The University of Texas at Austin
Center for Electromechanics

PULSED ALTERNATORS

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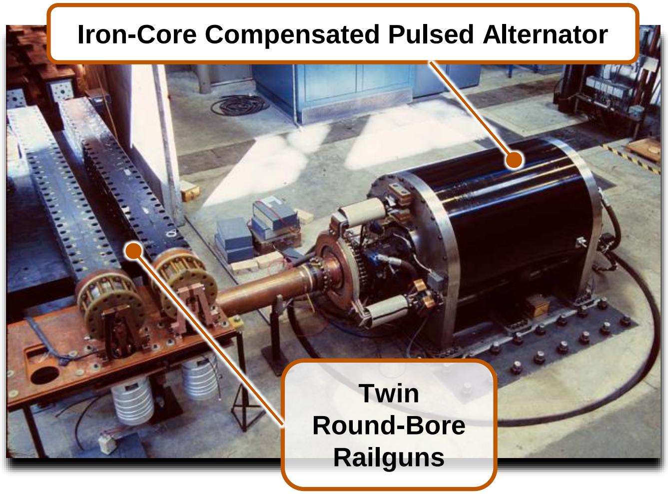
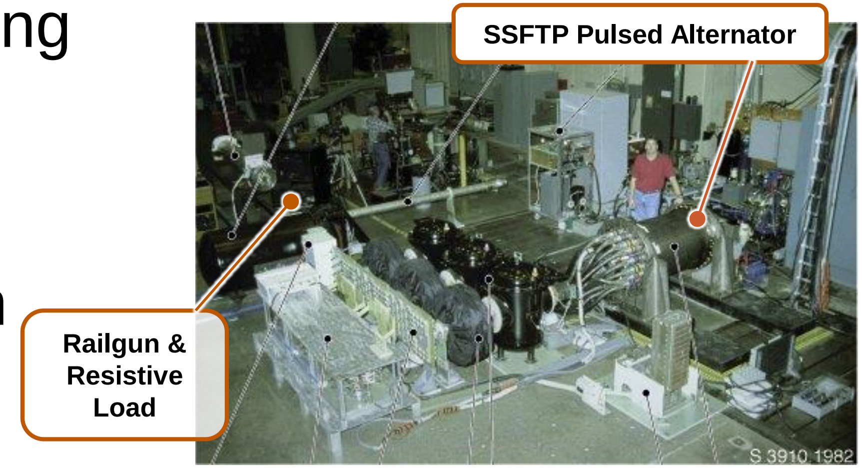
The University of Texas at Austin
8/14/17

Tutorial Objectives

- Provide a detailed understanding of rotating-machine-based pulsed power systems
- Review the maturation of pulsed alternator technology
- Introduce technologies enabling increased power and energy density
- Discuss shipboard integration





Presenters

Mr. Scott Pish

- Research Engineer, Program Manager
- Manufacture & test of prototype rotating machines,
- Design, analysis, & fabrication of composite structures
- B.S. Mechanical Engineering 1996

Mr. Jon Hahne

- Senior Engineering Scientist, Program Manager
- Development, design, manufacture, and test of prototype rotating electrical machines.
- B.S., Mechanical Engineering 1986

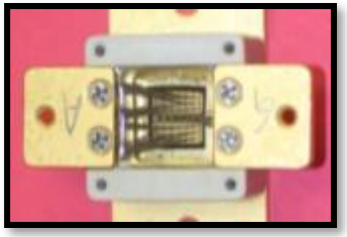
Dr. Angelo Gattozzi

- Research Associate, IEEE Senior Member
- Electric power system modeling and simulation, smart-grid/micro-grid systems, Navy power systems, high-speed motors/generators
- Ph.D., Electrical Engineering and Applied Physics 1978

TECHNOLOGY BACKGROUND

How We Got Here

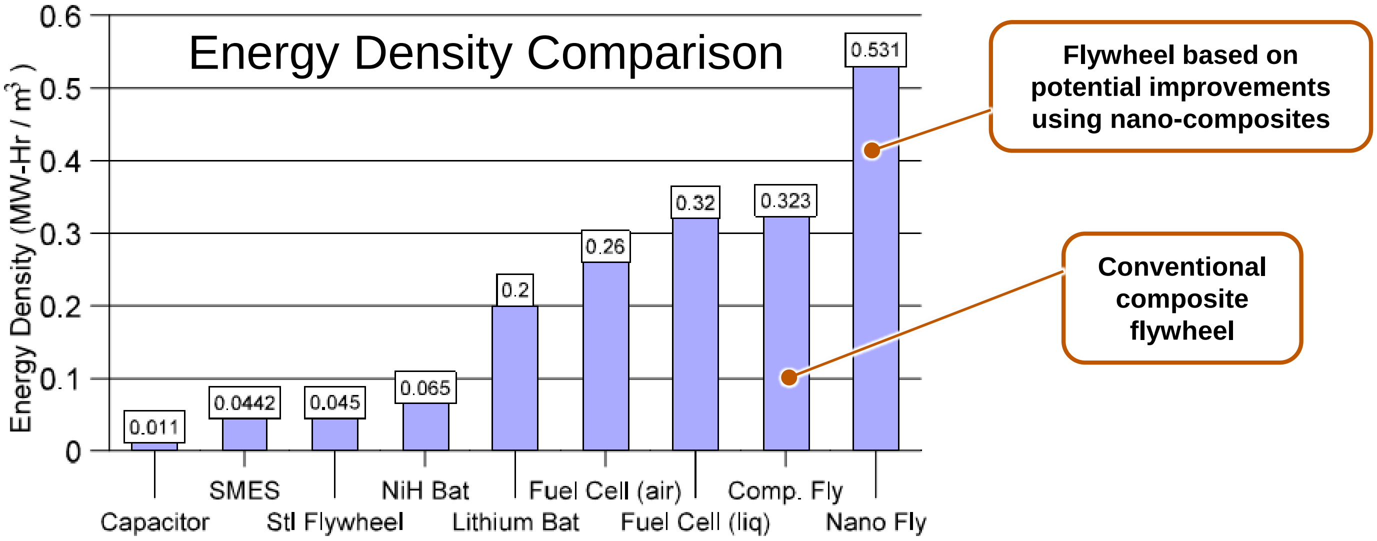
- Chinese technical literature credits the University of Texas researchers with the invention of the modern pulsed alternator
- But pulsed alternators evolved, rather than were invented, through UT's efforts to make rotating machines more power and energy dense (Motors, Generators, Energy storage)
- Increasing power and energy density is a long term research objective of UT and requires advances in
  - Rotating machine design
  - Materials
  - Power electronics
  - Advanced controls



All areas of traditional and growing expertise at UT's CEM

Power and Energy Density

- Critical for ships and aircraft, both manned and unmanned, tracked and wheeled vehicles, & trains because the weight of the power system reduces the weight of the payload
- Fundamental study of energy density by UT demonstrated that rotating machines most energy dense



From: "A FUNDAMENTAL LOOK AT ENERGY STORAGE FOCUSING PRIMARILY ON FLYWHEELS AND SUPERCONDUCTING ENERGY STORAGE" By: K.R. Davey R.E. Hebner Electric Energy Storage Applications and Technologies EESAT 2003 Conference Abstracts, SanFrancisco, California, U.S.A., October 27-29, 2003,

Powering EM guns

- EM guns have been successfully powered by
  - Rotating machines
  - Batteries
  - Capacitors
  - Inductors
- The Army and Marines both developed EM guns for wheeled vehicles
  - Both were based on pulsed alternators as they provided the greatest power and energy density
  - The Navy chose a less power dense solution for their initial efforts
    - Likely that the Army pushed the power density beyond the Navy’s threshold

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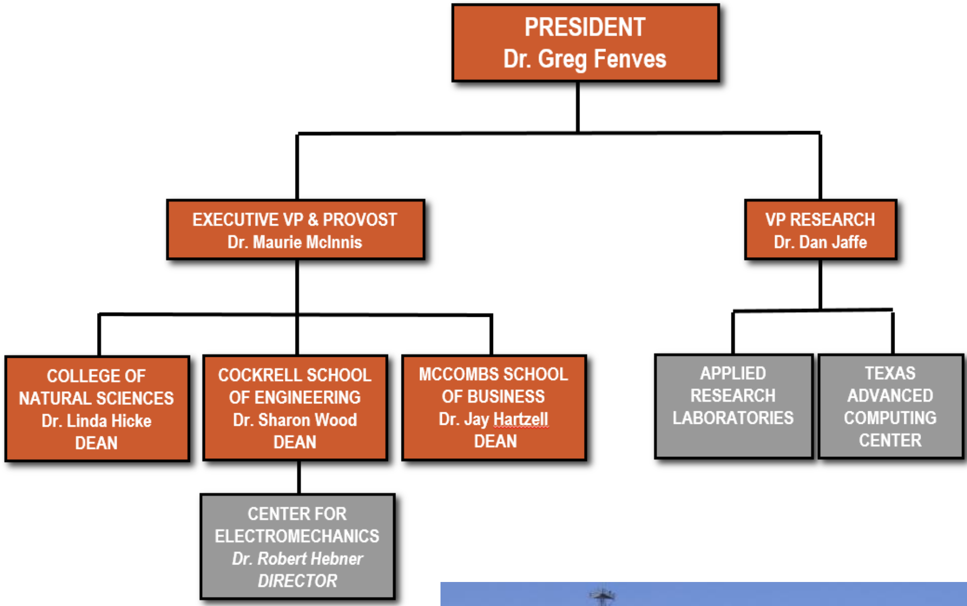
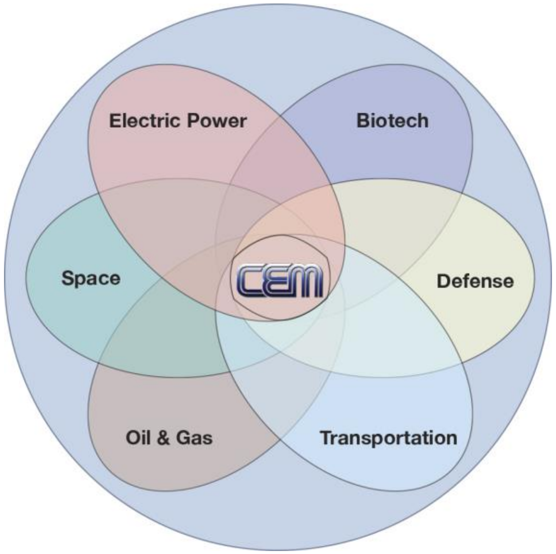
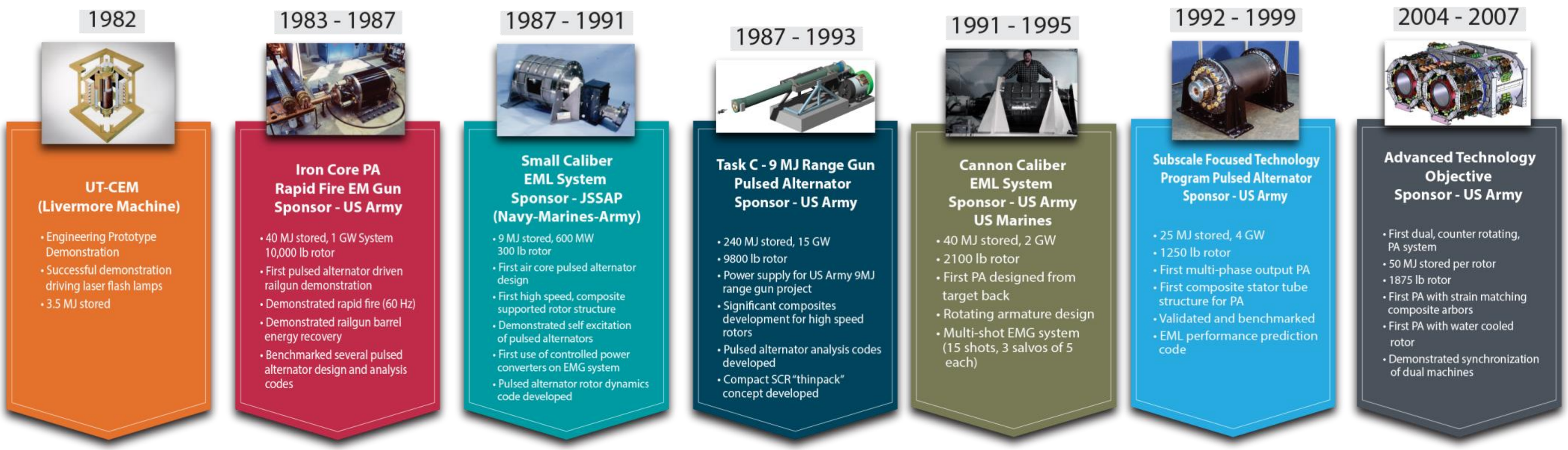




Prototype Manufacture and Assembly

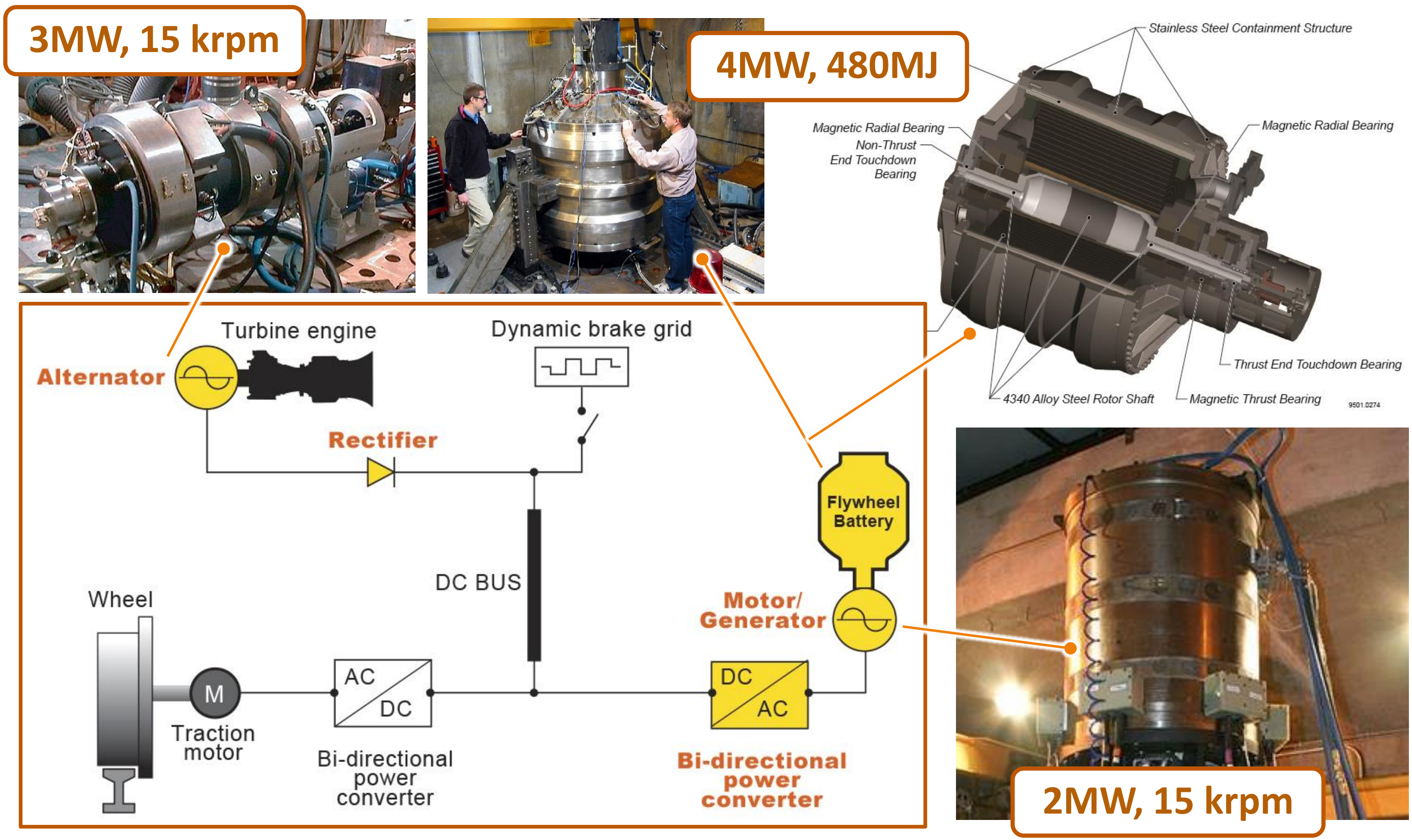
Over 140,000 ft^2 of conditioned space for prototype manufacture & test

EM Gun Research Provides Continuous Improvement

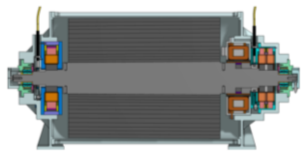


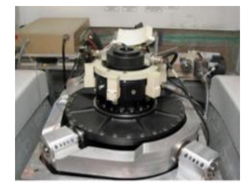
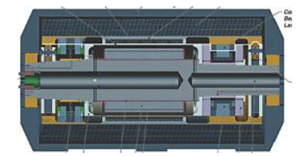
- 9 MJ Task B Railgun
  - 90mm bore, 10m long
- Vertical Gun Range
  - 15 ft dia., 140 ft deep
- Capacitor & rotating machine-based PPS
- High-energy spin test bunker
  - Withstand 5 psi internal overpressure
  - 30” thick FRP reinforced concrete walls
  - SS mount structure, anchored to bedrock
  - 5M lb vertical & 20M ft-lb torque
- Gas Turbine Test Cell
- EMI/RFI Screen Room for DAQ & controls

