages decades & $B's commercial investment
  - Leverages commercial mass production for low cost & high reliability
- **GA's Fault-tolerant Technology**
  - Prevents cascading failures
  - Keeps vehicle/platform safe through cell failures
  - Graceful degradation, battery module keeps working through cell failures
- **Proven performance**
  - GA's batteries have passed ALL Navy qualification & destruction testing
  - On their way to certification for shipboard use
  - GA's LiFT batteries are batteries of choice for Navy's LD-UUV program
- **Aplicable for a variety of applications**
  - Fault-tolerant technology is scalable to any size battery module/string
  - Form-factor can be tailored to specific vehicle/platform needs
  - LiFT batteries for airborne and ground applications currently in development

Energy Density	**kWhr/L**	**247**
Specific Energy	**kWhr/kg**	**160**

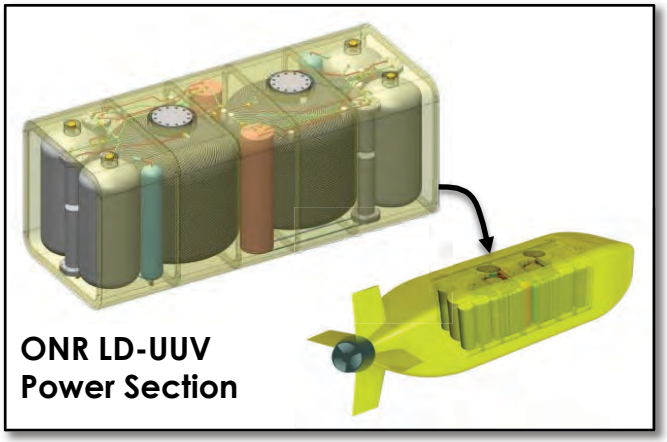


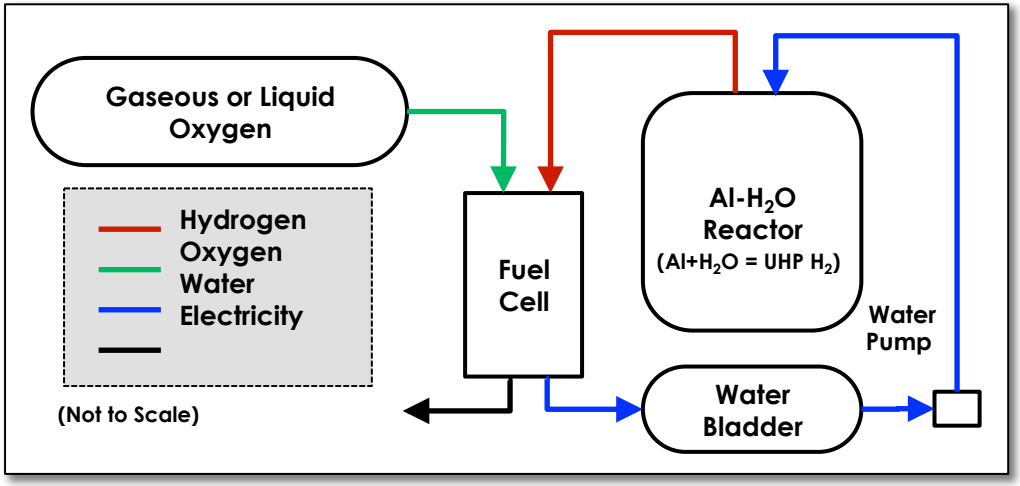
GENERAL ATOMICS ELECTROMAGNETICS

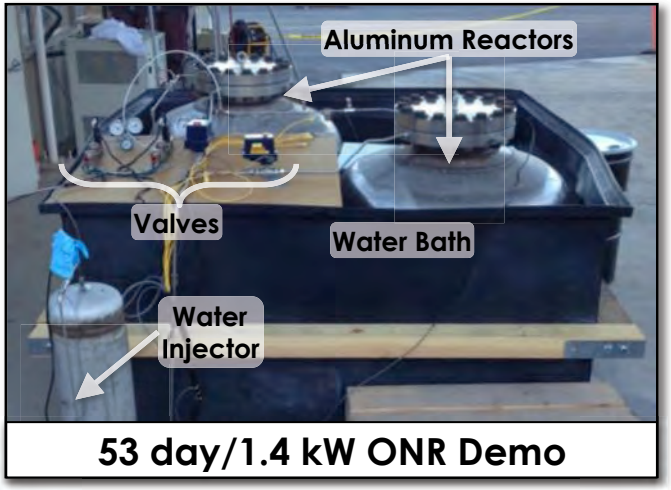
GA's Aluminum-Water Power System (AKPS)
High Energy Density, High Specific Energy, Affordable

- **Aluminum alloy mixed with water produces high-purity hydrogen on-demand**
  - Pressure can be set to any desired
- **On-demand H2 & stored O2 used to run high efficiency fuel cell**
  - Water is recycled to form a closed-loop system
- **2-5x increase in Energy Density over Li-batteries**
  - 290 – 1085 Whr/L; 495 – 550 Whr/kg
- **10-20x reduction in cost over Li-batteries**
- **GA manufactures Al-alloy, integrates system & delivers turn-key power source**