Design and Testing of Power Systems



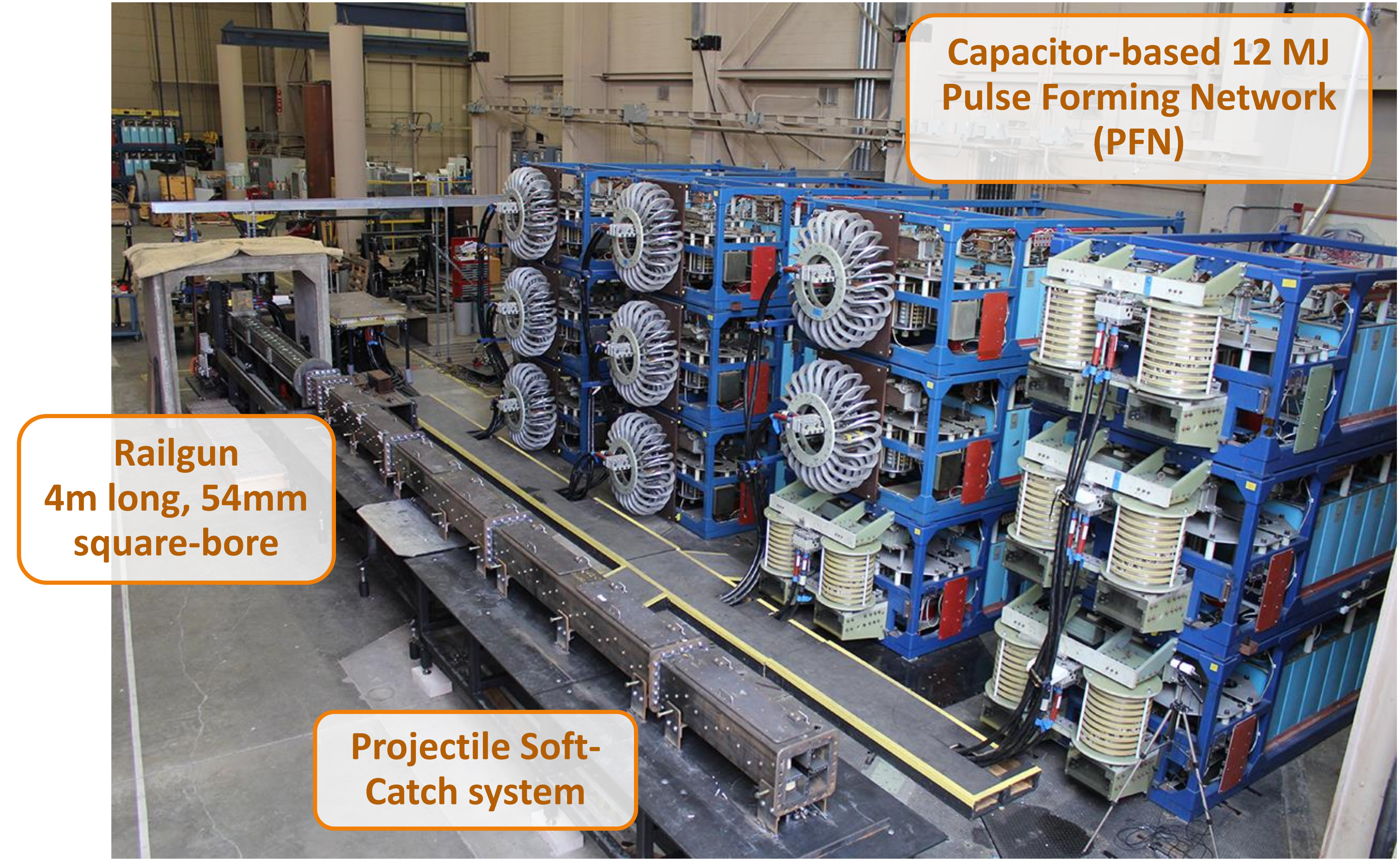
Rotating Machines for Energy Storage



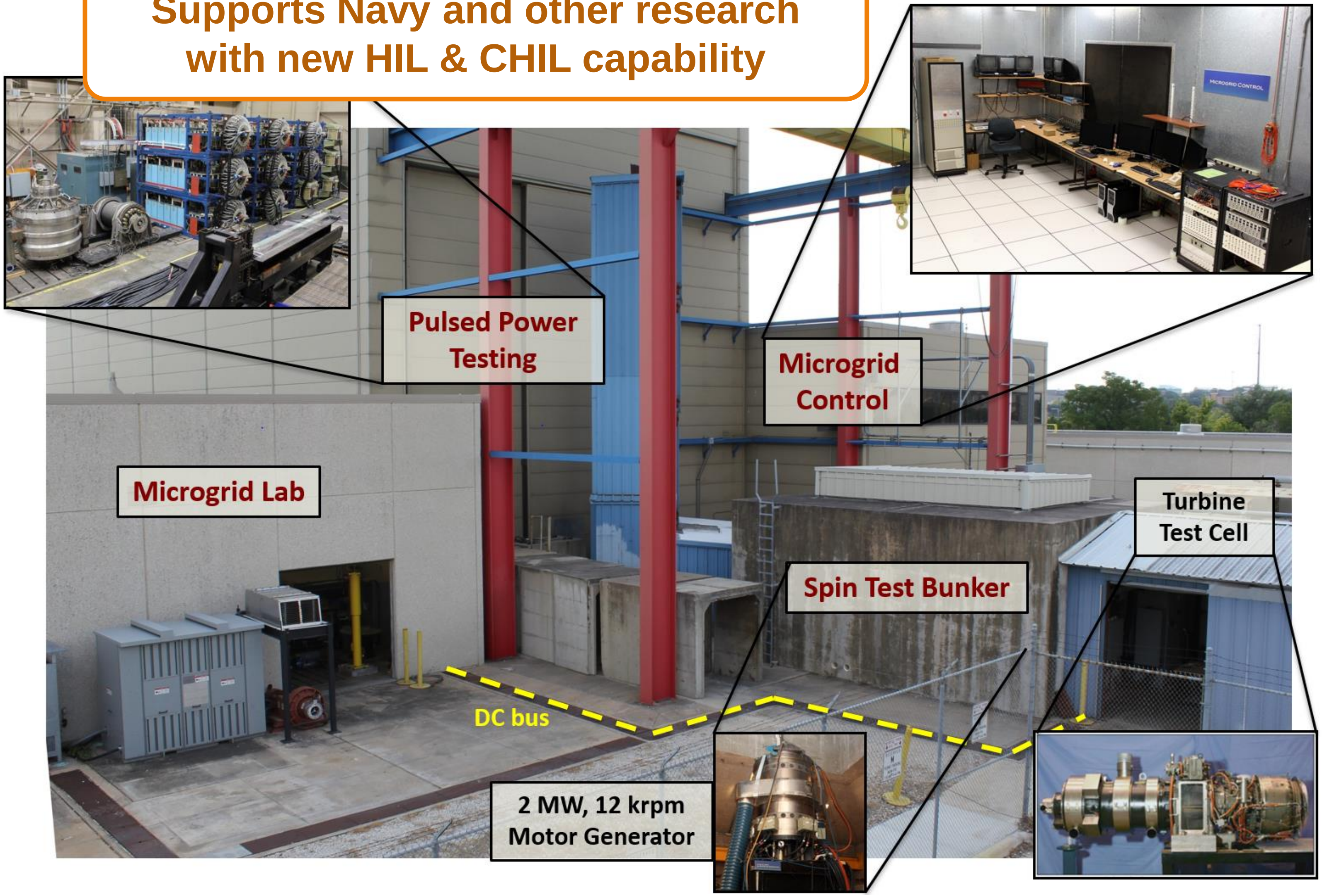
Parameter	NASA FESS	ALPS System	Bus System	CHPS System
Function	Energy Storage	Load Leveling	Load Leveling	Leveling/Pulsed
Energy Stored (kWhr)	3.6	133	2	7
Peak Power (kW)	5	2,000	150	5,000
Typical Discharge Time	30 minutes	~ 3 minutes	30 seconds	3 seconds
Rotational Speed (RPM)	53,000	15,000	40,000	20,000
Machine Weight (lbs)	250	19,000	450	1,100
Motor/Generator	Permanent Magnet	Induction	Permanent Magnet	Permanent Magnet
Topology	Partially Integrated	Non-Integrated	Partially Integrated	Fully Integrated
Cooling	Cold Plate	Air/Oil and Water	Oil and Water	Oil
Bearings	Homopolar Magnetic	Hompolar Magnetic	Homopolar Magnetic	Homopolar Magnetic
Backup Bearing Duty	Limited	Limited	Significant	Significant
Gimbal	NA (Torque Balanced)	Required	Required	Required
Flywheel Design	CEM Cylindrical	CEM Cylindrical	CEM Cylindrical	CEM Mass Loaded
Rotor Tip Speed (m/s)	920	1,015	935	600
Safety	RSL&NDE	RSL & Containment	RSL&Containment	RSL

Pulsed Power Testing



Microgrid Facility

Supports Navy and other research with new HIL & CHIL capability



Providing solutions

Prototype Navy EMALS generator developed at UT-CEM successfully transitioned to industrial partners for deployment

- Developed system simulation models
- Design, built, & tested the prototype generator
- 20% lower mass & volume than commercially available power supplies

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PULSED ALTERNATOR TECHNOLOGY BASICS OVERVIEW

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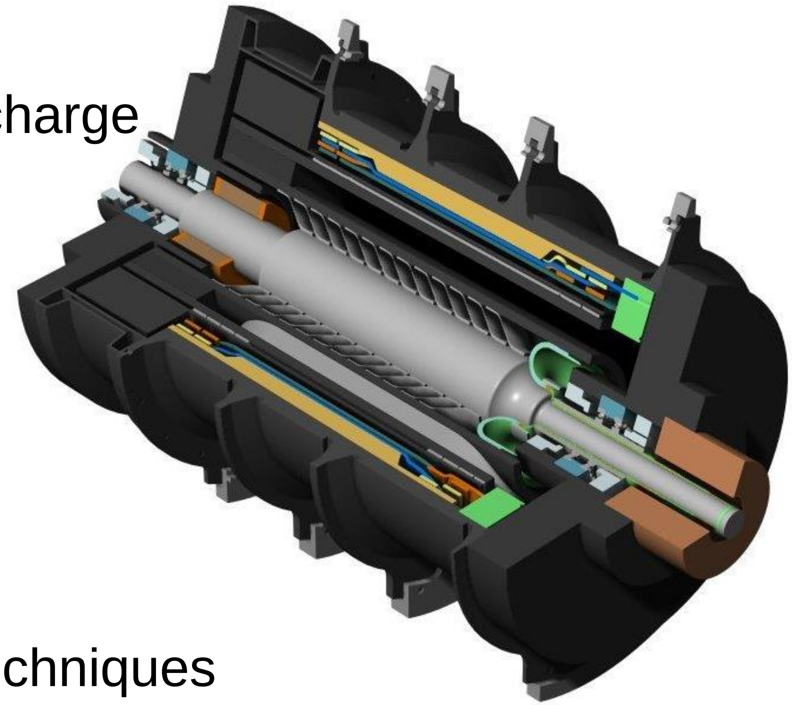
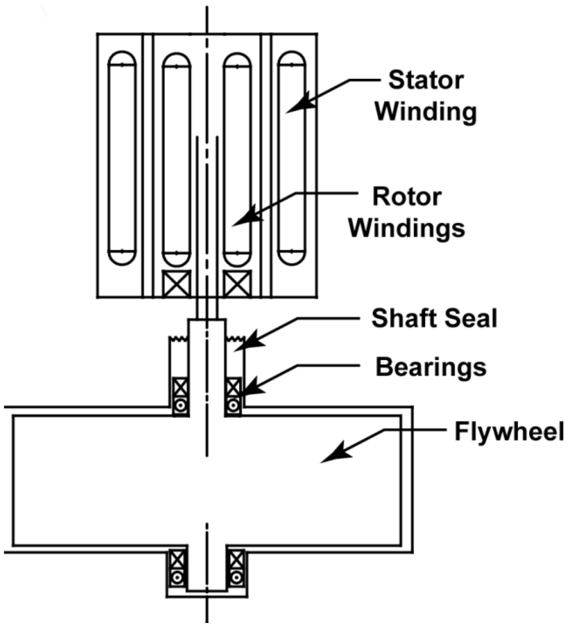
Rotating Machines for Pulsed Power

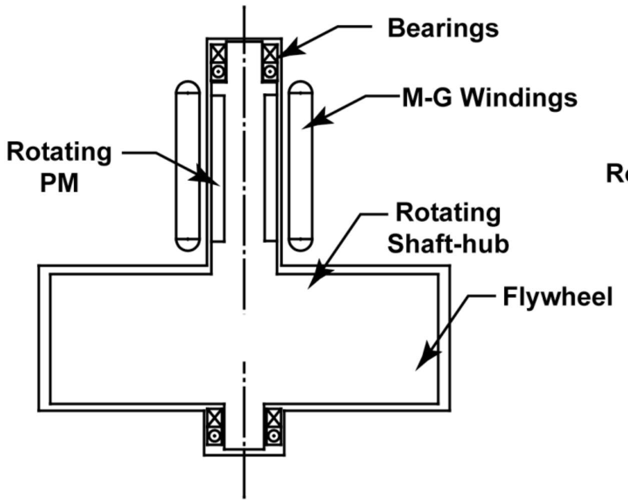
- Modular, multi-function systems
  - Combines Energy Storage + Pulse/Continuous Generation
  - High Power and Energy Density
  - Multiple pulse discharges with rapid recharge
  - Extended design/operational life
- Technology Advancements Offer Potential for Higher Performance
  - Advanced composite materials
  - Composite arbors
  - Solid-state power electronics
  - Thermal management materials and techniques

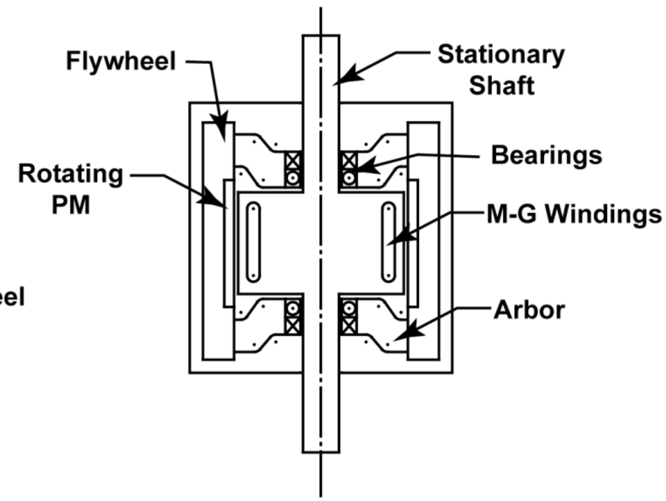


Core PA Technologies Extend to Other Rotating Machines

Flywheel Topologies







Non-Integrated Topology

- Larger than other topologies, but may have most simple assembly
- Maximum use of conventional M/G systems and technology
- Flexible / adaptive design
- Power generation outside of vacuum
- Requires shaft seal and coupling

Partially-Integrated Topology

- Smaller and more efficient than non-integrated
- Good use of available M/G technology, but integration required
- Good design adaptability
- Favors use of PM generator
- Heat generation on rotor requires careful engineering

Fully-Integrated Topology

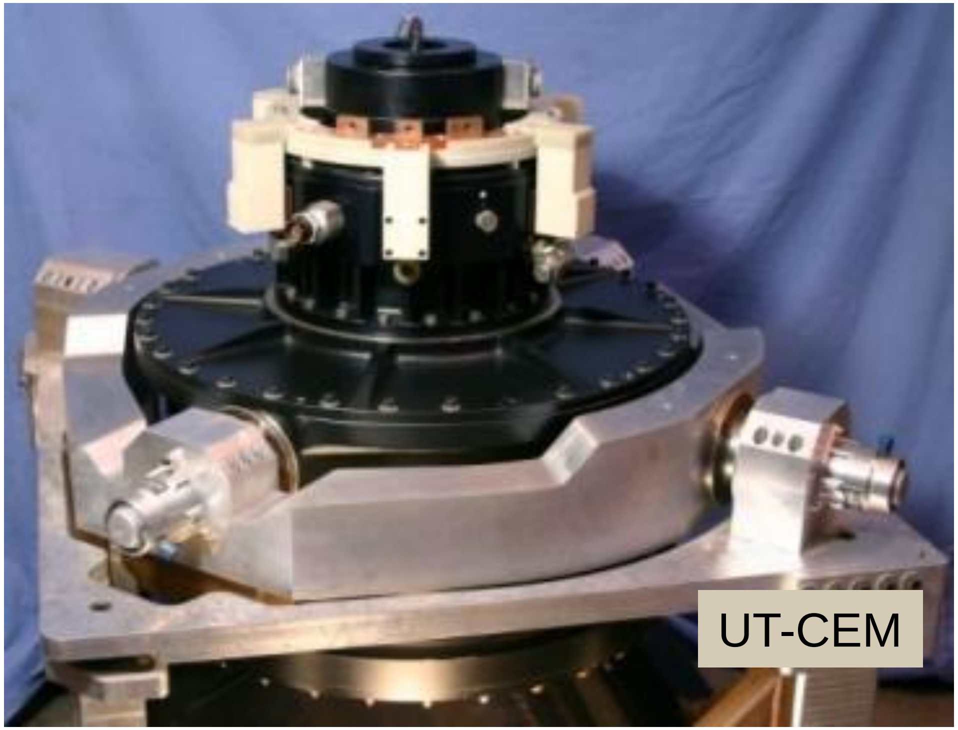
- Most compact system
- Special purpose flywheel system
- Favors use of PM generator
- Heat generation on rotor requires special engineering
- Rotating magnets at large radius

Non-Integrated Topology

- Federal Railroad Authority – Advanced Locomotive Propulsion System
- 480 MJ, 15 krpm flywheel
- 3 MW motor/generator
- Flex drive coupling interconnect

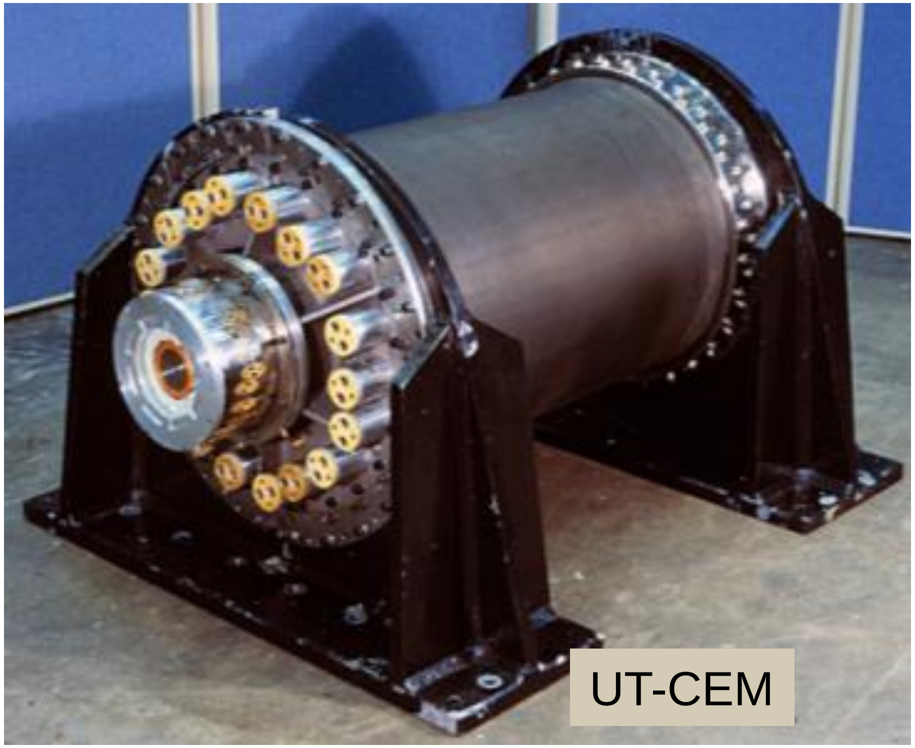
Partially Integrated Topology

- Transit Bus flywheel battery power system
- 7 MJ, 40 krpm flywheel
- 150 KW motor/generator
- Flywheel & Electrical section
  - On common shaft
  - Inside vacuum enclosure



Fully Integrated Topology

- US Army Subscale Focused Technology Program pulsed alternator
- 22 MJ, 12 krpm flywheel
- Wound field coil
- 2 GW peak delivered power
- Energy storage in power generation section



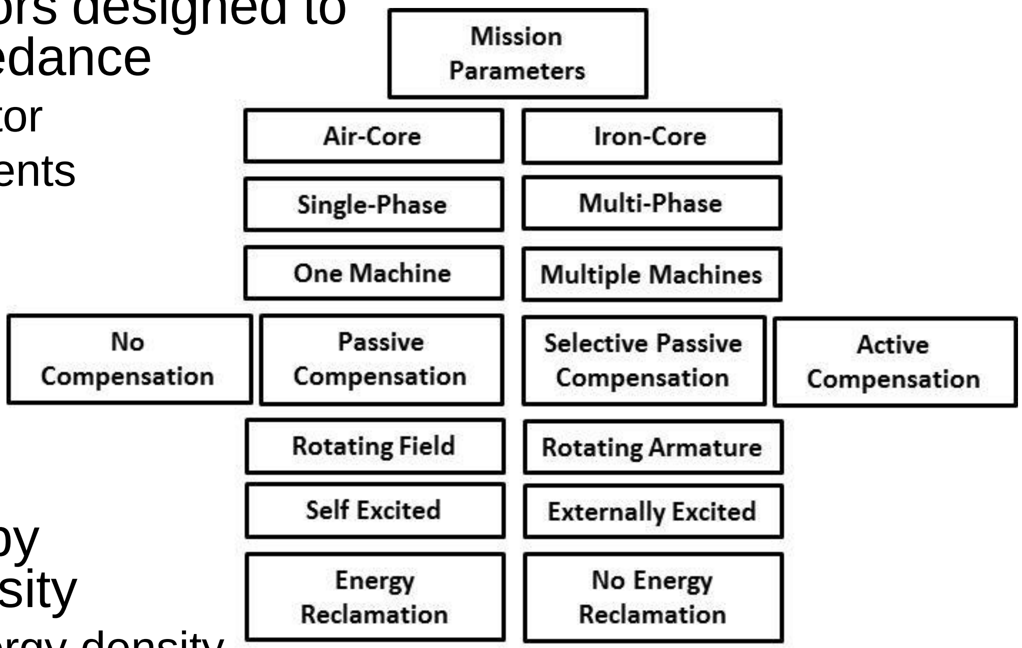
PULSED ALTERNATORS

Pulsed Alternators Are:

- A unique class of rotating electrical machines
- Specifically designed for driving transient loads
- A well-characterized and demonstrated technology
- “Conventional” electrical devices with “Non-conventional” challenges
  - Mechanical design
  - Thermal design
  - Assembly processes

Pulsed Alternator Options

- Compulsator ?– Compensated Pulsed Alternator
  - Not all pulsed alternators are compensated
- Specialized synchronous generators designed to minimize and control internal impedance
  - Inertial energy storage in spinning rotor
  - Capable of delivering MA output currents
- Range of machine topologies enable flexible designs tailored for specific application(s)
  - Mission, platform, load
- Design evolution primarily driven by need for higher power/energy density
  - Balance efficiency against power/energy density
  - Current SOA machines are self-excited, air core designs without explicit compensation

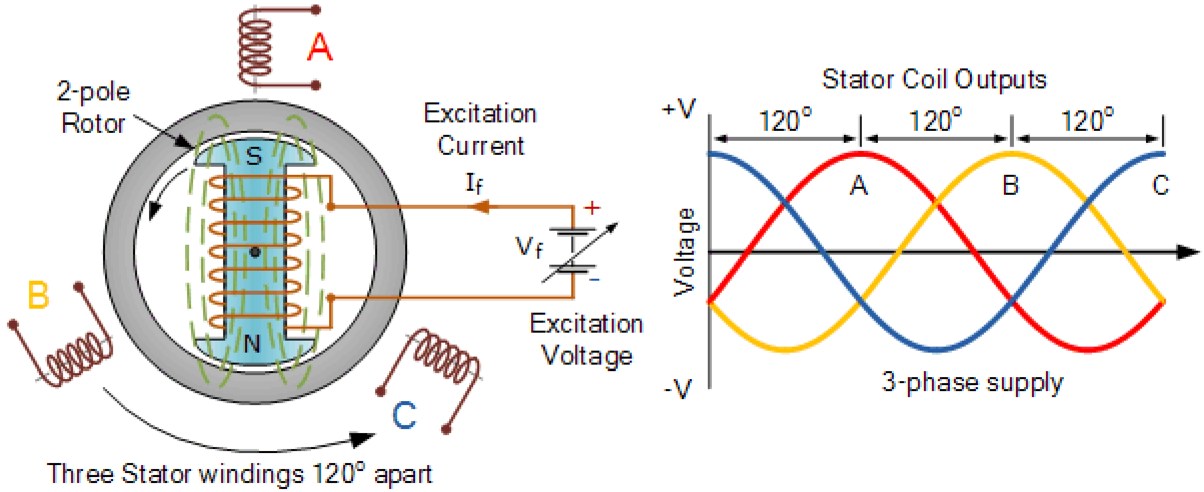


Armature Compensation

- Compensation: Methods used to control machine internal impedance
  - More critical for single phase, single-pulse machines
  - Determines output pulse characteristics
- Three basic approaches to compensation:
  - Active – compensation provided by a secondary armature winding in series with the primary winding. This provides a sharp “peaky” pulse
  - Passive – compensation provided by continuous conductive shield between the field and armature windings; impedance independent of rotor position providing roughly sinusoidal output pulse
  - Selective Passive – compensation provided by shorted compensating windings; varying impedance with rotor position provides pulse shaping

Compensation Increases Complexity and Technical Risk
Multi-phase Air-Core Machines do not Require Explicit Compensation

Synchronous Generator Operation

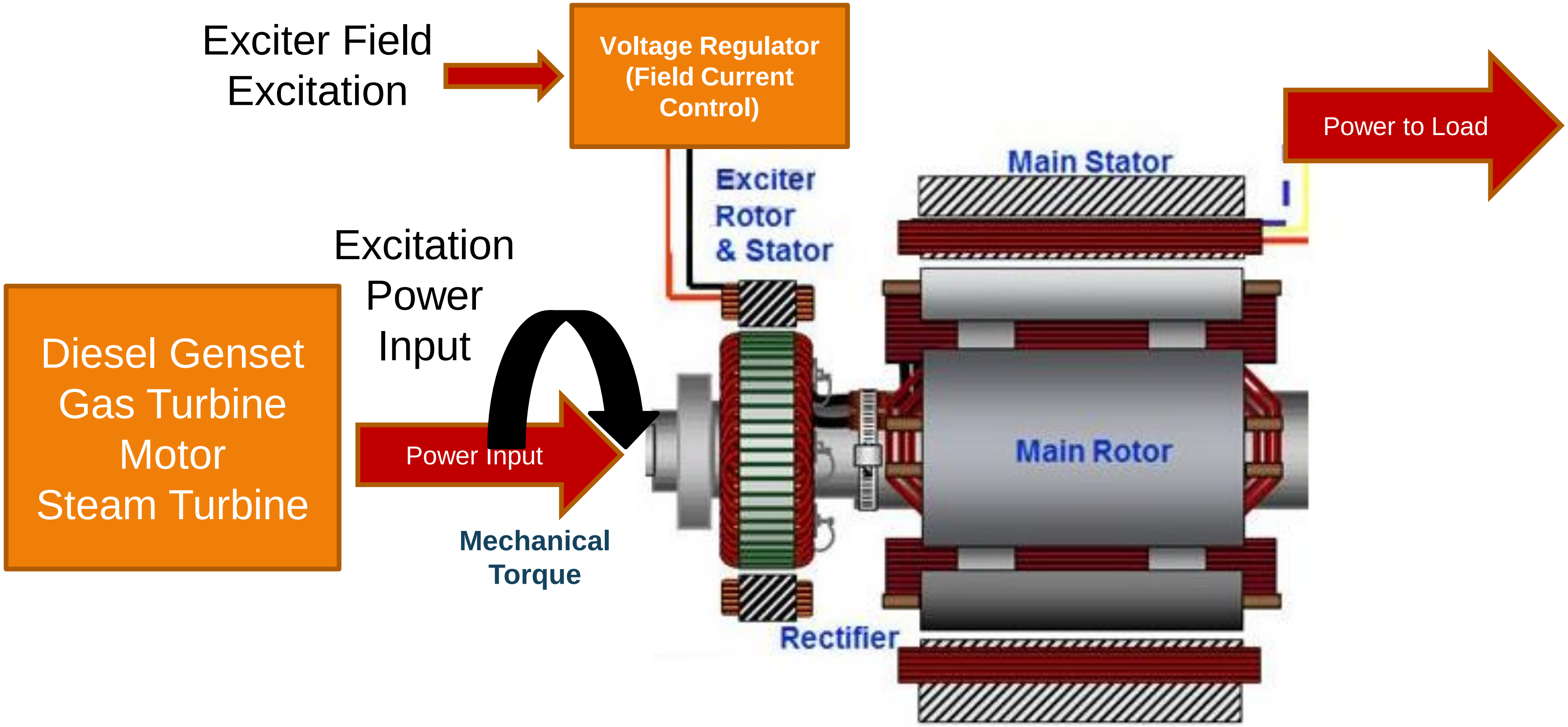


- Voltage induced in each stator winding by passage of the rotating magnetic field created by the field winding

$$P \propto A_s \times B \times L \times D^2 \times \omega$$

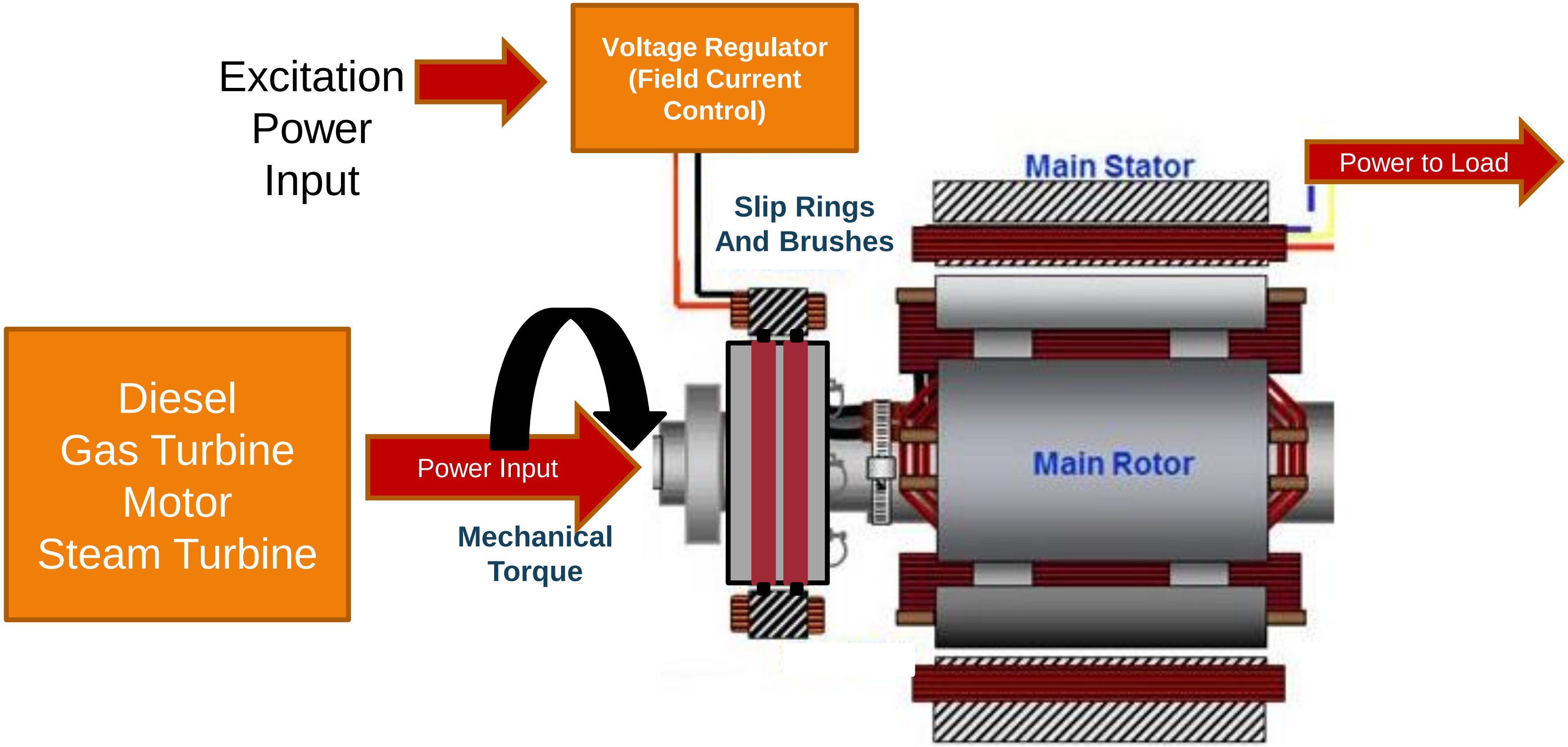
A_s – stator line current density
B – air gap flux density
L – length
D – diameter
ω – angular velocity

Brushless Synchronous Generator



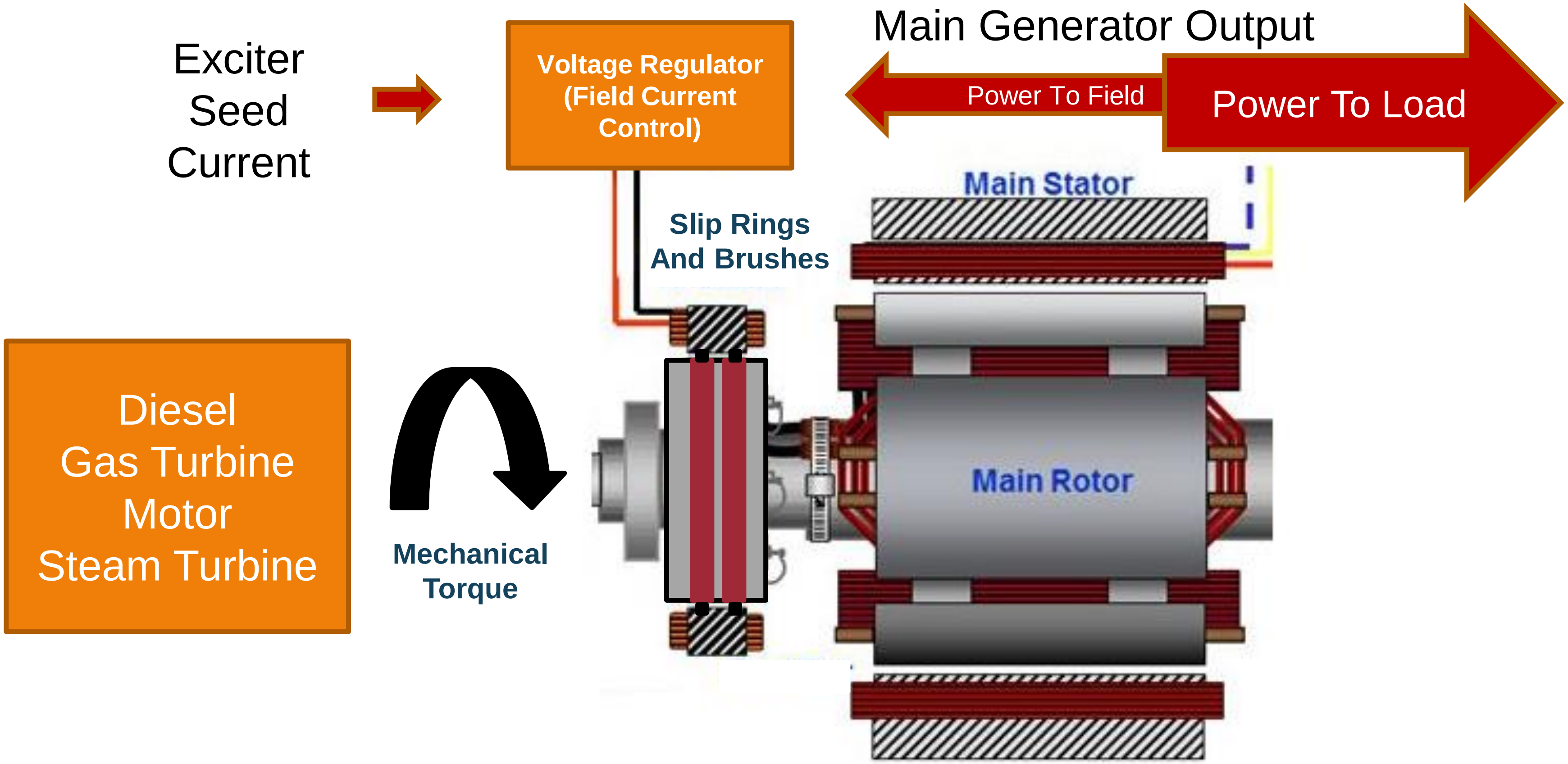
- DC field excitation provided by exciter and rotating rectifier
- Voltage regulator modulates exciter field current which in turn controls generator field current and thus the output voltage

Brushed Synchronous Generator



- DC field excitation provided from external source thru brushes and slip rings
- Voltage regulator modulates field current directly to control voltage

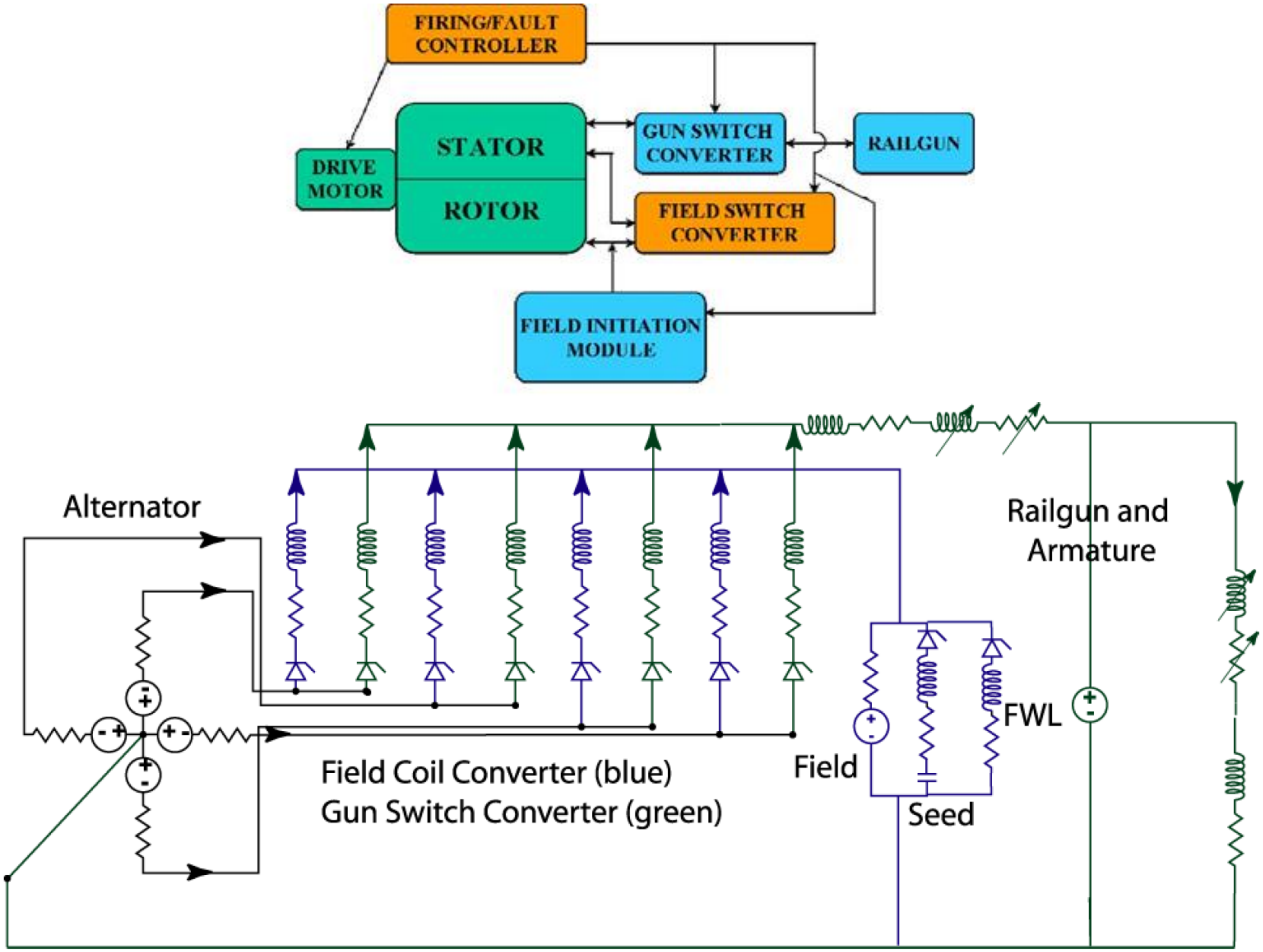
PA Self Excitation & Discharge



- Field excitation seeded by Field Initiation Circuit
- Generator ac output is rectified and fed directly back to field
  - Energy is extracted from rotor inertia at very high power levels
- Output switched to load when target field current is achieved

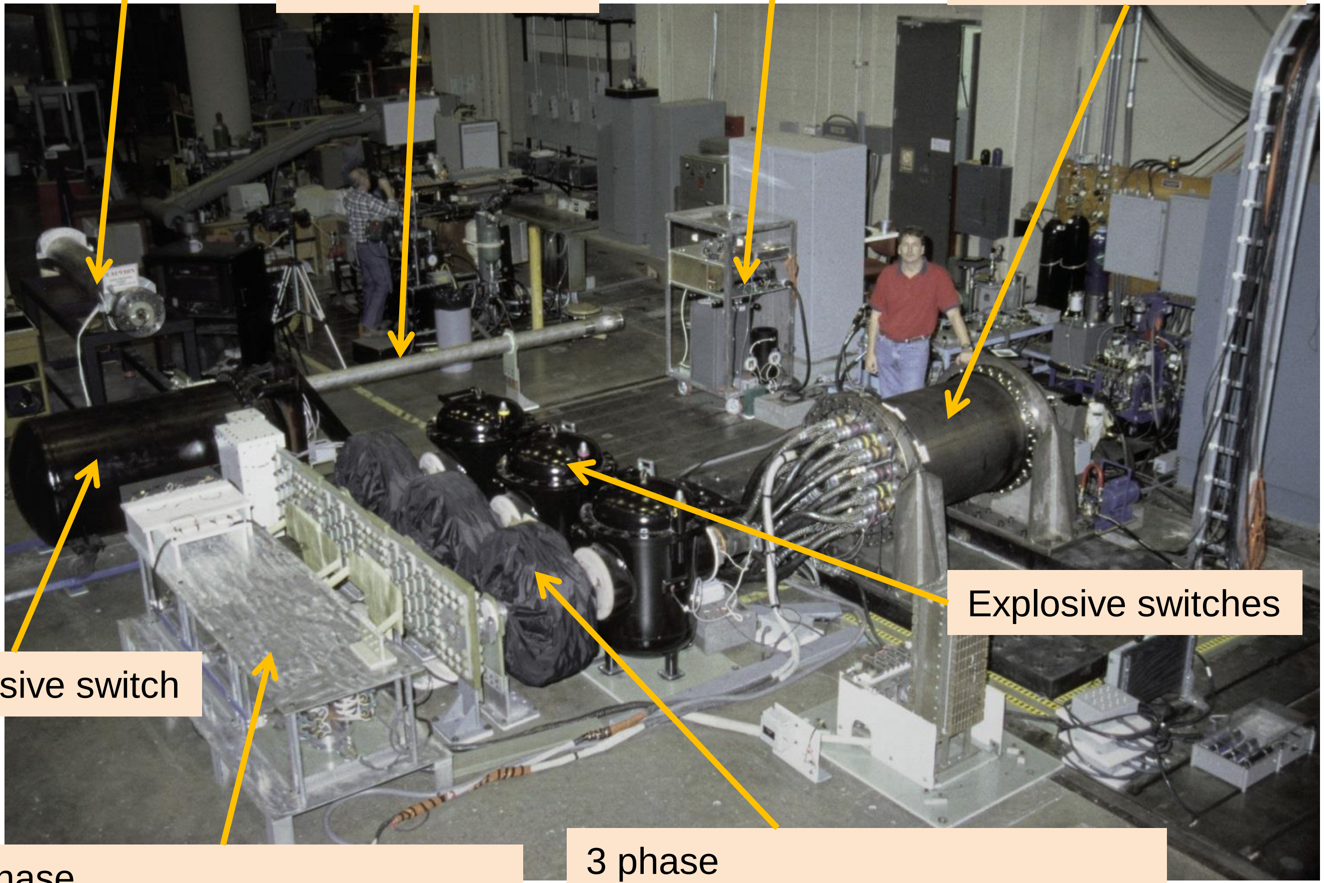
  Multiphase output is rectified to form output pulse to load

Pulsed Alternator System



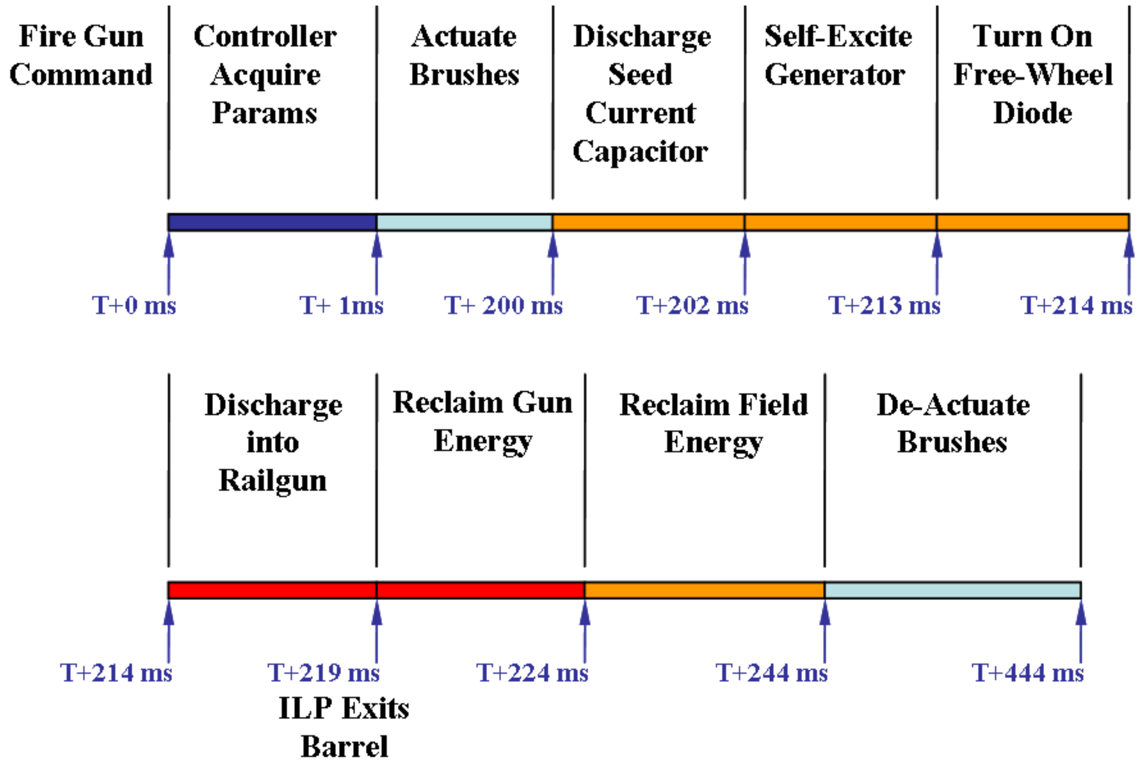
Hardware Example --Army Focused Technology System