Energy Density	kWhr/L	290 - 1085
Specific Energy	kWhr/kg	95 - 550

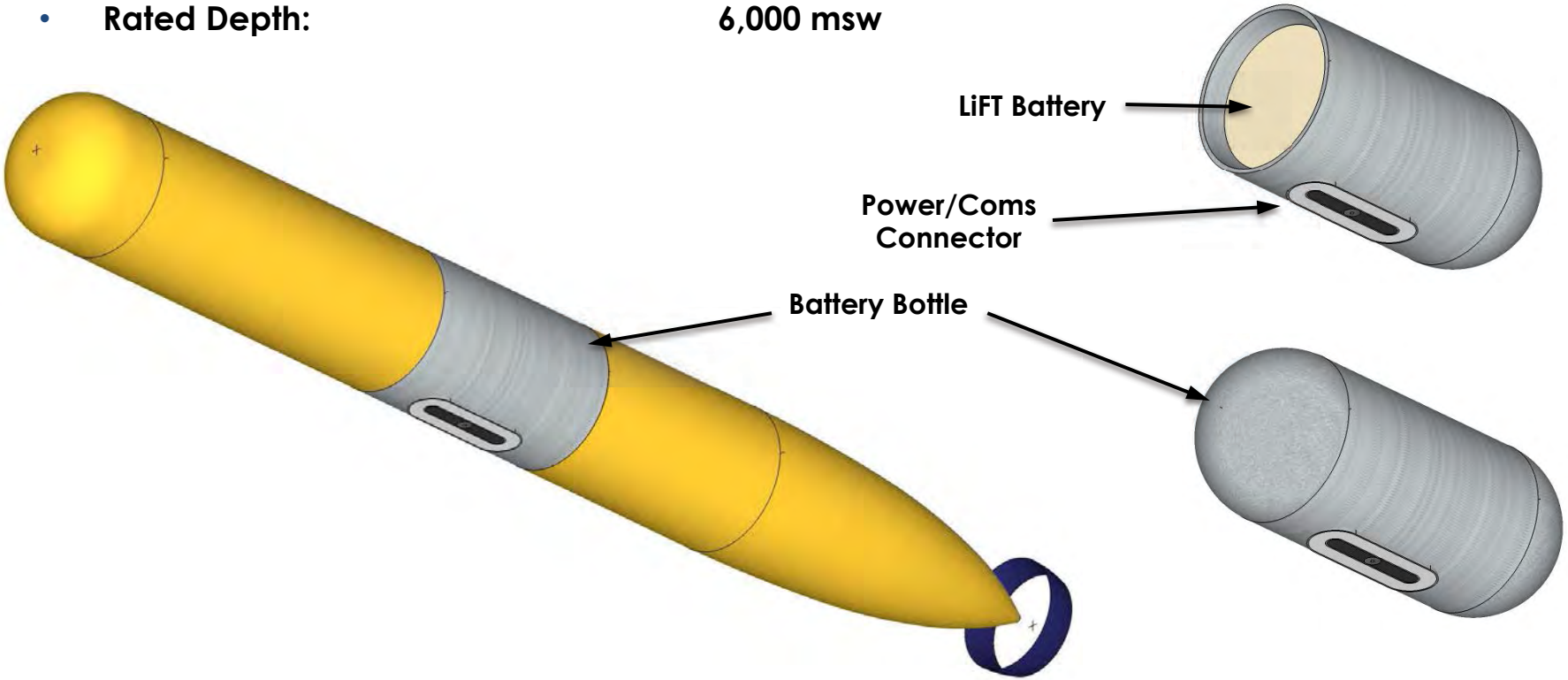






LiFT Battery w/Integral Power/Coms Connector for 21” Vehicle

- **Energy Store (@ 22C / @ 2C):** 23 kW-hrs / 18.4 kW-hrs
- **Battery Voltage:** 70 Vdc (can be designed to 70-140 Vdc)
- **Recharge:** 6 hrs @ 4.3 kW; 8 hrs @ 2.9 kW
- **Weight in Air/Water:** ~288 kg / ~0 kg
- **Displacement:** ~290 L
- **Dimensions (OD x LOA):** 21” x ~58”
- **Rated Depth:** 6,000 msw



Comparison of Li-ion Battery vs ALPS FC-based Energy Systems

System-level Parameters:	Units	GA LiFT Battery[1]	PEM Fuel-cell Systems[2]			
			5 ksi O2	5 ksi O2	LOX	KO2
			5 ksi H2	Open-ALPS		
Energy Density	Whr/l	247	290	640[5]	1042	1085
Specific Energy	Whr/kg	160	495	650[5]	930	550
Relative Cost[4]	-	10.8	1.0	0.42	TBD	TBD
TRL	-	6/7	6	4/5	4/5	3/4

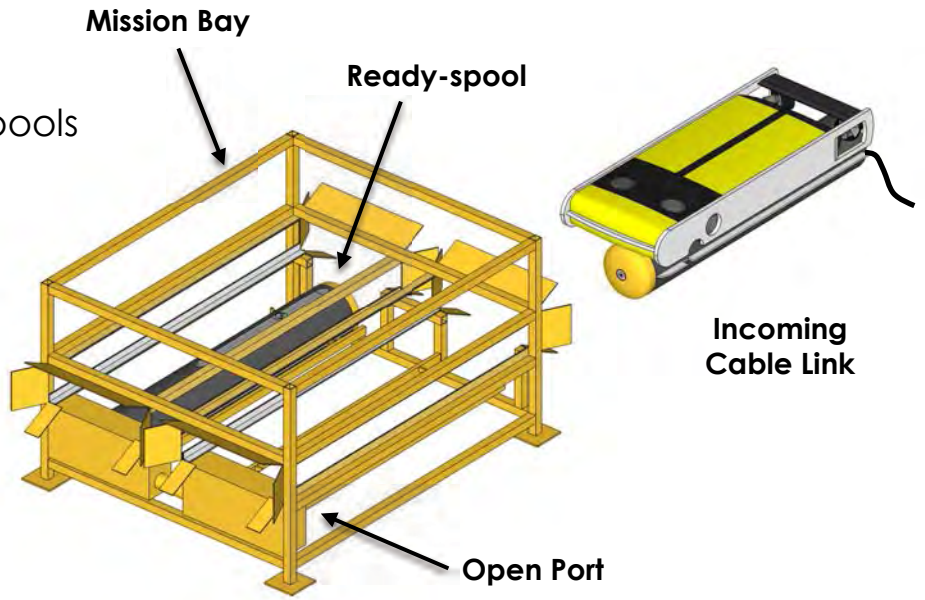
Note:
1 – Excludes power converter
2 – Includes housings & pressure vessels rated ~300 m depth. Based on fuel cells of a few 10 W up to 10's kW.
3 – Excludes water collection system.
4 – Relative to 5 ksi O2/5 ksi H2 Fuel-cell system.
5 – Approximate values.

- **Fault-tolerant batteries**
  - GA does not make battery cells
  - As cell energy density improves, so will Safe-battery energy density
  - Each different cell type requires adaption of the safety structure
- **Fuel Cell-based Systems**
  - Cryogenic O2 & H2: has some merits in specialized applications
  - Chemical O2 is hard & costly, development underway at GA

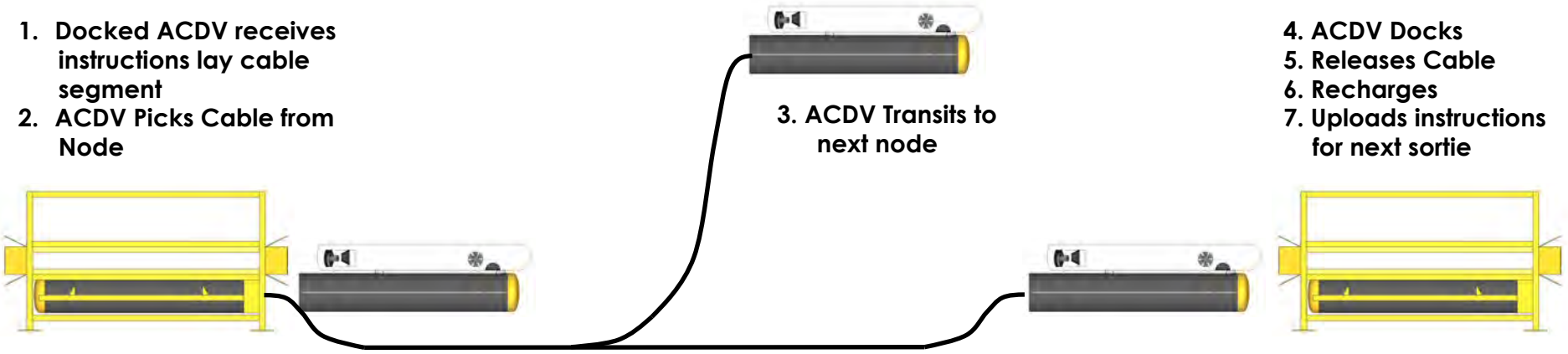
Other Things We're Working on in the Undersea Domain

Autonomous Cable Deployment

- **Two-port Connectivity Module**
  - 1 open port / 1 ready spool
  - ACDV lays cable by transporting ready spools between nodes
- **Netted Cable Laying**
  - Power/Coms connector in Cable Hanger
  - ACDV in continuous coms / powered form network during cable laying
- **Commercial AUV**
  - Inertial Navigation for transit
  - Acousto-optical guidance for docking
  - Fully Autonomous w/obstacle avoidance