- Self Excited
- Air Core
- 3 phase output
- Diode converters
- Explosives safety switching



Discharge Sequence & Timeline

- Initial Conditions:
  - Rotor at Speed
  - Field Initiation Capacitor Charged

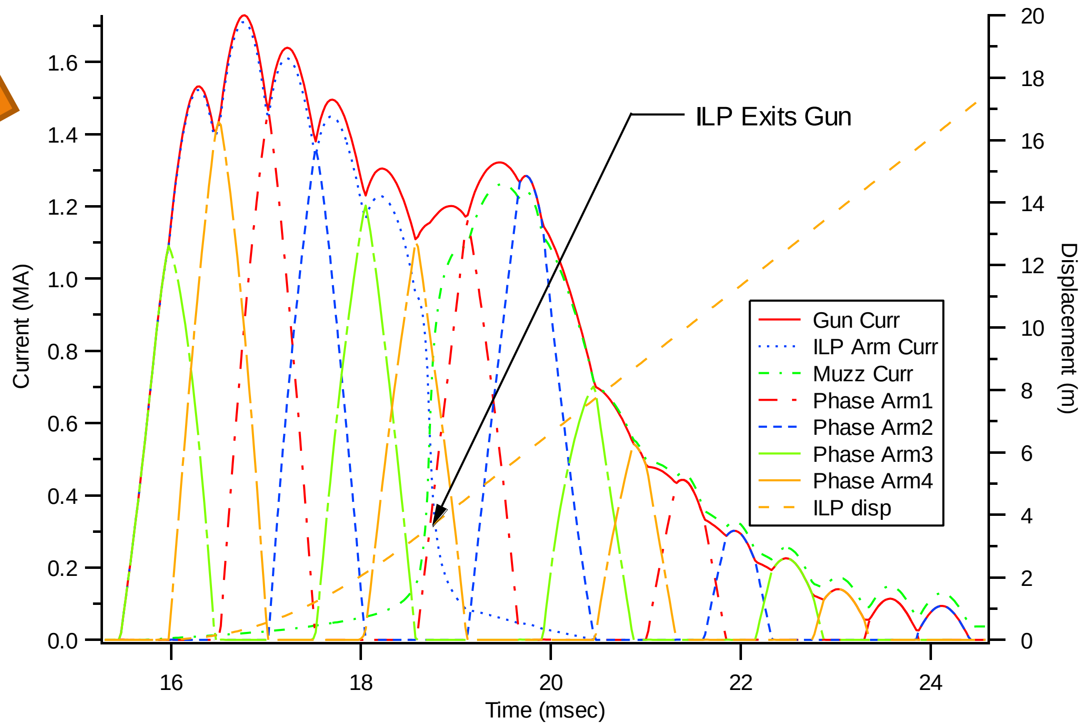


The electrical angle of the output is acquired with a cycle portion encoder and from here excitation of the generator and the discharge into to railgun along with energy reclamation is accomplished

Example PA Output

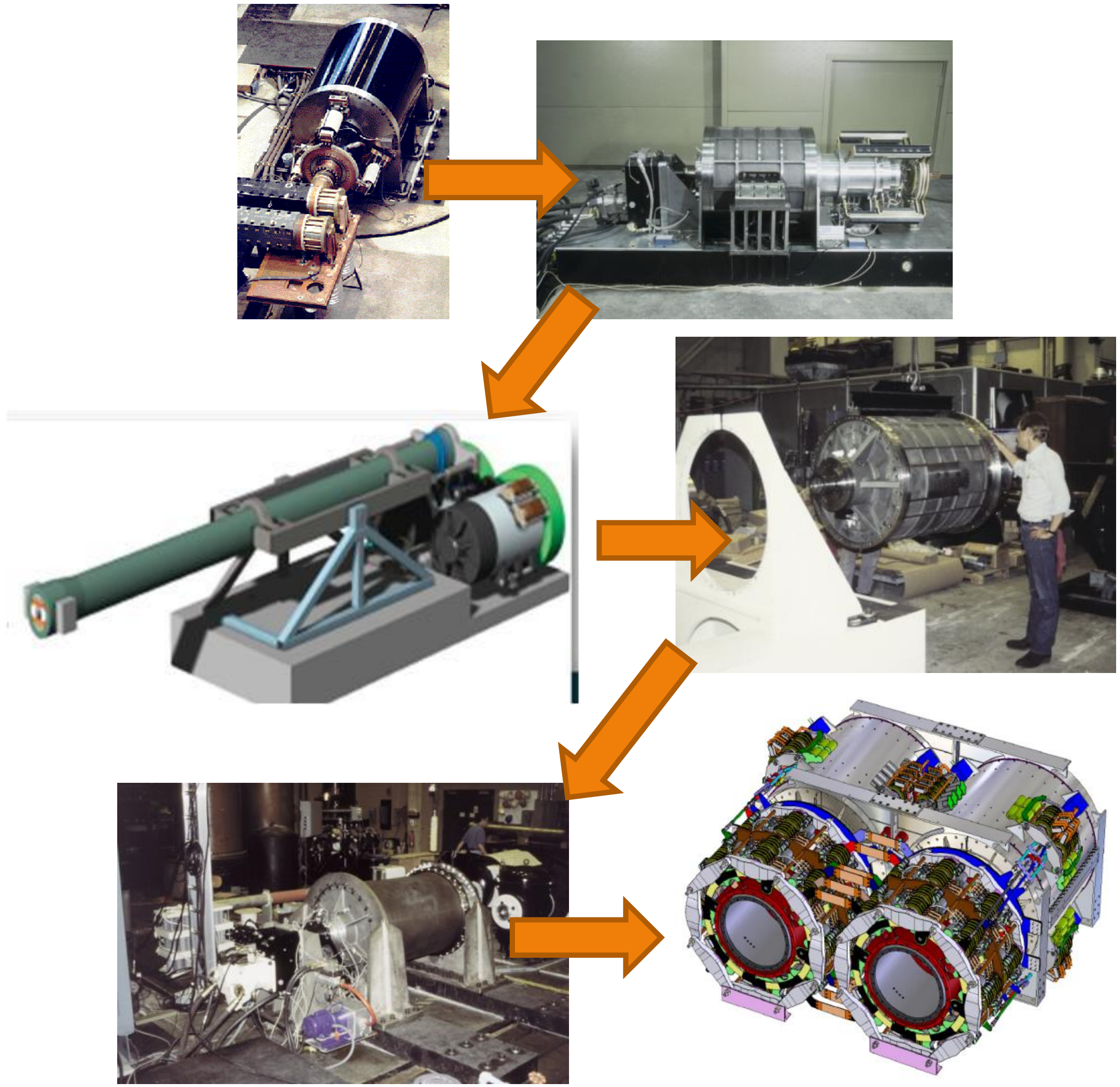
- 15,000 rpm discharge simulation
- 4 phase output
- 4 m launcher
- Pulses after exit are energy reclamation
- “Flatter” pulse shape is desired

- Higher frequency switching improves pulse shape
  - Faster machine speeds
  - Higher pole count
- “Phase shifting” multiple machine outputs smoothes pulse shape



Applying PA Technology to Real Hardware

- Six generations of pulsed alternator development history
- Each generation designed for specific system requirements
- Evolution of technology development
- Steady progression in energy and power density



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PA TECHNOLOGY DEVELOPMENT

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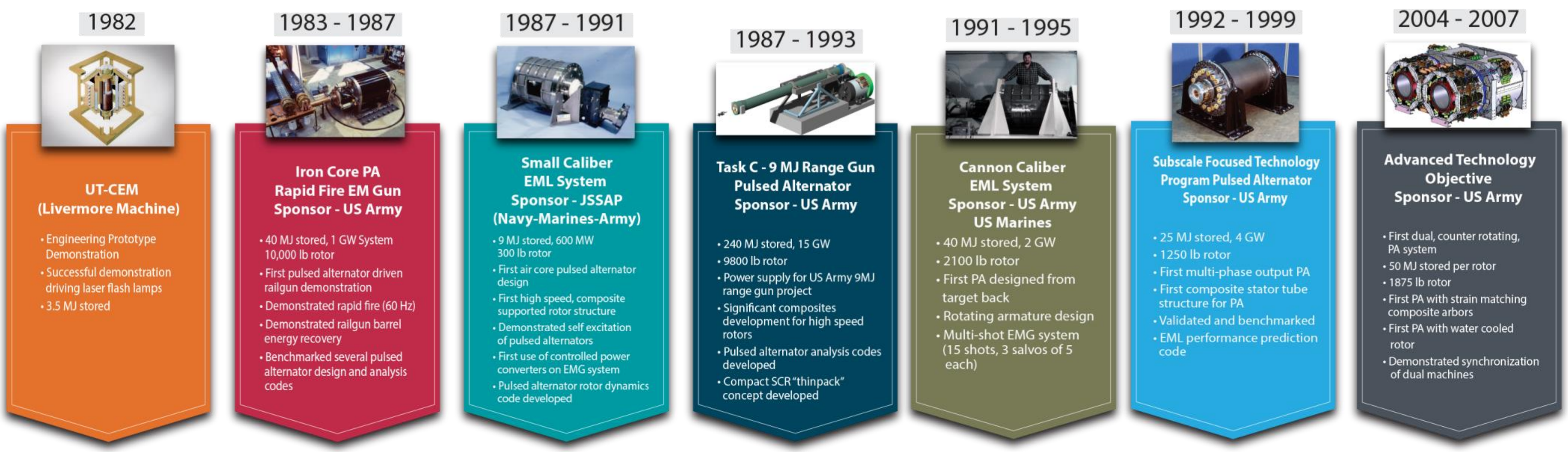
Pulsed Alternator Development at UT



Pulsed Alternator Research

- CEM invents CPA (1978)
- Livermore Machine Prototype
- Iron Core CPA
- Small Caliber EML System
- Subscale FTP PA System
- Army ATO PA System

Related Research:

- ESRDC (2003-present)
- EMALS generator demo (2003)
- EM Gun Soft Catch demo (2014)
- CHPS development spin test (2015)
- EM Gun Microgrid Integration (2016)

Iron Core CPA EML System

- Every contractor defined technical requirement was demonstrated
  - 40 MJ, 1 GW iron-core compulsator
- Demonstrated "firsts":
  - Fully operational multi shot system with auxiliaries
  - First demonstration rail gun energy recovery
  - First use of solid-state thyristor switch in PPS
- Benchmarked rail gun system and component design & analysis codes
- Developed resin-transfer VPI system (still in use today)

- **Fully demonstrated system performance**

- **Outcomes:**
  - Developed higher fidelity design and analysis tools that previously did not exist
  - Iron core too massive for tactical application and without adequate growth potential

Iron Core PA
Rapid Fire EM Gun
Sponsor - US Army

- 40 MJ stored, 1 GW System 10,000 lb rotor
- First pulsed alternator driven railgun demonstration
- Demonstrated rapid fire (60 Hz)
- Demonstrated railgun barrel energy recovery
- Benchmarked several pulsed alternator design and analysis codes

Small Caliber CPA EML System

- Order of magnitude increase in energy/power density
- Demonstrated “firsts”:
  - First self-excited air-core CPA
  - First demonstration of self-excitation in PPS
  - First demonstration of muzzle shunt with a passive muzzle switch to significantly reduce muzzle arc
  - First use of ceramic (rolling element) bearings and fluid dampeners in PPS
- Validated self-excited, air-core compulsator performance codes
- Demonstrated single shot predicted performance from 21,500 rpm
  - Complex non-conducting shaft led to rotor dynamics issue
  - Rotor vibration issues limited peak speed

- **Full electrical and shot energy performance was demonstrated**

- **Outcomes:**
  - Identified need for high fidelity rotor dynamic model.
  - Stationary two-pole field limits growth in energy and power density.

Small Caliber EML System
Sponsor - JSSAP (Navy-Marines-Army)

- 9 MJ stored, 600 MW 300 lb rotor
- First air core pulsed alternator design
- First high speed, composite supported rotor structure
- Demonstrated self excitation of pulsed alternators
- First use of controlled power converters on EMG system
- Pulsed alternator rotor dynamics code developed

Task C – CPA EML System

- First composite rotor structure developed
- Wet-wound rotor banding failed under pre-assembly hydraulic test
- **Outcomes:**
  - Foundation of advanced composites development
    - Led CAES and CEM to develop tow-wound, press fit rotors
    - Enabled tight control of manufacturing process and as-wound properties.
    - Led to development of ASTM standard test for determining composite material properties in hoop configuration
    - Enabled knowledge of strength capability and rotor stress state
  - TEMPST, AXIROTOR, TXROTOR codes developed
  - **These technology developments enabled successful demonstrations on subsequent programs:**
    - **CCEML, SSFTP, ATO**

Task C - 9 MJ Range Gun Pulsed Alternator
Sponsor - US Army

- 240 MJ stored, 15 GW
- 9800 lb rotor
- Power supply for US Army 9MJ range gun project
- Significant composites development for high speed rotors
- Pulsed alternator analysis codes developed
- Compact SCR "thinpack" concept developed

Cannon Caliber EML System

- Demonstrated "firsts":
  - First complete PPS fully optimized from the target back through the energy store
  - First controlled rectifier self-excitation (single armature winding)
  - 4-pole single phase air-core topology
  - Demonstrated barrel energy recovery
- Full-wave field excitation with custom-designed thyristors
- **Full electrical and shot energy performance was demonstrated**
- Outer banding was damaged during maching operation
  - 12,000 rpm design speed not achieved
- **Outcomes:**
  - Developed engineered tooling required to perform extreme banding assembly fits
  - Four pole topology eliminated challenges encountered in SCEML.

Cannon Caliber EML System
Sponsor - US Army
US Marines

- 40 MJ stored, 2 GW
- 2100 lb rotor
- First PA designed from target back
- Rotating armature design
- Multi-shot EMG system (15 shots, 3 salvos of 5 each)

Subscale FTP EML System

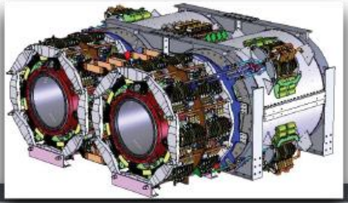
- Demonstrated "firsts":
  - First rotating field, multi-phase, air-core PA (no compensation)
  - First demonstration of field energy recovery
  - First composite stator and armature structure
  - First use of LSS thyristor device technology developed for EML application
  - Development of very high-speed, high accuracy encoder for measuring rotor position
- Originally conceived as a rotor spin test, after the start of manufacturing two requirements were added:
  - Operation of machine electrically
  - Very accurate a-priori performance prediction
- Rotor field winding insulation failure prompted rotor redesign.
- **Met every program goal and objective including matching a-priori predicted performance simulations**
- **Outcomes:**
  - Led to improvements in high strain-capable insulation systems
  - Led to designing all composite rotor rim structure on ATO program.
    - SSFTP rotor titanium shell and end bells limited efficiency and power and energy density.

Subscale Focused Technology Program Pulsed Alternator Sponsor - US Army

- 25 MJ stored, 4 GW
- 1250 lb rotor
- First multi-phase output PA
- First composite stator tube structure for PA
- Validated and benchmarked EML performance prediction code

Army ATO EML System

- Design features:
  - Highest power and energy density PA rotor
  - Dual, counter-rotating PA system
  - All-composite rotor rim structure supported by six composite arbors
  - Compliant high-performance power and cooling connections
- Beginning of technology transfer to industry
  - CEM responsible for preliminary electrical design of PPS and rotor fabrication
  - CW prime contractor, responsible for balance of system
- **New technology demonstrated**
  - Composite growth matching arbors validated via spin test
    - 333 deep cycles to operating speed and 30% overspeed
    - Multi-arbor stability while supporting hardware for power and cooling connections
  - Major material and subcomponent validations
    - Elevated temperature composite banding performance
    - Large scale field winding VARTM process
    - Assembly and pressure test of heat exchanger structure
    - Inner strain matching banding approach



Advanced Technology Objective
Sponsor - US Army

- First dual, counter rotating, PA system
- 50 MJ stored per rotor
- 1875 lb rotor
- First PA with strain matching composite arbors
- First PA with water cooled rotor
- Demonstrated synchronization of dual machines

Technology Development Summary

- Major technical accomplishments across six generations of rotating machine based PPS system research
- Each system demonstrated significant leaps in power and energy density
- Design and simulation models benchmarked across several generations of demonstrated PPS
- Suite of design tools to develop and analyze PA conceptual designs
  - Electromagnetic Analysis: finite filament analysis used to calculate internal inductances and mutual coupling parameters to support circuit simulation models
  - Structural Analysis: calculates composite material stresses and strains
  - Energy Balance: calculates distribution of system losses to support thermal analysis and circuit simulations
  - Visualization: generates export file for solid model of machine based on user selected topology
- Led to improvements in high strain-capable insulation systems
- Foundation of advanced composites development
- **Technology development implies there will be lessons learned and requires willingness to tackle challenging problems with vision, creativity and technical expertise.**

- **Significant expertise, design tools, and material component validations ready to be leveraged for future Navy PPS.**

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CRITICAL TECHNOLOGIES

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Critical Technologies

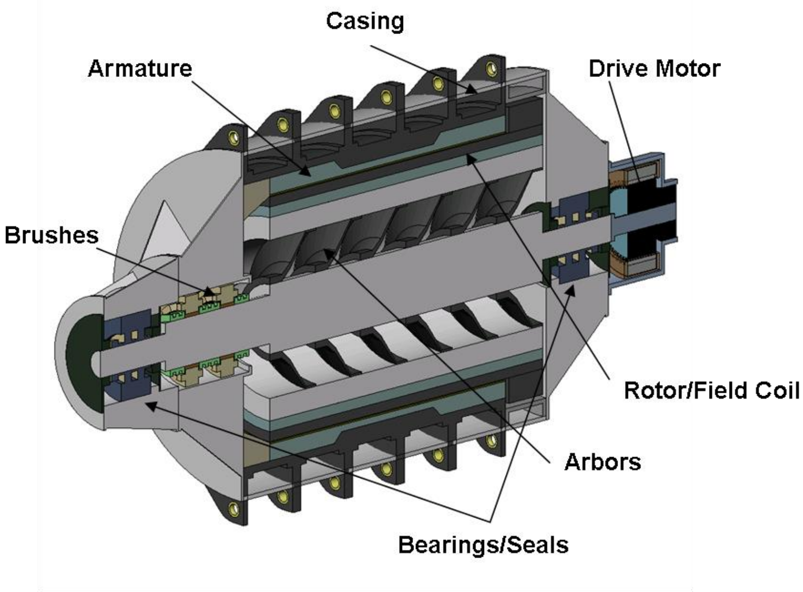
- Alternators are well-understood rotating electrical machines.
- The *Pulsed* Alternator is a special class of alternator designed for high power and energy density.
- To achieve the highest power and energy densities, the PA must be optimized in several ways.
- This requires specialized capabilities and knowledge including:
  - Refined performance simulations and modelling capabilities
  - High-fidelity thermal models and active cooling
  - Advanced switching and controls experience
  - Unique manufacturing and assembly expertise
  - High performance composite design and manufacture

Simulation and Modelling Tools

- A general design code has been developed for the PA system
  - Combines previous simple EM design modeling of linear air-core pulsed alternators with practical mechanical design experience in SOA rotating machinery.
  - Benchmarked against several generations of demonstrated systems.
  - Set-up to optimize in a range of tip speeds (shortest rotor, highest tip speed, highest short circuit current capability).
- Requires advanced EM knowledge and specific experience in the field of advanced pulsed alternator design to create the input file.
- Selected inputs to the code:
  - Muzzle energy and velocity of the ILP
  - Gun acceleration length, L', R'
  - Number of shots stored inertially and thermally in the rotor and stator
- Experience based embedded parameters
  - Current density in the field winding and the peak DC current.
  - The average magnetic flux density at the armature.
  - The allowable hoop stress of the rotor banding material.
  - Armature winding active length to diameter ratio is set in a dynamically stable range.
  - Flywheel tip speed

Simulation and Modelling Tools

- An output is a 3-D model of the alternator.
- Detailed 3-D modeling of windings is performed and passed to 3-D finite filament code to produce impedance matrix for simulation
- Bearings and seals are commercial items and TXROTOR sizes damper
- The casing design uses TEMPEST to size containment
- Drive motors are designed in Maxwell 3-D to meet recharge requirements
- Polar moment of inertia of arbors is calculated at this point detail design follows
- Brush design comes from multi-generations of pulse discharged rotating machines



PULSED POWER SWITCHING

Pulsed Power Converters

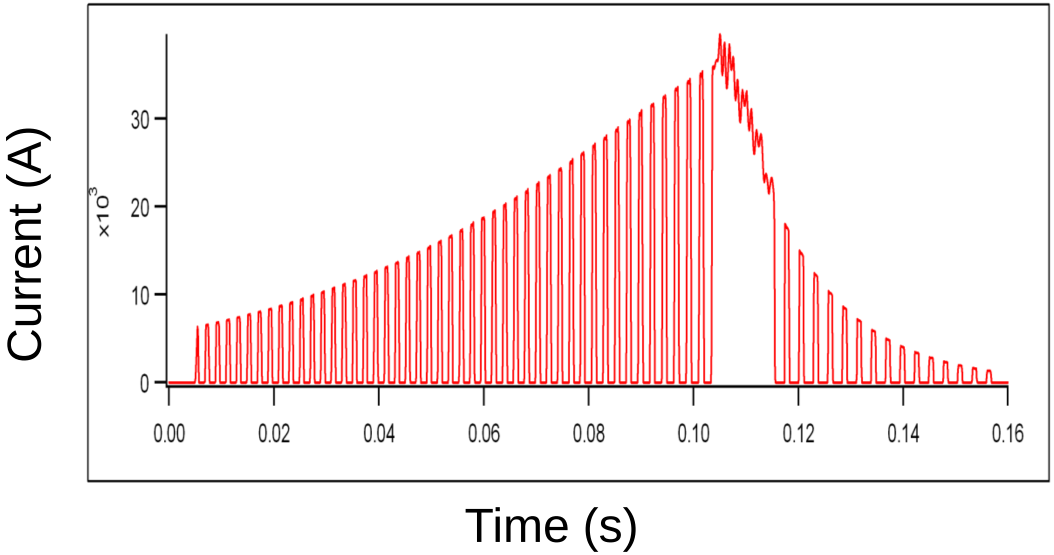
- **Generations of converter and controls experience for pulsed power systems.**
- **CEM characterized prototype switch devices on the Army program.**
  - Conducted thousands of device tests on switch development capacitor bank
    - Individual device characterization
    - Series stack voltage sharing tests
    - Module current sharing tests
    - Module checkout tests
    - Trigger circuit development and demonstration
  - SSFTP pulsed alternator used to demonstrate prototype SCRs and field energy recovery.
- **Recently worked with ARL to develop electrical and thermal model to help optimize switch device packaging.**

Electrical Requirements

	Worst Case Stress	Device Rating	Required Devices	Units
$\int i^2 dt$	26	15	2	MA^2s
I_{pk}	40	-	1	kA
di/dt	279	3000	1	A/μs
V	6.89	5	3	V

Converter Leg Configuration

2 parallel by 3 series



Device Stress	Units	Factor of Safety
6.5	MA^2s	2.3
20	kA	-
139.5	A/μs	21.5
2.3	V	2.2

125 mm SCR Test Results

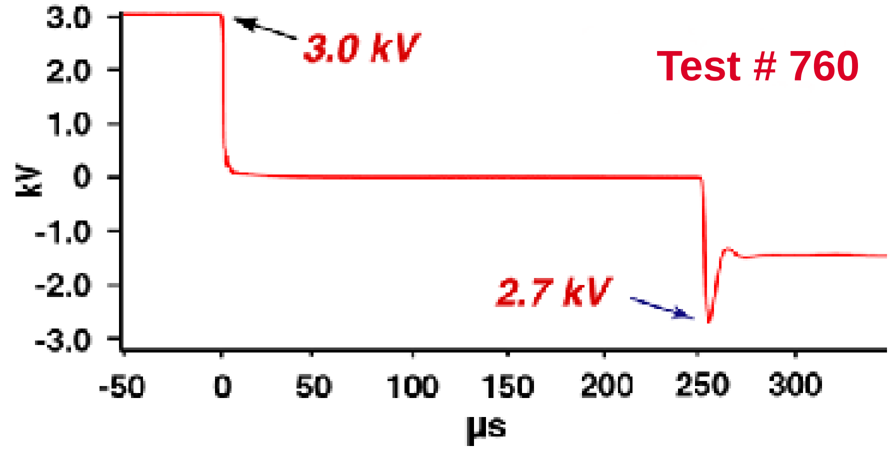
Device Performance Data

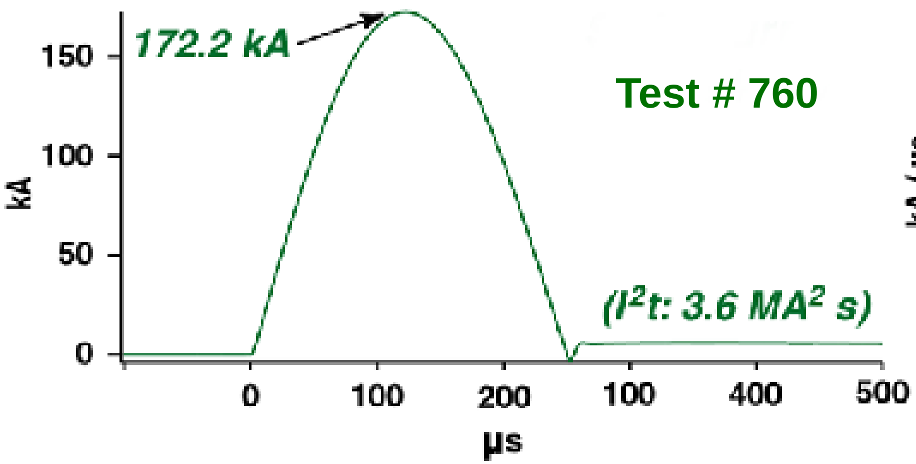
I_{pk} = 172.2 kA   Test # 760

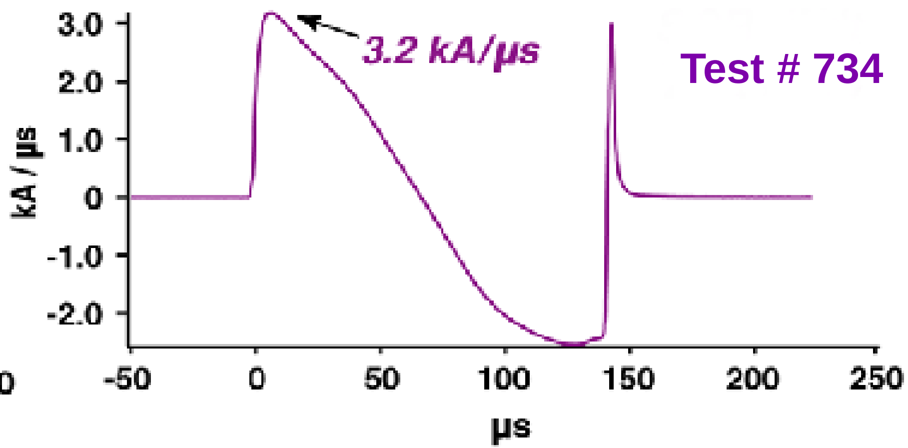
$I^2 t$ = 3.6 MA^2s Test # 760

Di/dt_{on} = 3.2 kA/µs   Test # 734

$V_{forward}$ = 3.0 kV   Test # 760

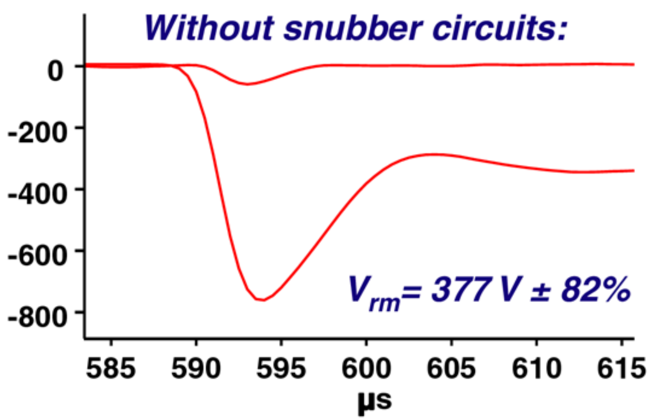


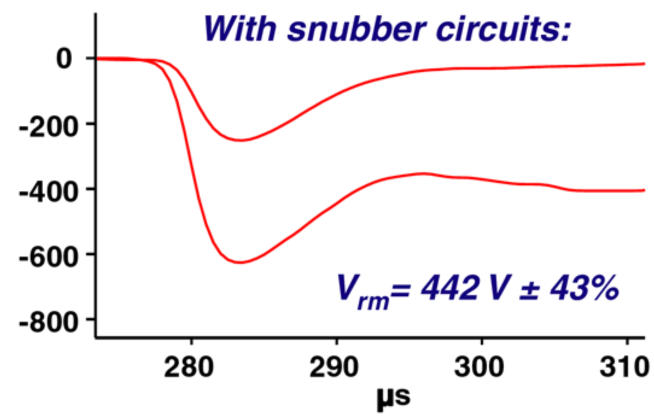




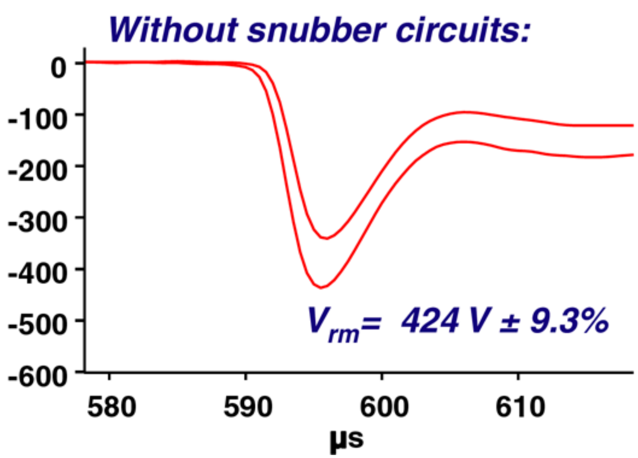
Voltage Sharing Tests

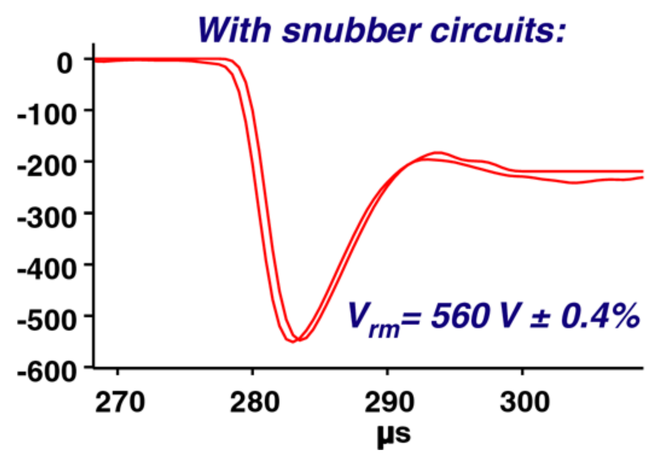
Poorly Matched Devices (I_{rm} ± 11%)



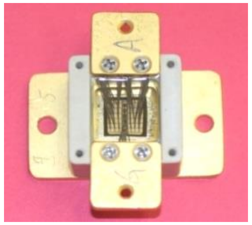


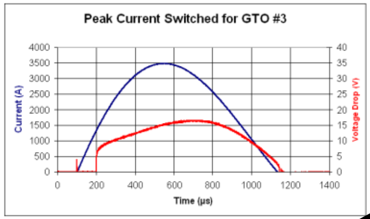
Well Matched Devices (I_{rm} ± 0.6%)



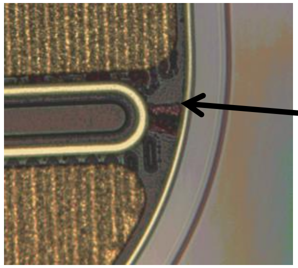


SiC SGTO Failure Investigation





ARL SGTO Pulse Test Results

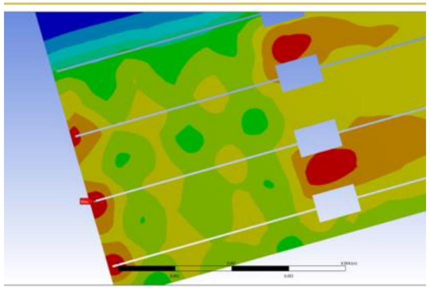


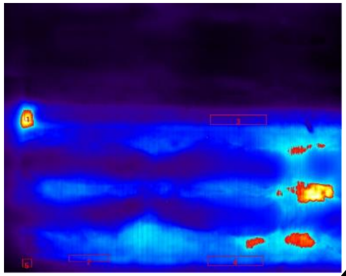
Polyimide Damage

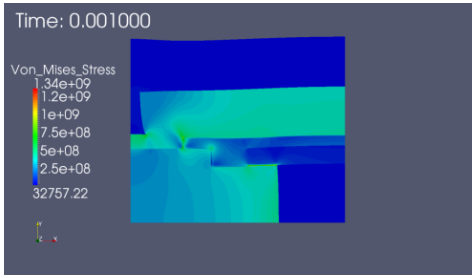
ANSYS Conduction Current Coupled Simulations

Thermal Imaging Experiments

EMAP3D Semiconductor Physics Simulations



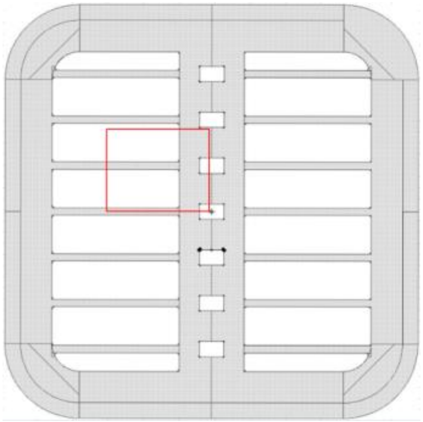




SiC Device Design Improvements

SiC Thermal Imaging Test

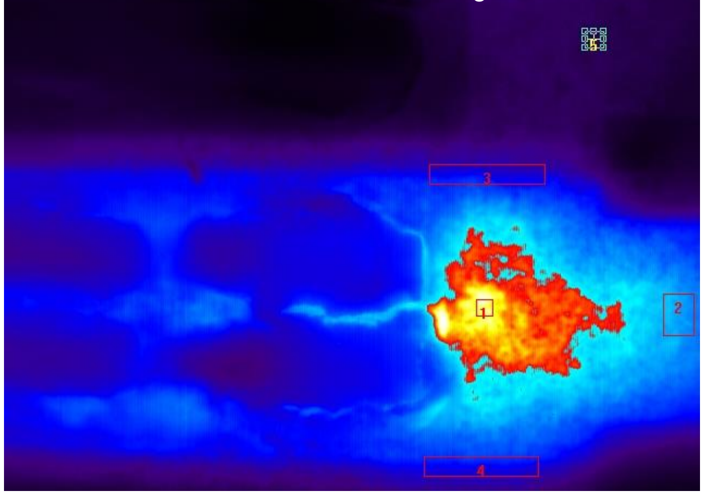
Pulse test SiC wire-bond devices and use high speed thermal imaging to determine hot spots due to current concentration.



ROI	Temp (°C)	ΔT (°C)
1	97.8	74.8
2	73.8	50.5
3	50.7	27.9
4	53.1	30.2
5	34.1	10.9

Pulsed Device Tester

X8Y6 Thermal Data: t_0 + 862 μs



HIGH-PERFORMANCE COMPOSITES

Composites for Rotating Machines

Composites can operate at higher strengths and strains than conventional metallic materials.

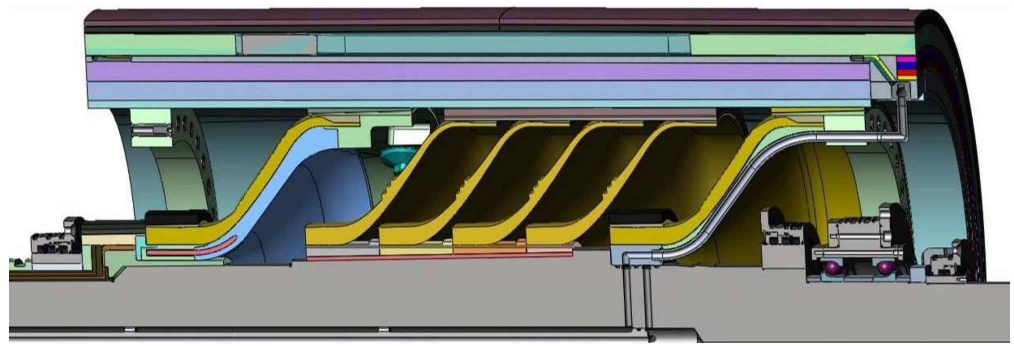
For advanced rotating machines, composite components:

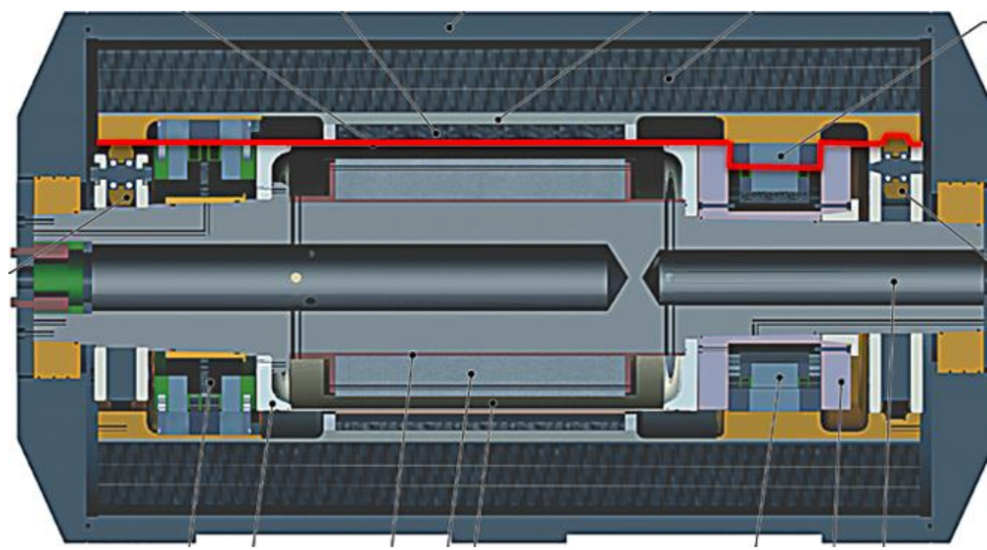
- Enable **higher (tip) speed operation**,
  - Increases the amount of energy that can be stored in the rotor
  - Increases power density of electric machines
- **Maintain radial compression** at all component interfaces,
  - Required for stable mechanical operation
- Ensure other rotor components do not fail (or yield) during operation

Different machines types

- Flywheels

- Electrical machines





Design considerations

- **Ultimate strength**
  - High strength is often required for retention (outermost) bandings.
    - In many electrical machines, must be thin because they reside in magnetic air gap.
    - Unlike other components, outer bandings are not biased in compression at rest.
- **Hoop modulus**
  - High hoop modulus can lower deflection in the operating speed range.
  - Intermediate modulus materials often have higher strain capability.
  - *Often the highest modulus composites do not have the highest strength.*
- **Peak service temperature**
  - Composite components subject to heat loads
    - **Resistive or eddy current losses** in electrical machines.
    - **Windage heating** (in flywheels & electrical machines) is caused by friction when there is relative motion between the rotor and air gap (even when operating in partial vacuum).
  - Composites typically have **lower thermal conductivity** than conventional metallic materials.
  - Higher temperatures can accelerate viscoelastic response

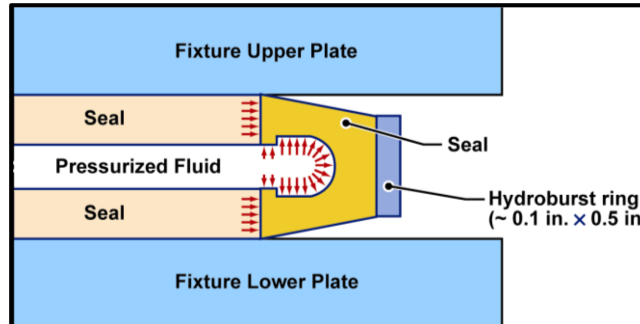
Quality Control & Material Characterization

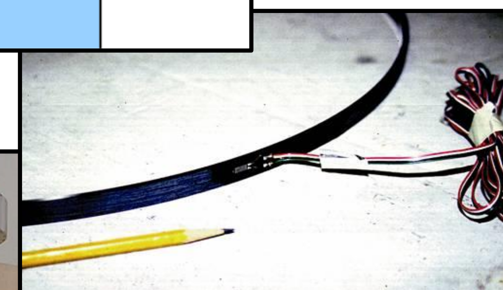
High performance rotating machines demand:

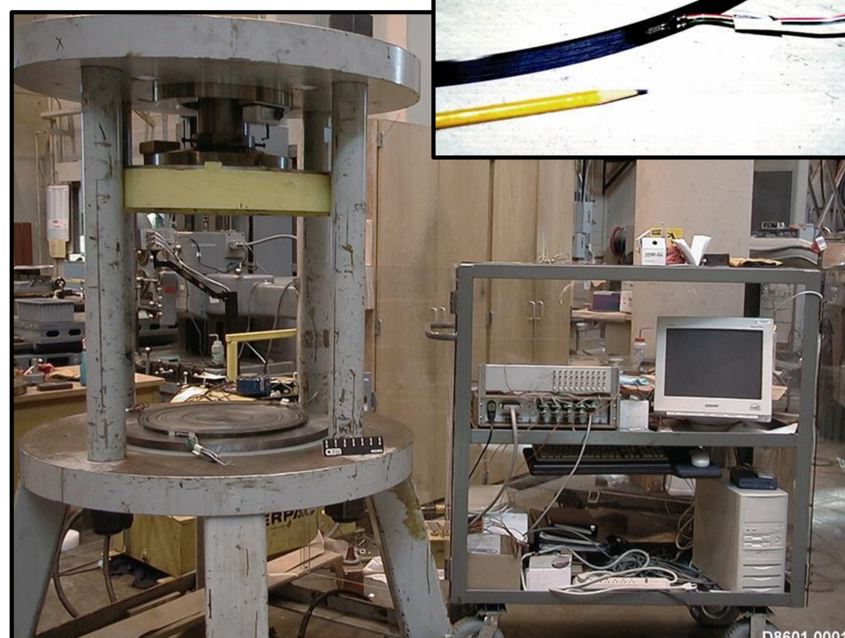
- High-fidelity analytical tools
- Well-characterized materials
- Refined manufacturing and assembly processes

CEM developed now standard hydroburst test for:

- Quality control
- Assessing material lot variability
- Tensile strength, modulus
- Fatigue properties (elevated temp.)
- Establish Factor of Safety