1. Docked ACDV receives instructions lay cable segment
2. ACDV Picks Cable from Node

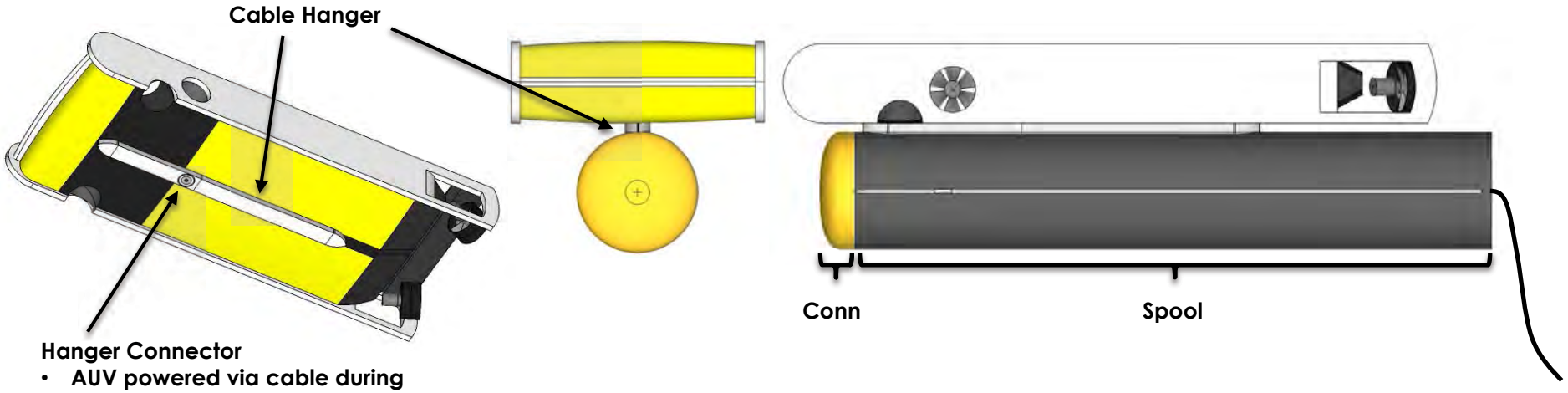


3. ACDV Transits to next node

4. ACDV Docks
5. Releases Cable
6. Recharges
7. Uploads instructions for next sortie

Autonomous Cable Deployment Vehicle (ACDV)
(Medium Power ~1 kW, Medium Range ~30 nmi)

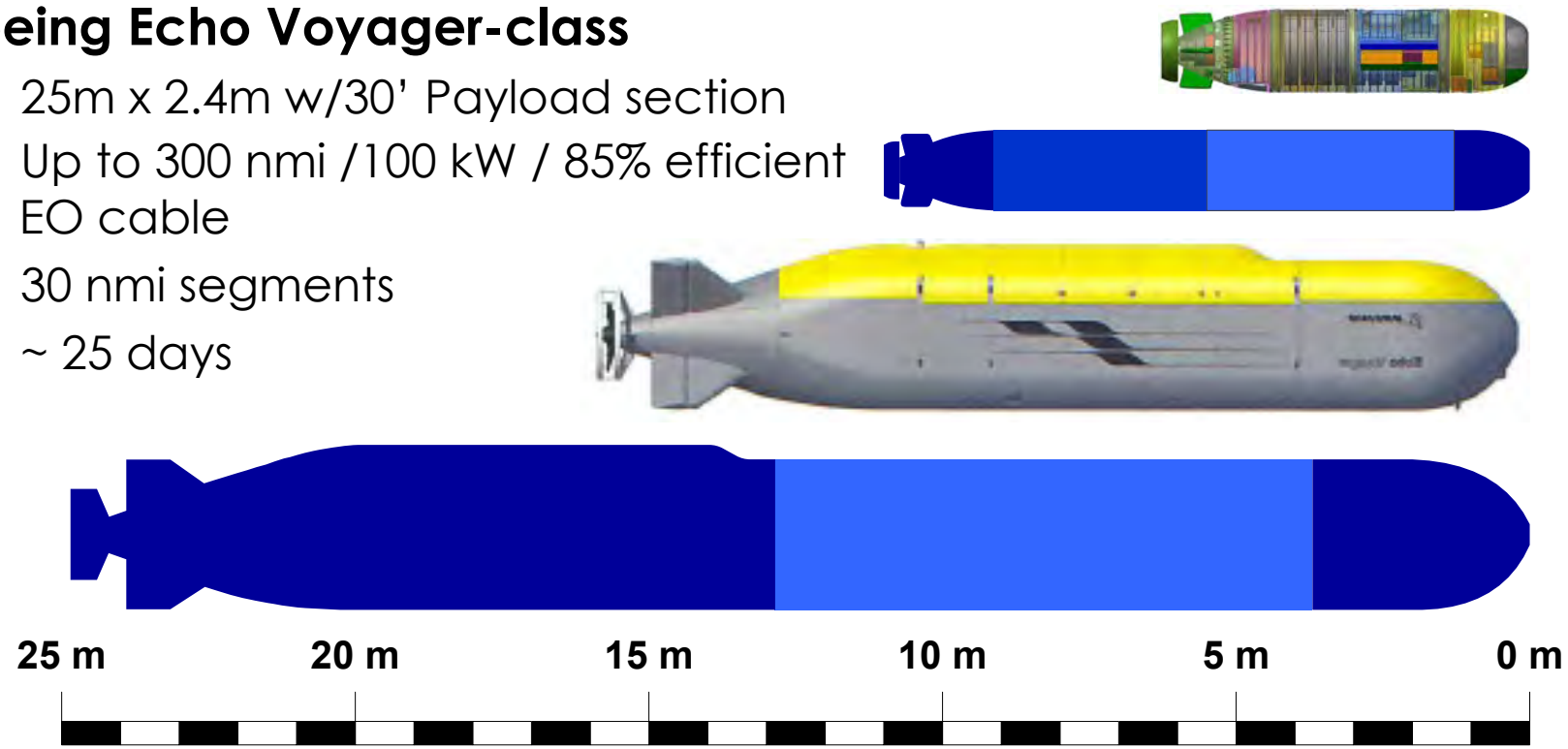
- **ACDV based on commercial AUV**
  - Saab Sabertooth AUV
  - Currently in discussions w/Saab to evaluate payload capacity and control authority
- **Cable-laying Mission**
  - 28 nmi cable, 25 nmi node spacing
  - 1 kW, 80% net power transfer efficiency
    - Sufficient to recharge vehicle when docked
  - Optical fiber, > 1 Gbps data rate