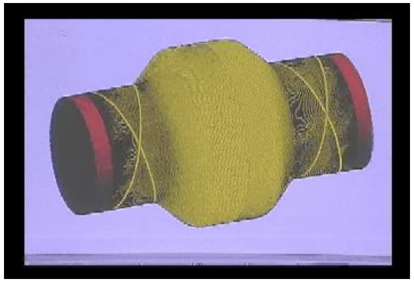


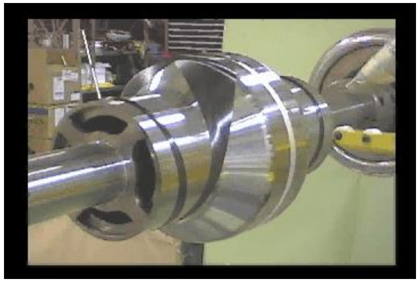
Composite Arbors

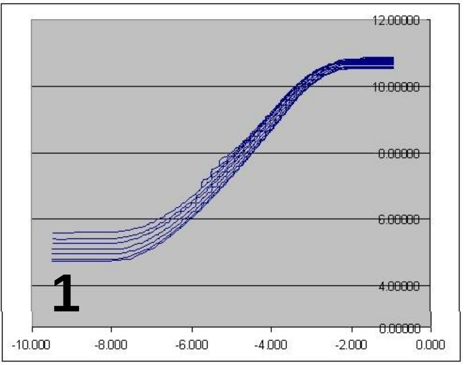
- **Arbors improve power and energy density by focusing rotor weight at the outer rim where it is most effective.**
- Provide structural attachment of rotor rim to rotor shaft
- Match rotor rim’s radial growth due to spin loads
- Transmit discharge torque
- Provide lateral stiffness for stable mechanical operation
- Can support additional mechanical hardware for connection of power and cooling circuits to the rotor rim.
- **Several arbor designs successfully validated in spin test**

Design and Analysis Methodology

1. **Define candidate design**
    - Mandrel shape, wind angles, layer thicknesses
    - CEMWIND performs fabrication checks (friction, bridging)
    - Creates input file finite element model & winding machine
2. **Finite Element analysis**
    - Radial growth, stresses at rest and design speed
    - Stiffness calculated for rotordynamics model
3. **Post-processing of finite element results**
    - Strain and stress translated to fiber principal directions
4. **Rotordynamic analysis**
    - Stiffness values used to determine critical speeds



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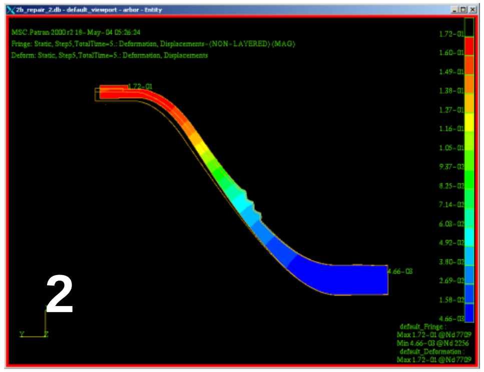
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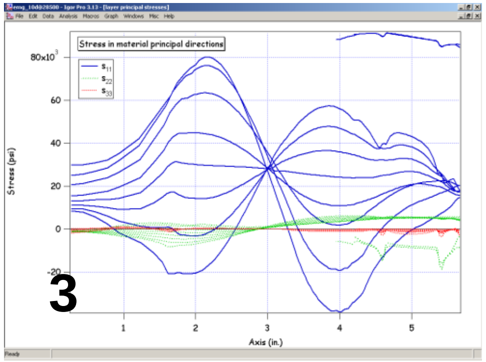
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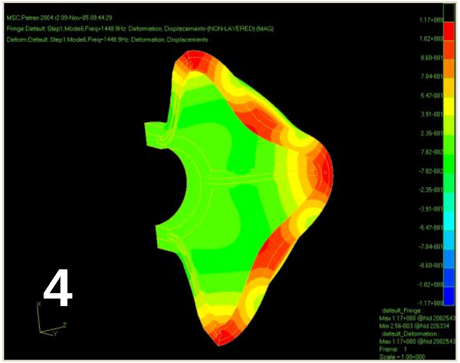
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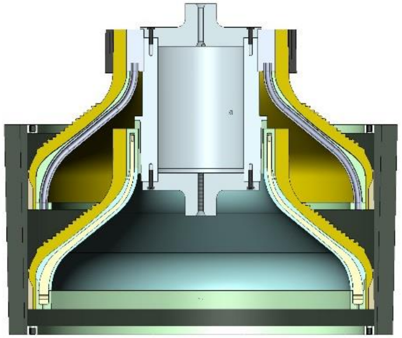
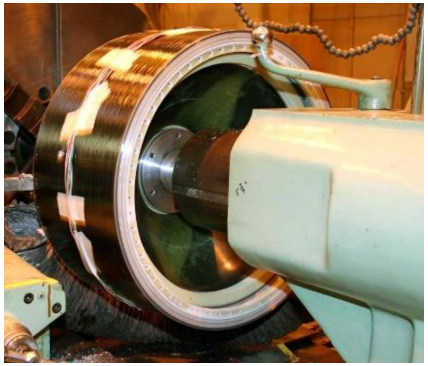
Composite Characterization & Validation

- Structural tests (rap, deflection)
- Spin tests
  - Validate analysis tools, mechanical performance, and can demonstrate how composite components fail.
  - NASA Arbor Development (2003)
    - Demonstrated 50,000 rpm (1100 m/s)
    - Overspeed test (1340 m/s) demonstrated 1.5 FoS
    - Matched analysis predictions,
    - Well behaved, stable operation
  - DARPA Flywheel Program (2002)
    - Over 112,000 fatigue cycles completed
    - Flywheel speed excursions from 27 to 36 krpm
    - Peak tip speed 825 m/s
    - Operating temperature of 140 F
    - No structural degradation
  - Army ATO Program (2004-2006)
    - Structural arbor tests: 1000 cycles (7.5k - 15k rpm)
    - Multi-Arbor Spin Test: 333 cycles (2k - 12k rpm)
    - Matched analysis predictions,
    - Well behaved, stable operation





Summary

- Prior programs made significant investment in several critical technology areas
  - Refined performance simulations and modelling capabilities
  - Advanced switching and controls for pulsed power systems
  - High performance composite design and manufacture
- Specialized engineering knowledge exists including:
  - High-fidelity thermal modelling
  - Active cooling solutions
  - Unique manufacturing and assembly expertise for high-performance composite structures

- Large potential payoff of recent and near-term technology advances in a Navy system.

SHIP INTEGRATION

Angelo Gattozzi

Ship Integration of Large Pulsed Mission Systems

- Previous presentations have discussed the characteristics, and potential benefits of Pulsed Alternators. They should be evaluated as a possible option along with other technologies.

- Therefore, large pulsed mission systems can be supported by:
  - Batteries
  - Capacitors
  - Flywheels
  - Pulsed Alternators

- In all cases, the technology of choice needs to be integrated with the ship power system. This will be discussed next summarizing the results of three studies done for the US Navy by the Center for Electromechanics of The University of Texas.

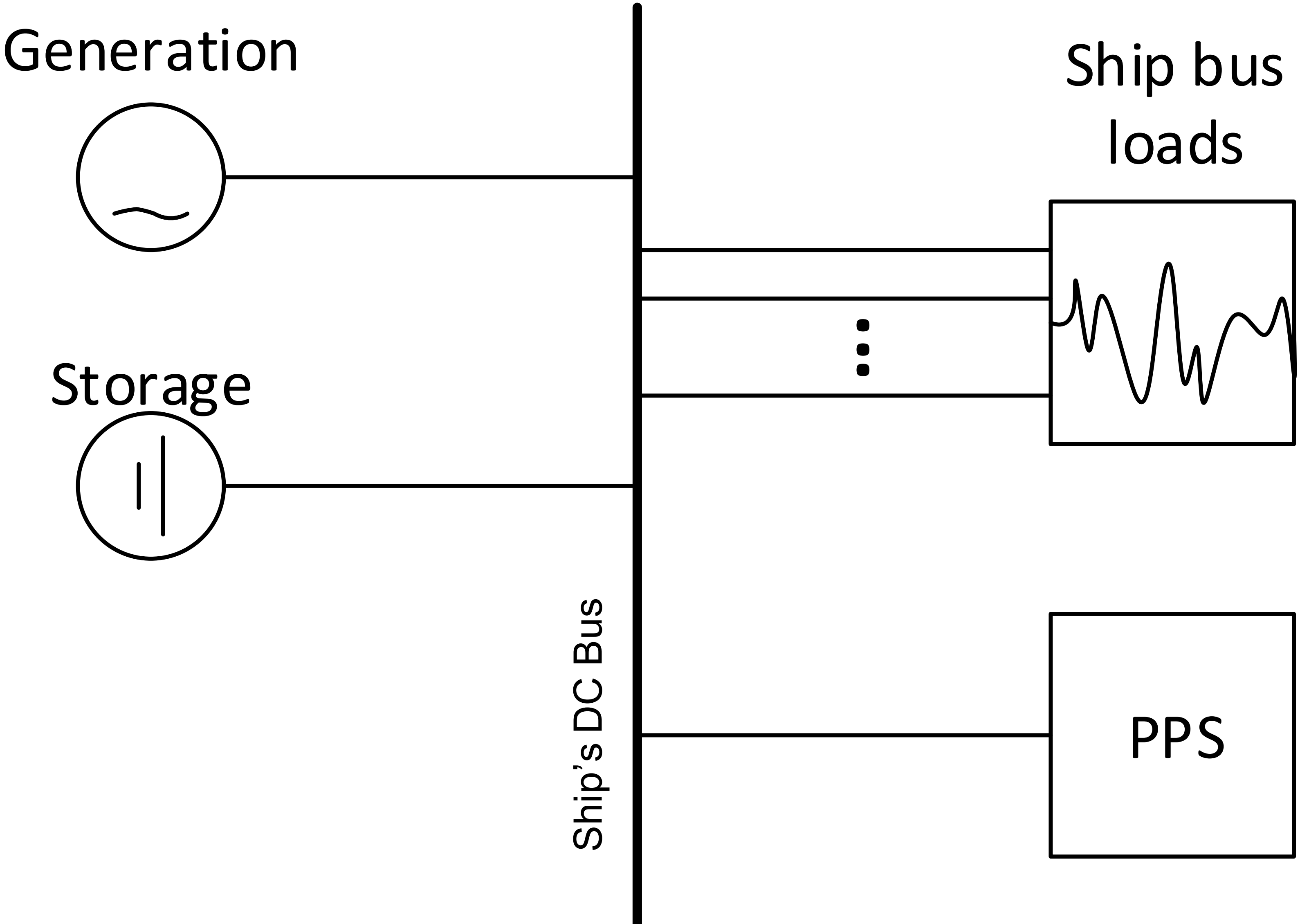
Storage Design Example 1: Generalized Energy Magazine Concept

- System-level comprehensive evaluation of energy storage and power conversion systems for a notional Energy Magazine (EM).

- Its simulation results apply equally well to systems using a broad variety of generators, pulsed power loads, or ship bus loads, provided they can be represented by an equivalent mathematical model.

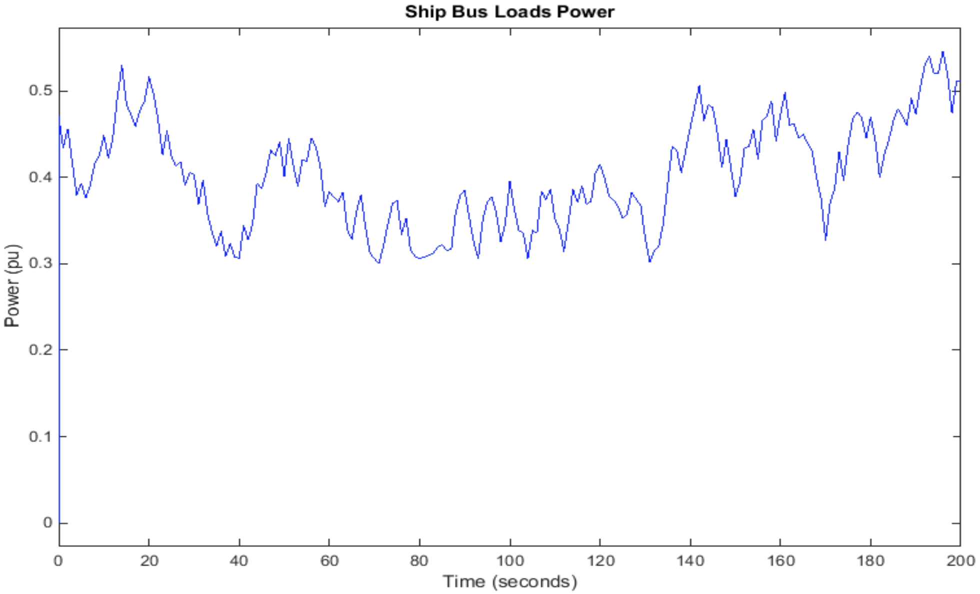
- This rather general approach, allows the definition of the performance attributes of an EM system and an estimate of its benefits independent of the specific technology adopted for its realization.
  - Best solution may be a combination of different technologies

Basic Reference System Used



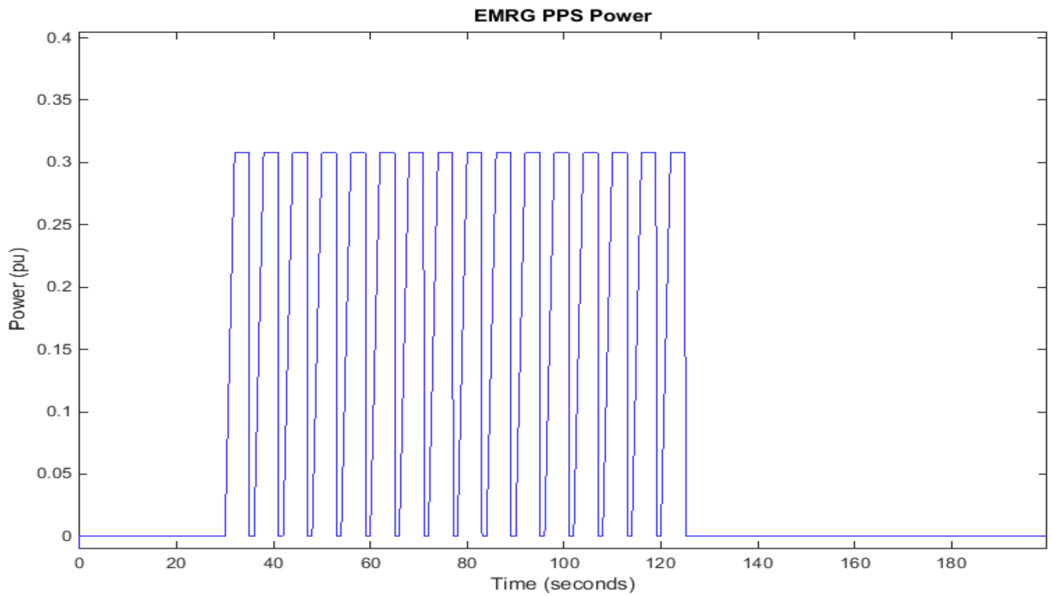
Assumed Ship Bus Load Characteristics

- **Ship Bus Loads**. Aggregated load to represent power requirements for all loads other than PPS. Stochastic nature as bounded random walk:
  - step amplitude changes – Less than 0.6 pu and greater than 0.3 pu
  - number of points – 200 (1 point per second for a 200 second simulation)
  - maximum change point-to-point – 0.5 pu
  - start to finish change – 0.3 pu.

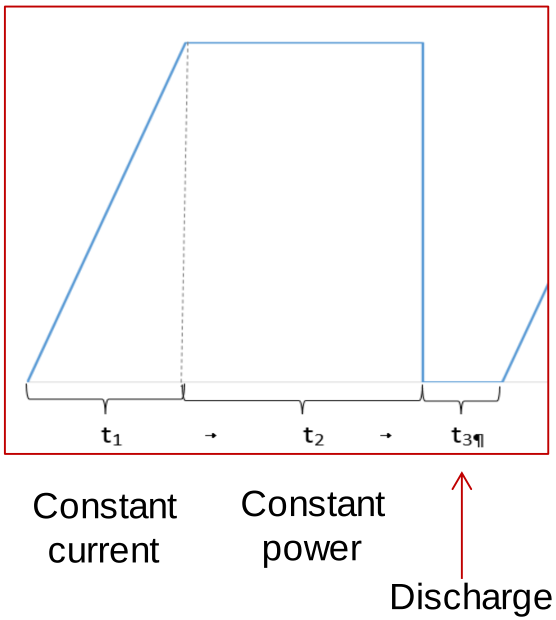


Assumed PPS Load Characteristics

- **PPS load.** Modeled as follows:
  - Number and rate of charge/discharge cycles - 16 times at a rate of 10 per minute
  - Peak power – 0.3 pu
  - Starting time – between 10 s and 30 s
  - Duration of initial power ramp up in constant current mode – 2 s
  - Duration of completion of charging in constant power mode – 3 s
  - Duration of discharge time – 1 s



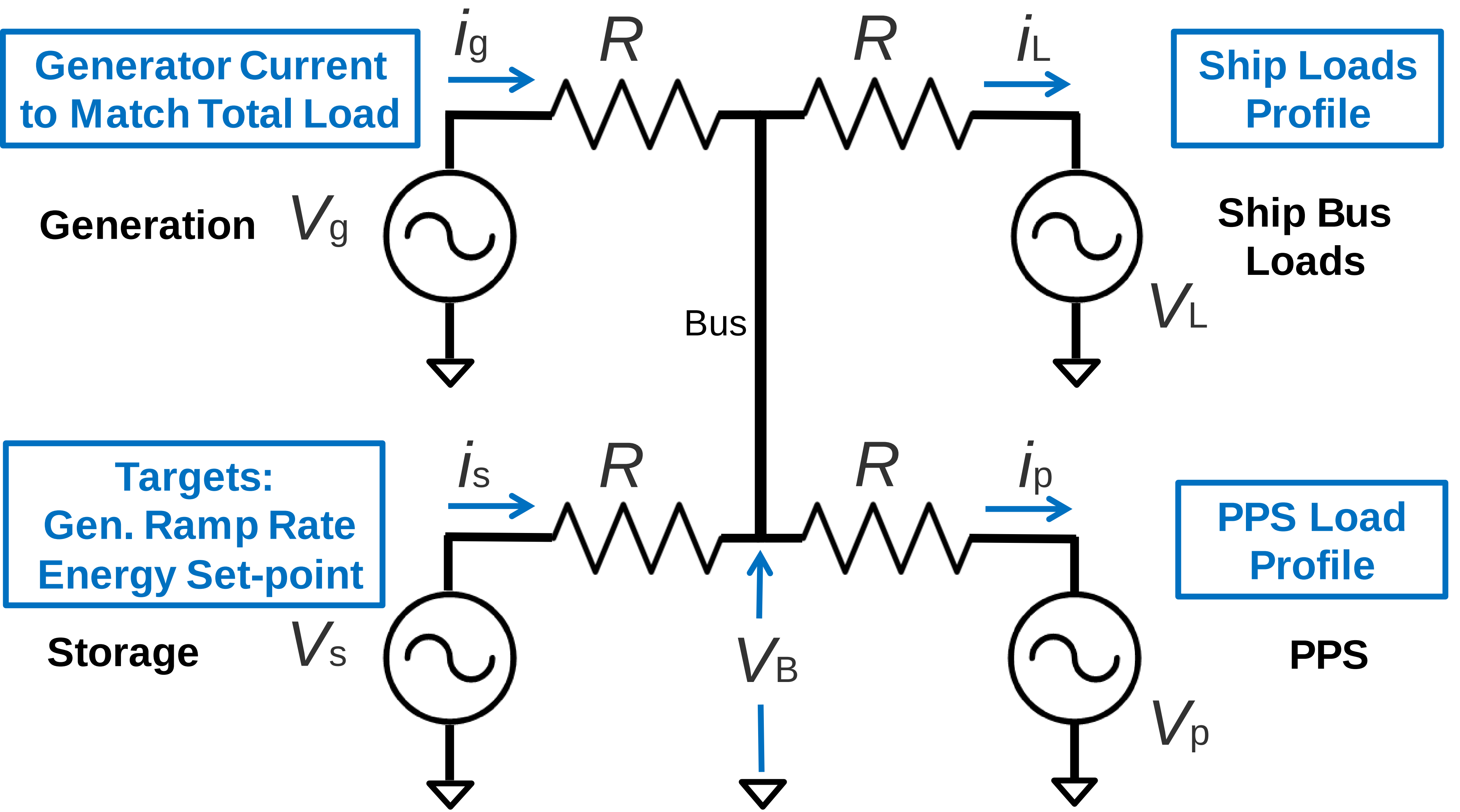
Pulse detail



Generator and EM Characteristics

- **Generation.** Both diesel and turbine generators perform best when the rate of change in load power is limited. In the model it was assumed that the power ramp rate limit per generator should be no more than 1MW/s. If n identical generators supply power equally in parallel, the maximum power ramp rate for the generation block could be raised to n MW/s.
  - In the model, the generation block was represented as a power source for the ship bus responding to the combined needs of the ship bus load, the PPS load, and the EM block when this is in need of recharging.
- **EM storage.** The EM storage supplies power to the loads when they exceed the capability of the generators and absorbs the excess generated power when the total load collapses. Thus, power flow is bidirectional, and balances the combined power of the generation (under its prescribed ramp rate limits), ship loads, and PPS blocks.