Hanger Connector
- **AUV powered via cable during cable laying**
- **Recharges whenever docked**

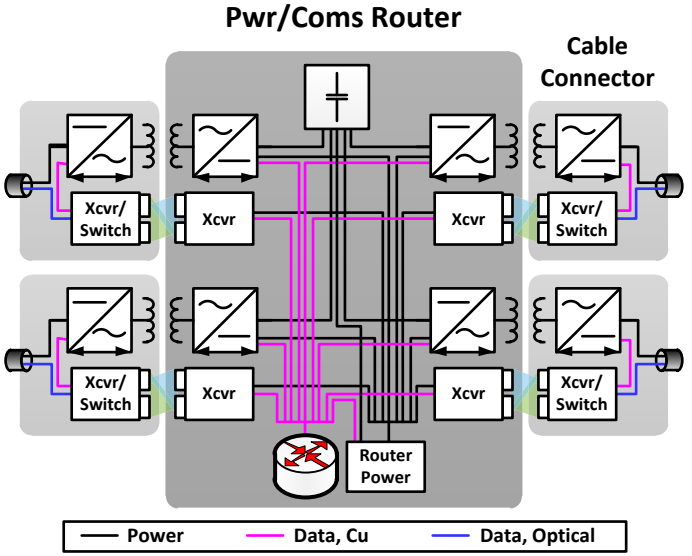
Autonomous Cable Deployment Vehicle (ACDV)
(High Power 10-100 kW, Long Range ~300 nmi)

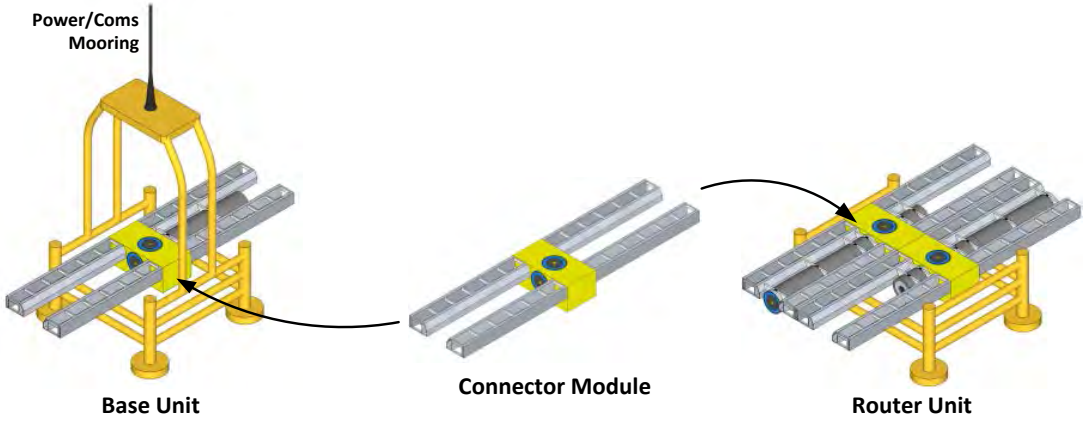
- **NAVSEA LD-UUV-class**
  - 11m x 1.4m w/13' Payload section
  - Up to 300 nmi /10 kW / 85% efficient EO cable
  - 20 nmi segments, ~ 31 days
- **Boeing Echo Voyager-class**
  - 25m x 2.4m w/30' Payload section
  - Up to 300 nmi /100 kW / 85% efficient EO cable
  - 30 nmi segments
  - ~ 25 days



Power/Coms Router & Base Unit

- **Routers & Base Units**
  - Based on Power/Coms Connector
  - Employ a common Connector Module
  - Base Unit anchor mid-water FDECO modules, provide power/coms through mooring
  - Routers connect multiple Base Units
- **Connector Modules house**
  - Power distribution layer
  - Coms Network layer
  - Ganged to form multi-port units
- **Landing pads & Connectors interface to**
  - ACDS
  - Cable Assemblies

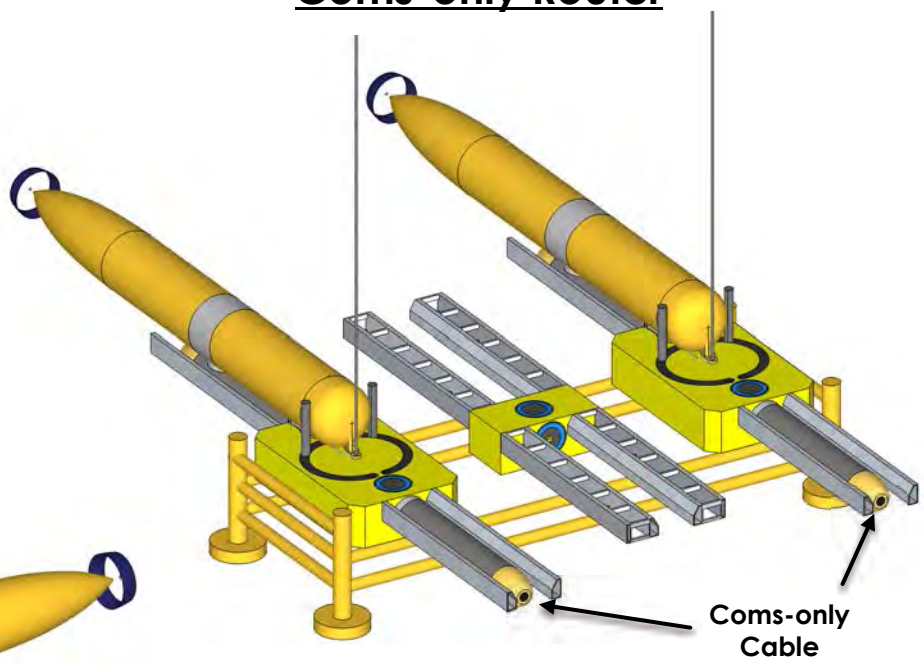




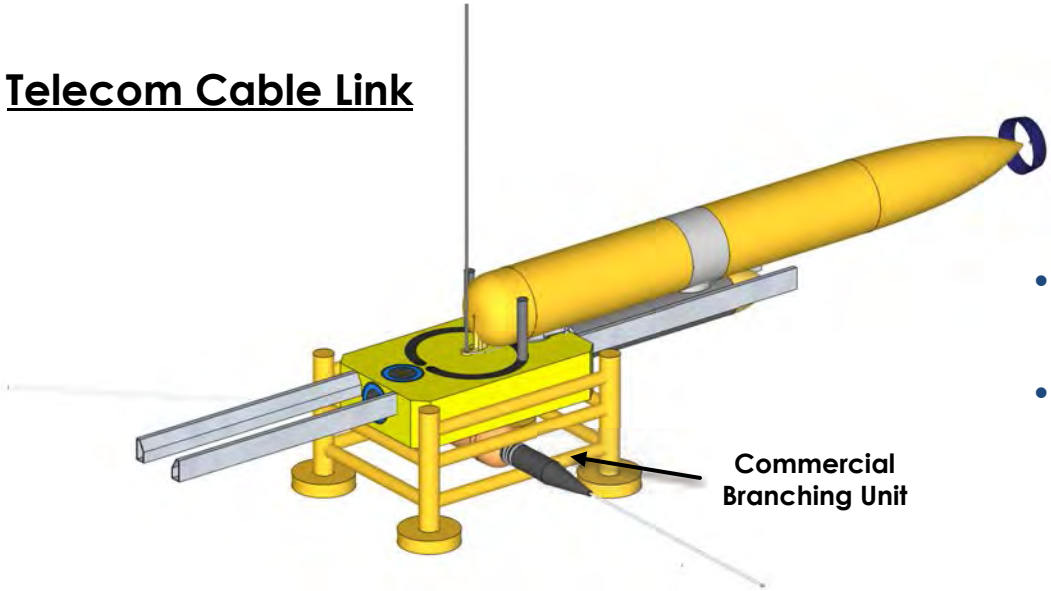
Autonomous Link to Telecom Backhaul Provides Secure Global Connectivity

- **30 nmi Coms-only cable**
  - Contactless connectors
- **BF-21-based Cable-layer**
  - ~60-75 nmi range
  - Recharges from FDECO Docking Module
  - Lays cable to Backhaul, then returns to outpost for other missions

Coms-only Router



Telecom Cable Link

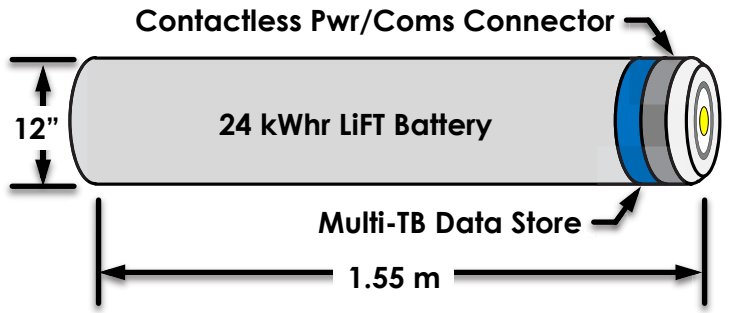


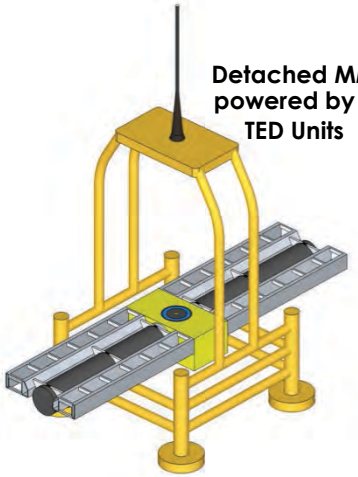
- **Links to FDECO Power/Coms distribution layer**
- **4-port Router shown**
  - 2 "inbound" / 2 "outbound"
  - Connects to 3 other outposts 1 backhaul cable

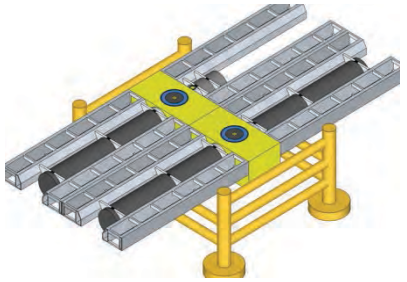
Transportable Power & Communications
Upload Data/Recharge Mission Module in Minutes