System and Variables Definition



First Result: Generalization of a Known Instability

Given that it must be $v_L i_L = p_L(t)$ (Prescribed Power Load – PPL)

The differential impedance ζ_L is, therefore, given by

$$\zeta_L = \frac{dv_L}{di_L} = -\frac{p_L}{i_L^2} + \frac{1}{i_L}\frac{dp_L}{di_L}$$

Analysis shows that stability is possible if the following condition is met

Condition for stability:

$$\boxed{p_L \geq k\ i_L^{\alpha}}$$

where *k = constant > 0* and α *> 1.0*

in which case the differential impedance would be equal to

$$\zeta_L = \frac{dv_L}{di_L} = -\frac{k i_L^{\alpha}}{i_L^2} + \frac{k\alpha i_L^{(\alpha-1)}}{i_L} = k(\alpha-1)i_L^{(\alpha-2)}$$

First Result: Every load for which the power drawn is prescribed is potentially unstable

Second Result: Topology Induced Instability

In order for both i_L and i_p to be real, the following condition must be met:

$$\frac{\left(v_g - Ri_g\right)^2}{4R} \geq \text{greater of}\left(p_L, p_p\right)$$

This leads to requiring that the following be both true at the same time:

$$p_L \leq p_p \qquad\qquad p_p \leq p_L$$

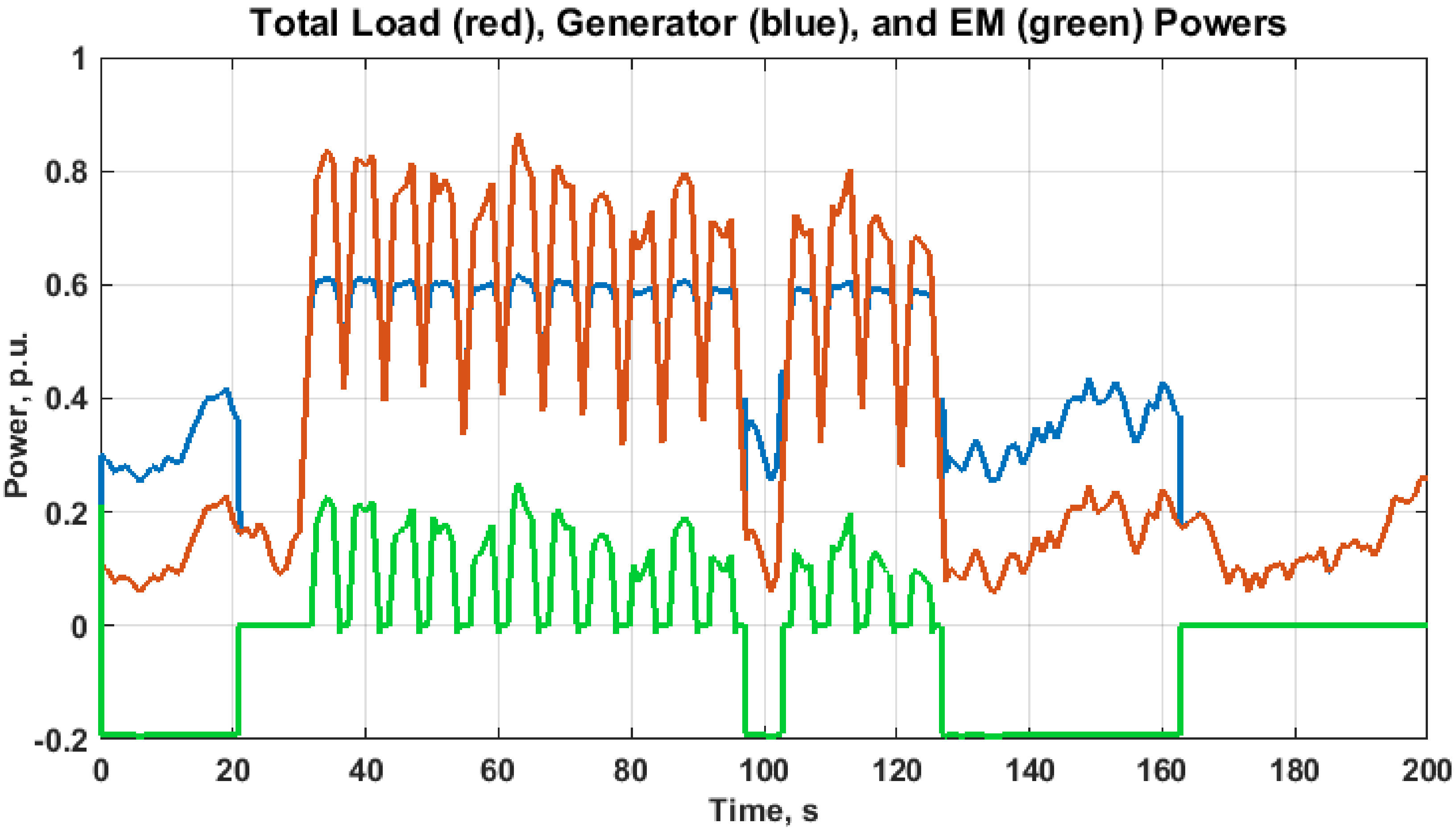
We conclude that the only way both i_L and i_p can always be real is if

$$\boxed{p_p = p_L}$$

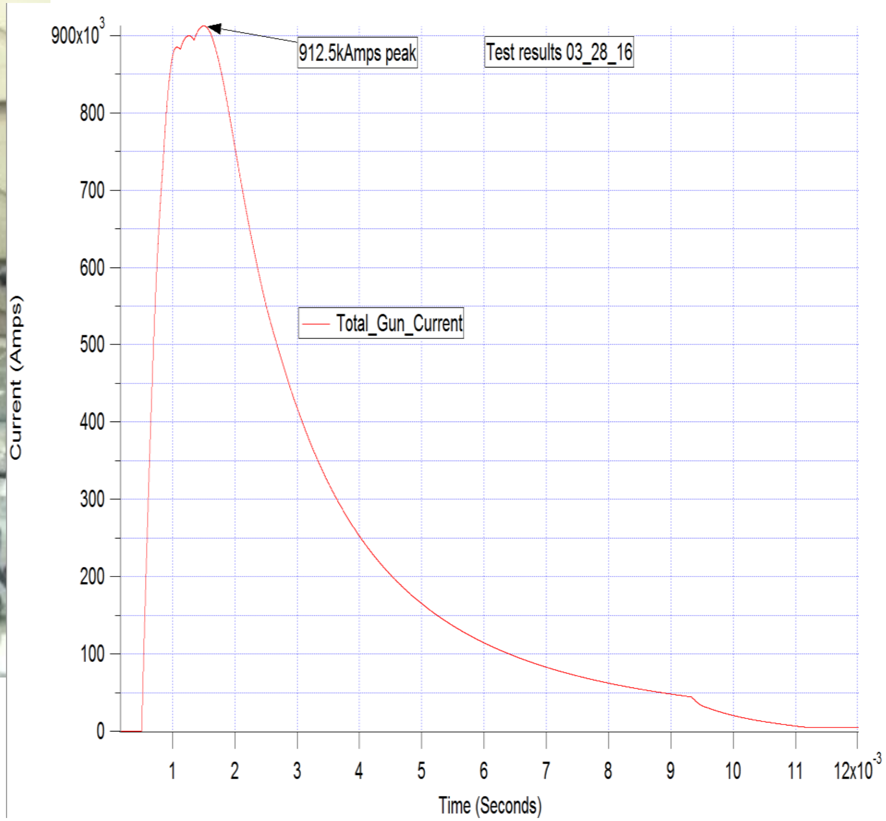
which would be a very peculiar case, since p_L and p_p are presumed to be quite arbitrary functions of time and independent of each other.

Second Result: PPLs located in close electrical proximity induce system instability

Solution Example

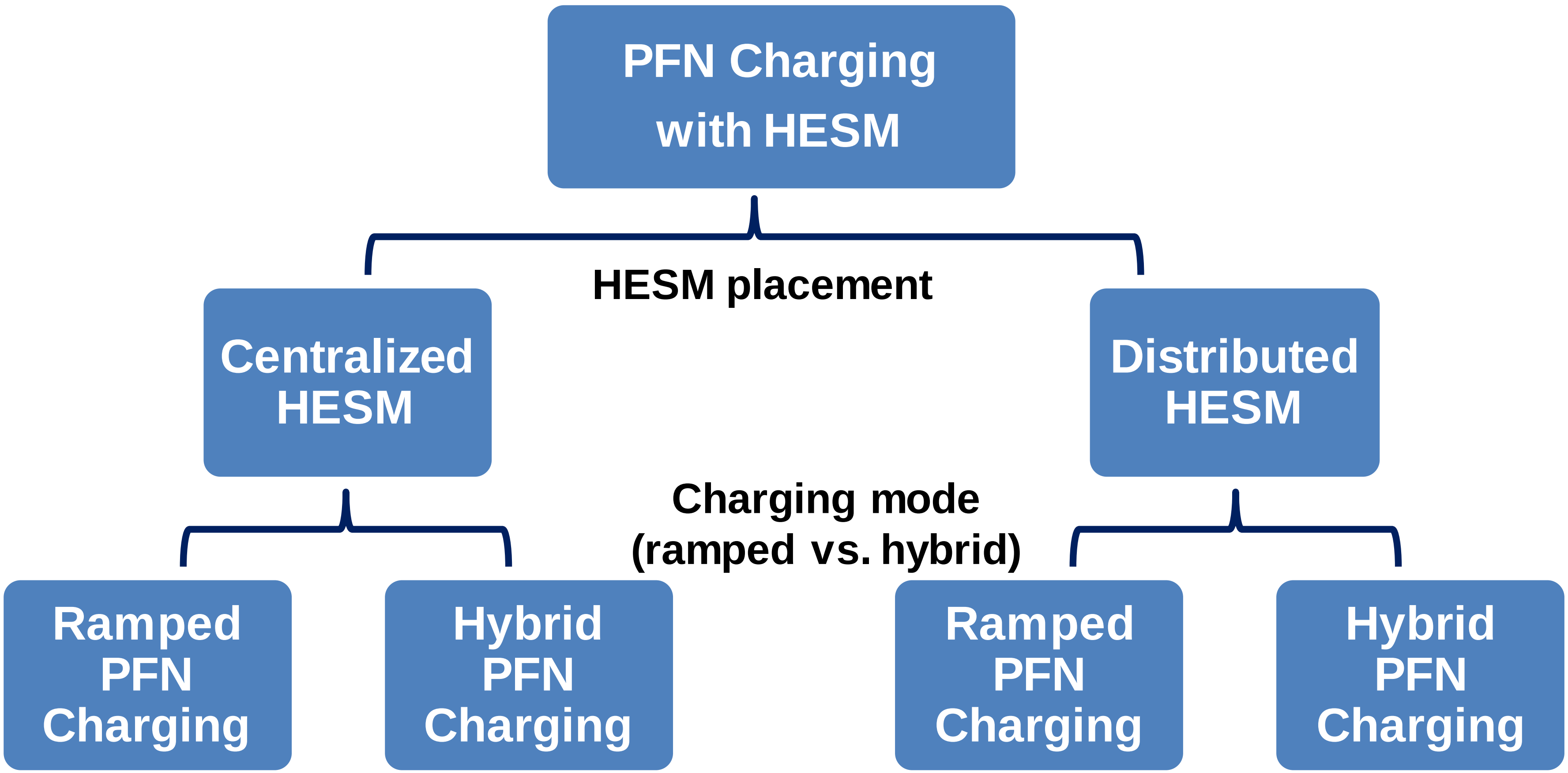


Actual Demonstration:
Railgun Shot from Microgrid



The electromagnetic gun system. The launcher is in the concrete bunker in the foreground and the longer concrete bunker contains the soft catch system for the projectiles. The capacitor bank is adjacent to the gun and soft catch. Maximum stored energy of 12 MJ and muzzle energy of 2 MJ.

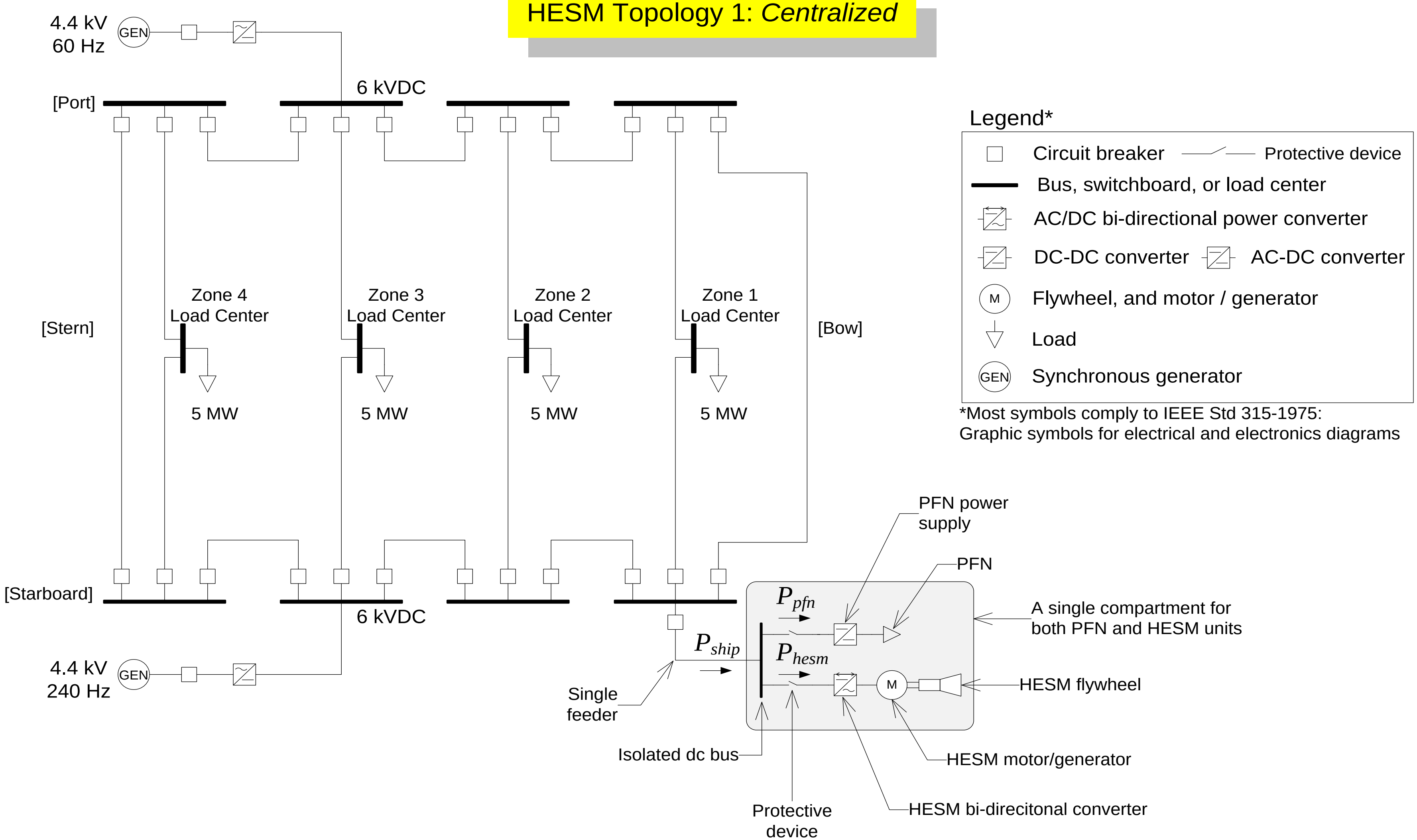
Storage Design Example 2:
Hybrid Energy Storage Module (HESM) for Railgun



PFN = Pulse Forming Network (capacitor bank)

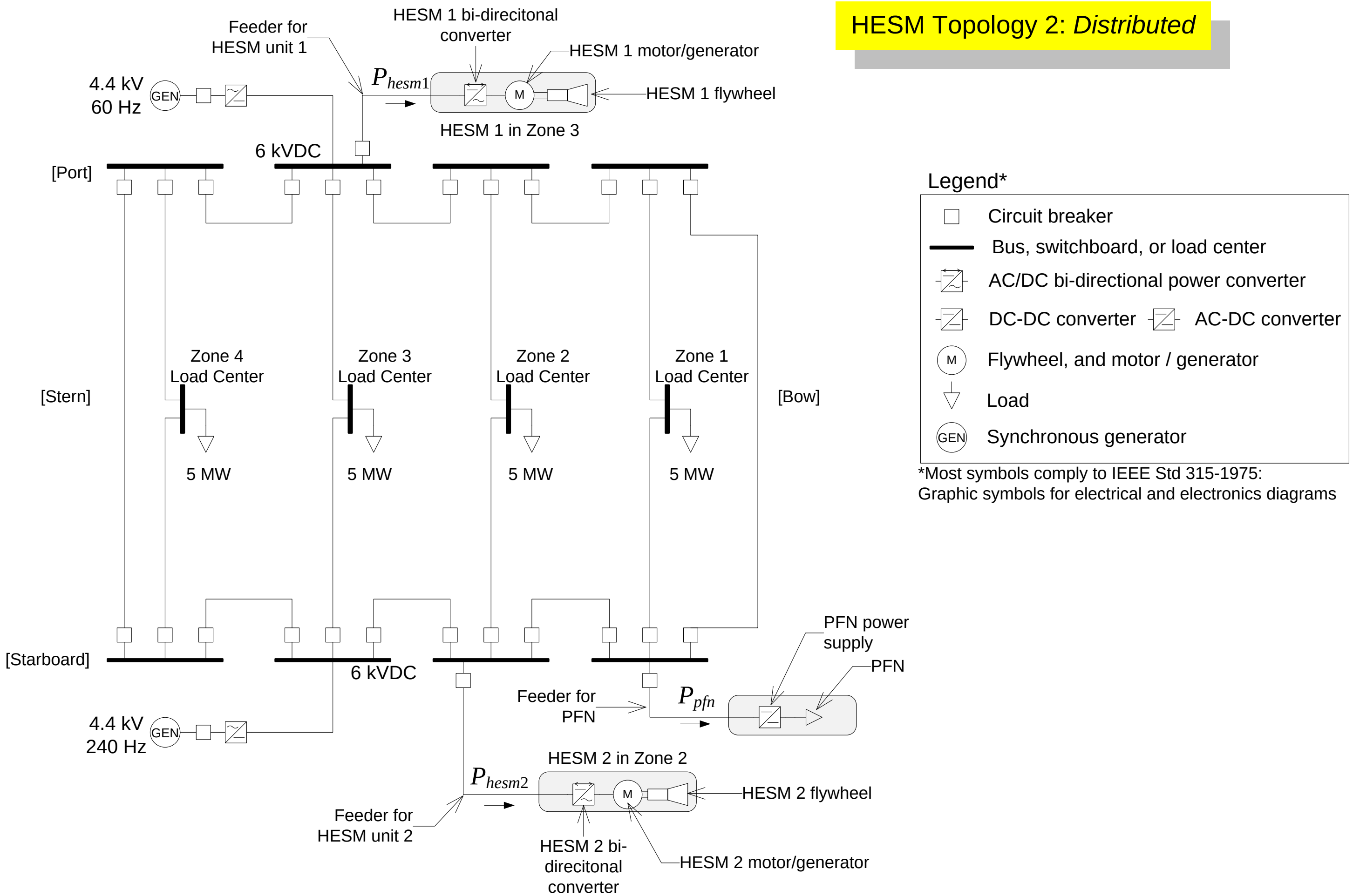
NOTE – Concept of operation (CONOPS): Both ship power system and HESM power mission system at the same time

HESM Topology 1: *Centralized*



The PFN and HESM are connected from zone 1 at an isolated dc bus. This topology implies a single dc feeder to serve both the HESM and PFN, compartmental proximity between the HESM and PFN, and the maximum storage requirement for the single HESM unit.

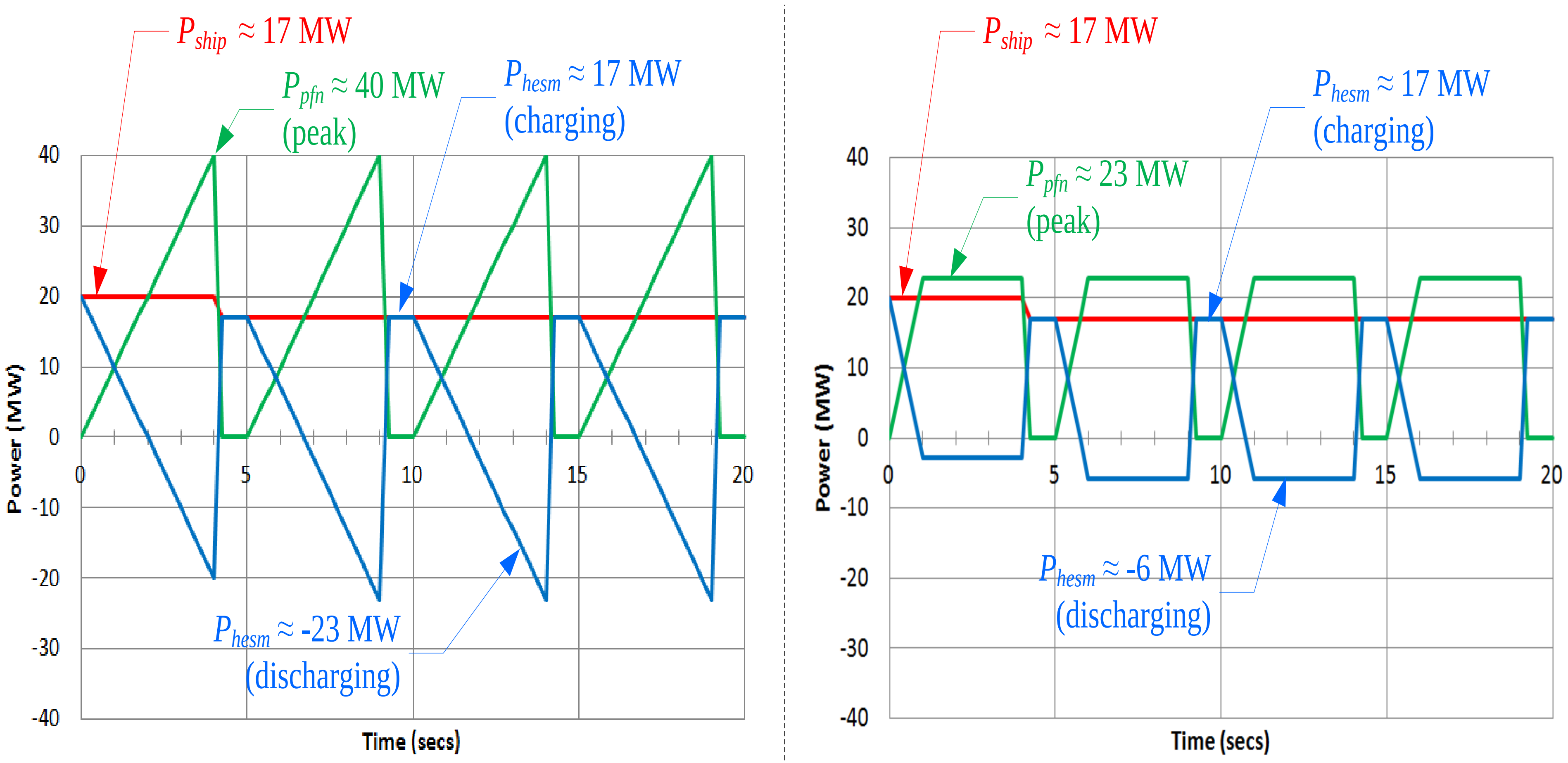
HESM Topology 2: *Distributed*



The two HESM units considered for this topology are distributed over zones 2 and 3. Additional HESM modules can be considered. The advantages of the distributed topology are the inter-zonal placements that allow the HESMs to supplement generation ride-though, reduced failure probability under battle impact, and simplified integration. Furthermore, each distributed HESM unit is smaller and weighs less than the single HESM unit in the centralized case.