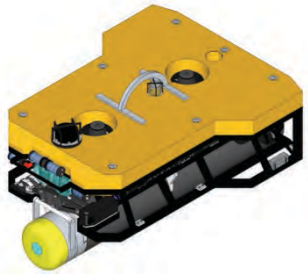
Transportable Energy/Data requires three components:

1. **Transportable Energy/Data (TED) Unit**
   - Mission module recharge & data exfil in minutes
   - Employs:
     - Li-ion Fault-tolerant (LiFT) Batteries
     - Contactless Pwr/Coms Connector
     - High-capacity data store, up to 10s TB
2. **TED Recharge Module**
   - Network connected pwr/coms
   - Recharges LiFT batteries ~6 hrs
   - Exfil data at Gbps
3. **TED Mule**
   - Same vehicle as used for cable deployment
   - AUV transports TED units between TED charger & mission modules




Detached MM powered by 2 TED Units


Pwr/Coms Router recharging 3 TED Units




TED Transport Vehicle

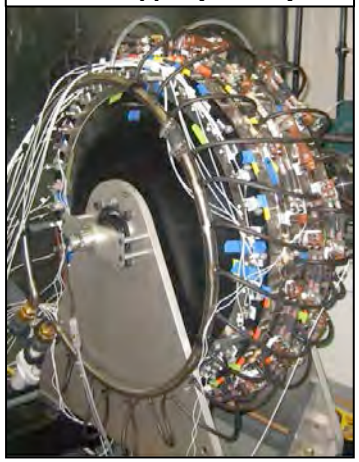
GA's Ultra-Quiet, Direct Drive Axial Flux Motor/Generator
Compact, Efficient, Quiet

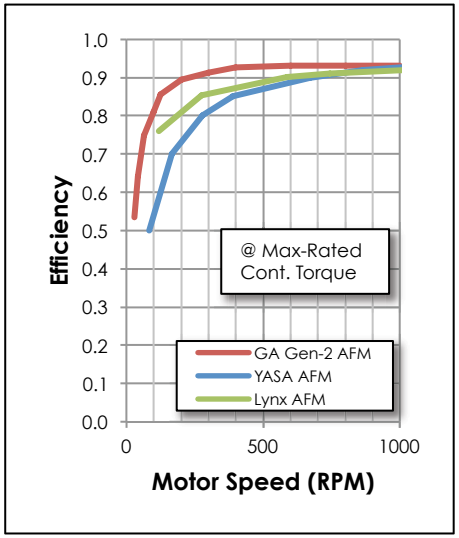
- **Operates as either/both a motor or a generator**
- **Optimized for high torque at low RPM**
  - No gearbox or reduction gear
- **Optimized for "flat" efficiency curve**
  - >90% from 20%-rated to max-rated
- **Optimized for low acoustic signature**
- **Scalable from 10's kW to MW's**
- **Suitable for wetted & deep sea applications**
- **Applicable to…**
  - Propulsion motors, generators, gensets, actuator drives, winch drives, etc.

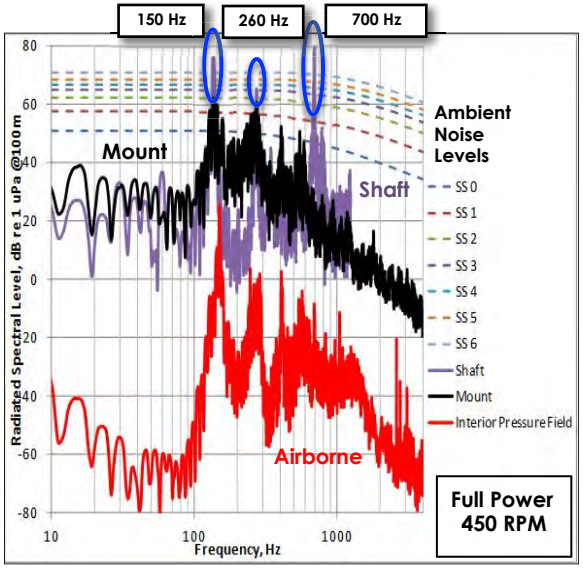
Parameter:	Units:	Gen-1[2]	Gen-2[3]	Ohio-R
Power	MW	0.1	0.26	40[4]
Torque[1]	kN-m	2	5	1,000[4]
Speed	RPM	0-500	0-500	0-360[4]
Efficiency	%	93	93	~99
OD	m	0.9	0.9	~3.2
Length	m	0.3	0.3	~1
Mass	kg	~700	~700	~2,020

NOTE:
1 – Continuous rating
2 – Gen-1 prototype built and tested in GA's Mixed-reality Simulator lab
3 – Gen-2 LD-UUV propulsion unit design specification.
4 – Estimated by GA, not derived from any official source

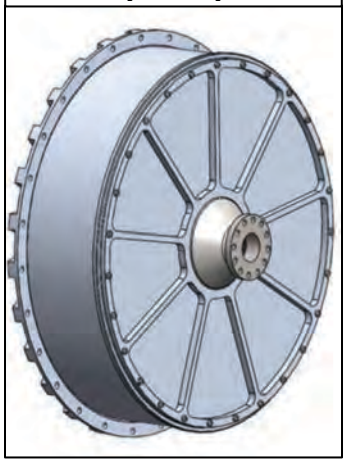
Proof-of-Concept Prototype (Gen-1)







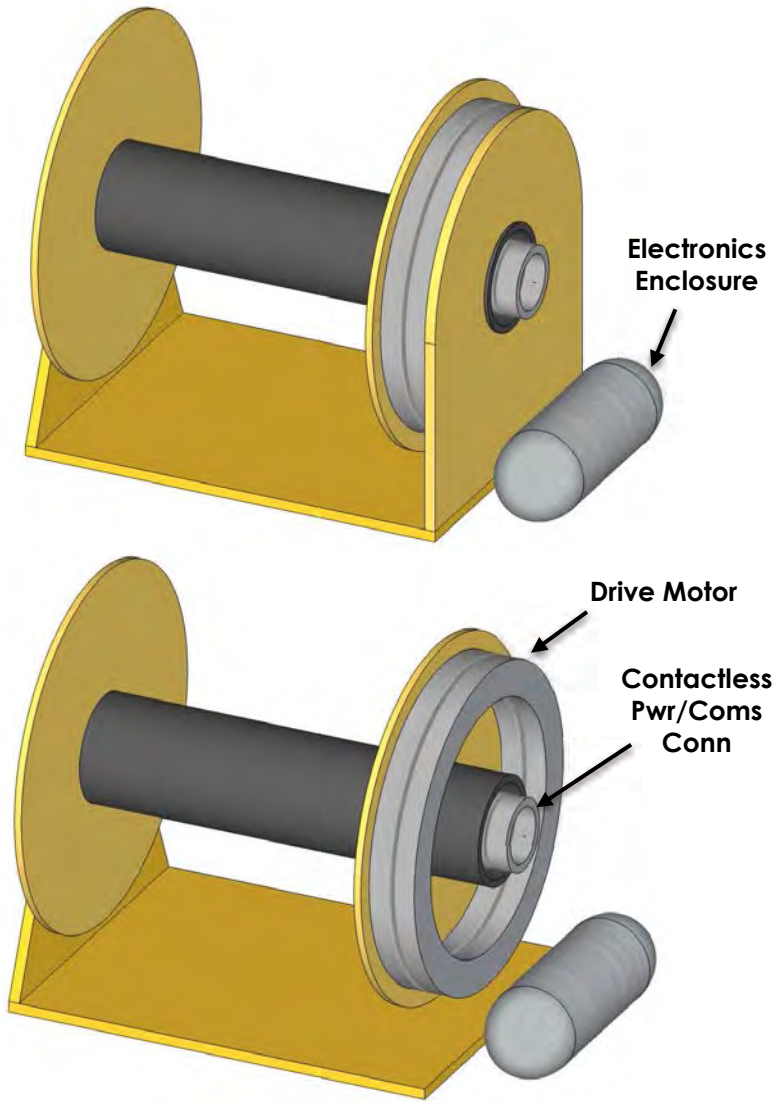
Production Prototype (Gen-2)



GENERAL ATOMICS ELECTROMAGNETICS

High-reliability Subsea Winch

- **For retractable coms-buoys**
- **Only 1 moving part – Drum Assy**
  - No gearbox, chain-drive
- **High-efficiency, direct drive motor**
  - Permanent magnet synchronous motor
  - Seawater in the gap
  - Leverages novel GA magnetic configuration
  - High torque at low RPM
- **Contactless Pwr/Coms Connector**
  - Mounted on axis
  - Acts as a slip-ring to the drum

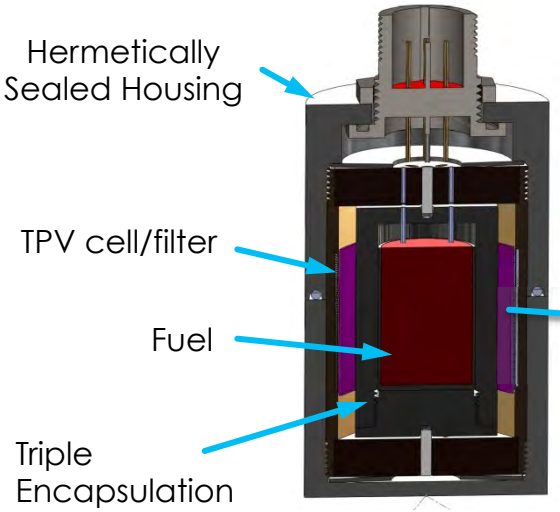


GA's Thermophotovoltaic Autonomous Power Source (TAPS) Provides Unattended Power up to 20 yrs

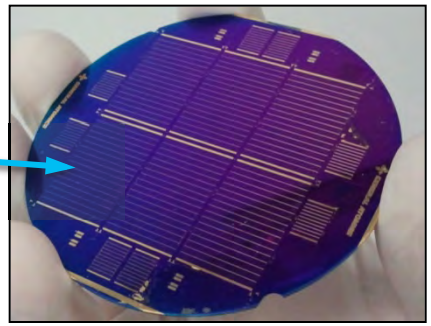
- **Isotope fueled Power Source**
  - 2 We, 20 year life, Pu-238
  - Scalable: 0.5 to 50 We (~1 to 20 lbs.)
  - Triple encapsulated fuel containment
  - Passively cooled to air, water or soil
  - Designed for extreme environments
    - Ocean, arctic or desert
  - No gas (He or FP) release to environment
  - Low thermal signature; virtually no radiation signature

Hermetically sealed 2We TAPS battery next to D-cell

TAPS Battery with Cooling Fins



Heat (~1050K) to electric conversion using thermophotovoltaics (TPV)



Backup