Charging Profiles for Capacitor Bank PFN

Constant Current vs. Hybrid (Constant Current and Constant Power)



Constant current: more efficient but needs peak charging power of twice the average.
Hybrid constant current/constant power charging: reduces peak power demands on the charging power supplies and energy storage sub-system.

Result Examples

- The notional load used in the comparison was a high energy, capacitor-based, Pulse Forming Network (PFN) operated with a repetition rate of 12 charge/discharge cycles per minute.

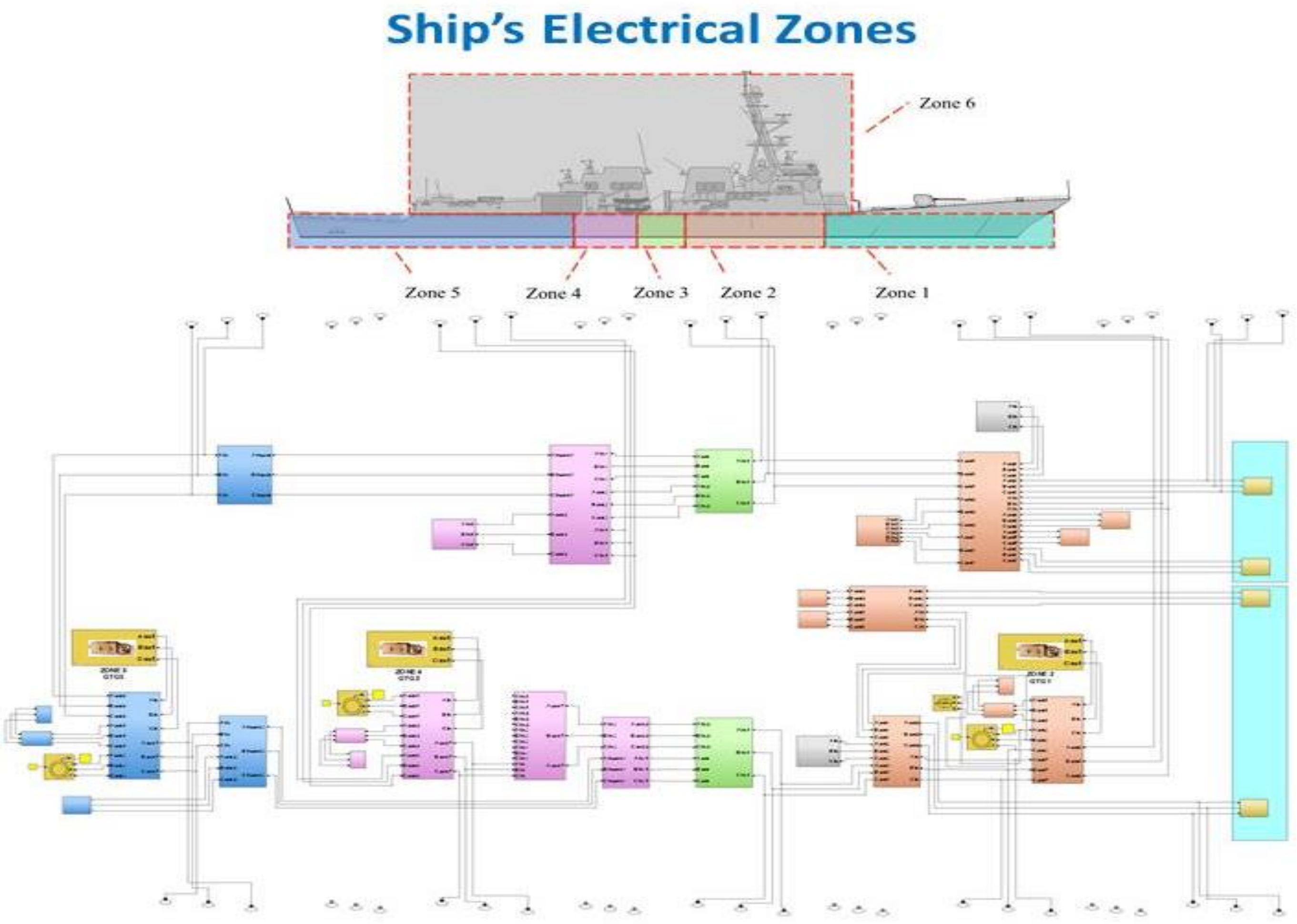
- Two hybrid solutions were evaluated:

1. One was based on lithium ion batteries and used a flywheel to improve the power delivery.
2. The other was a rotating-machine based HESM designed to mitigate the impact of transient (pulsed) loads on the ship's distribution power system.

- An important finding was that the transient load could be effectively buffered with only the flywheel energy storage element.

Storage Design Example 3: Back-fit of Laser Load on a DDG51 Destroyer

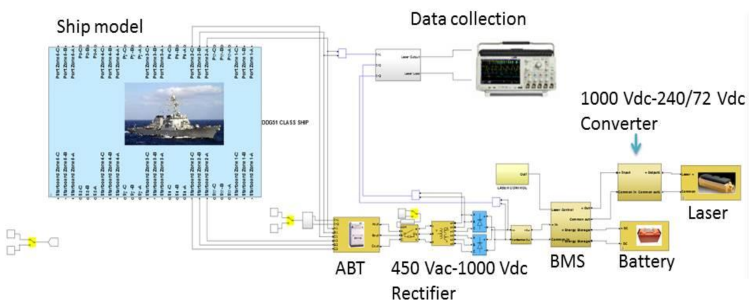
- Collaboration with NPS: laser power (30-125 kW)



Modeled Four Storage Scenarios for Laser

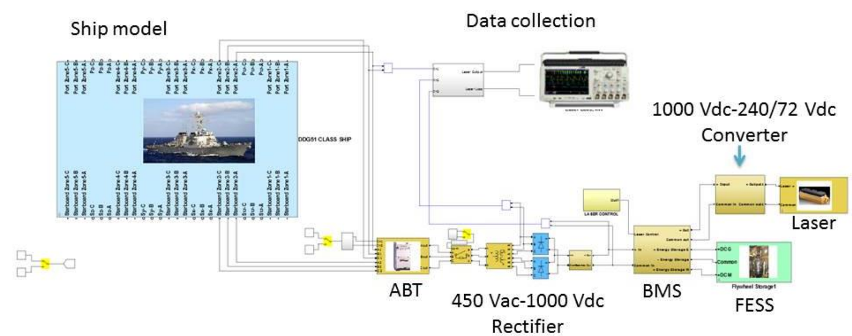
Lead-Acid Battery

Destroyer with Laser Load and Lead-Acid Battery Storage



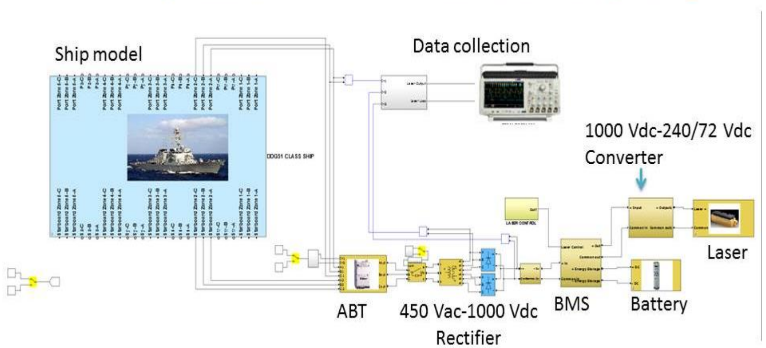
Flywheel

Destroyer with Laser Load and Flywheel Energy Storage System (FESS)



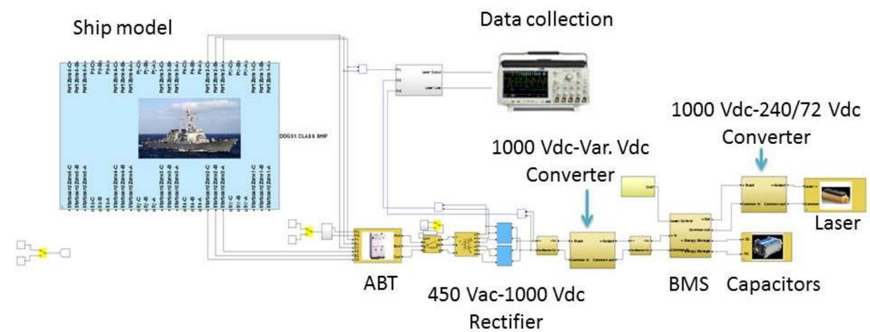
Li-Ion Battery

Destroyer with Laser Load and Lithium-Ion Battery Storage

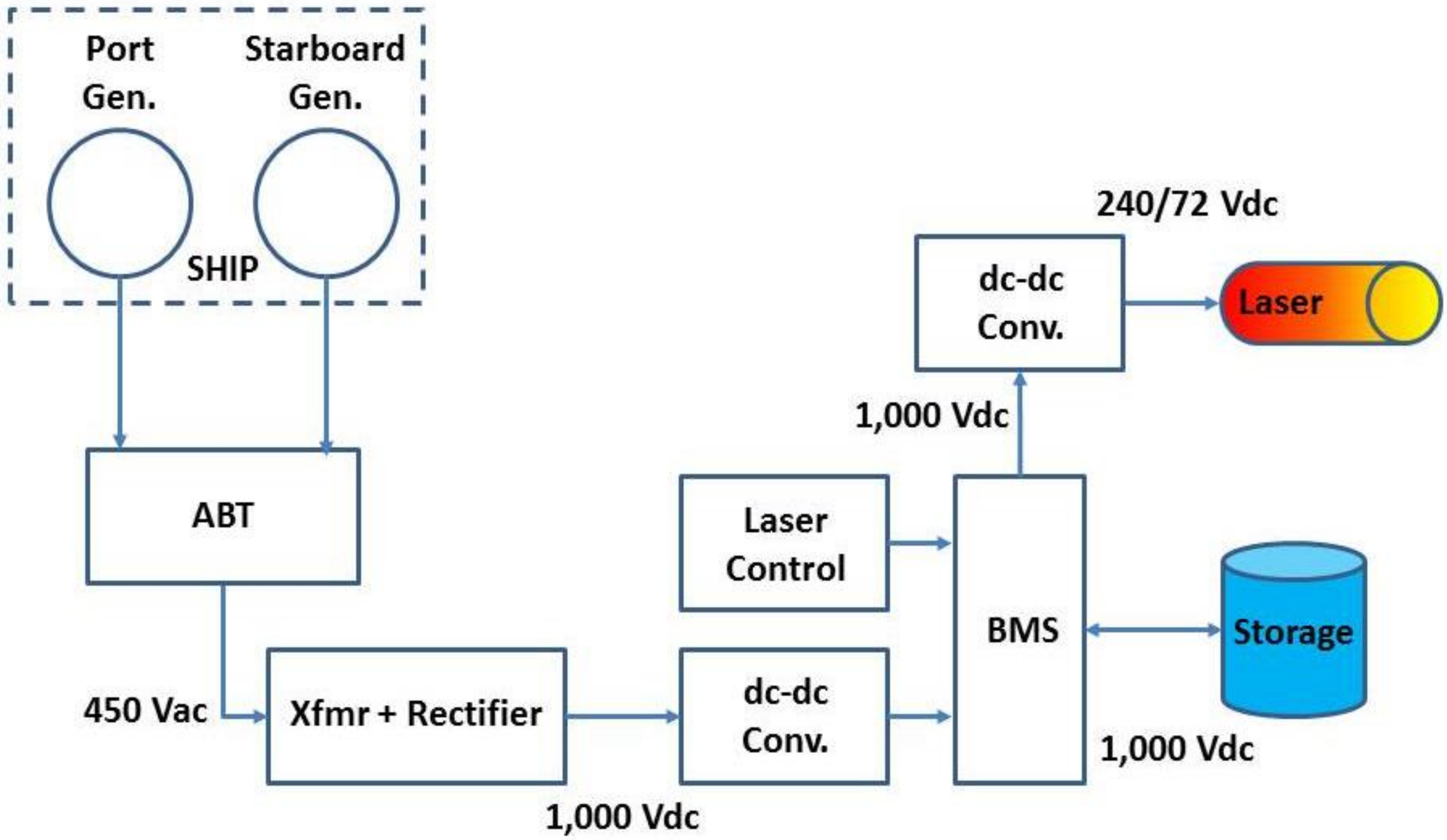


Capacitor

Destroyer with Laser Load and Capacitor Energy Storage



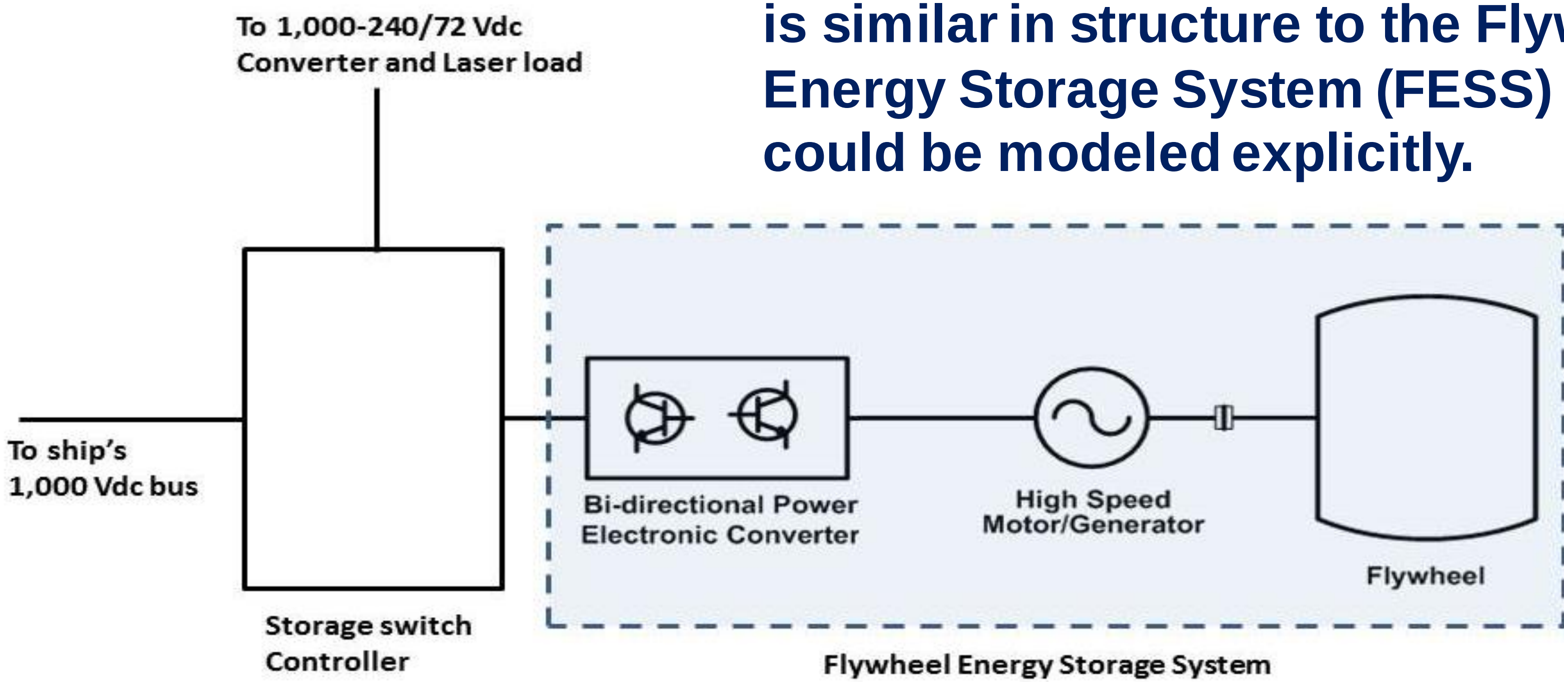
General Structure of Models

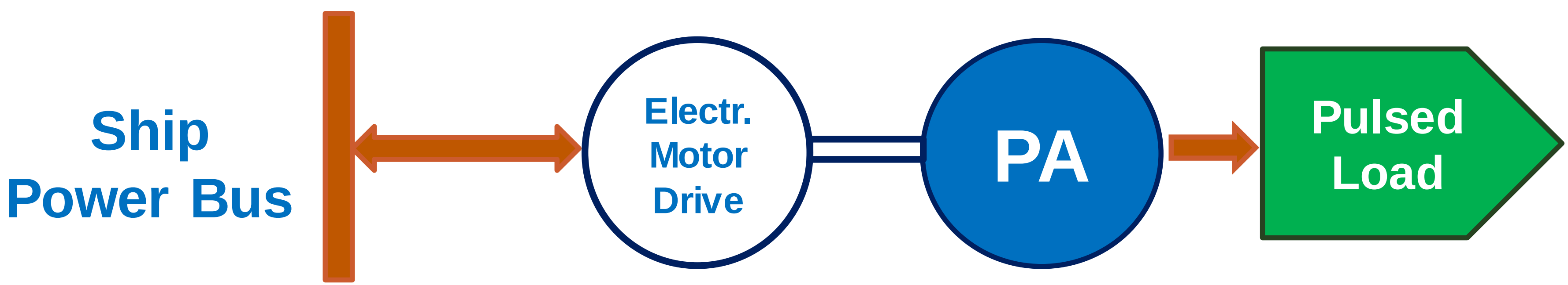


ABT = Automatic Bus Transfer
BMS = Battery Management System

Schematic diagram of the FESS and PA interface

Although the PA was not modeled, it is similar in structure to the Flywheel Energy Storage System (FESS) and could be modeled explicitly.



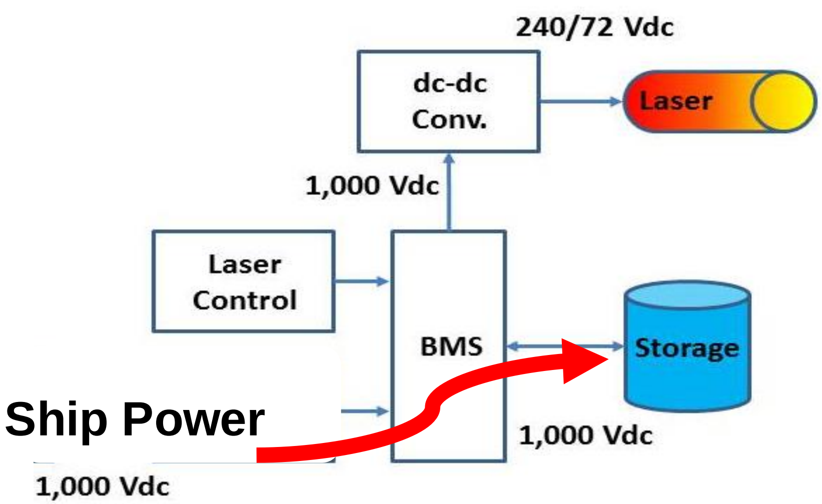


Operation, Critical Parameters, Performance

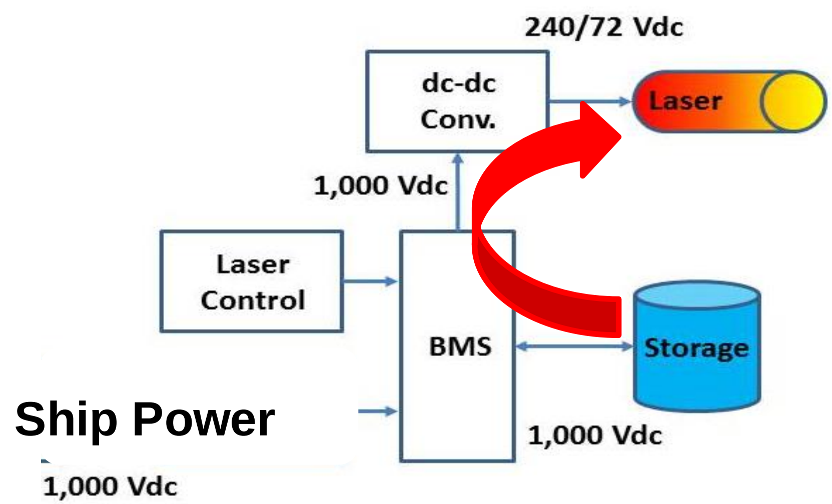
In the given CONOPS, the mission system is powered only by the energy storage module, which in turn is recharged by the ship power system when the laser is not firing. Critical parameters are:

- The laser power rating
- The laser duty cycle
- The capacity of the available energy storage
- The charge-discharge characteristics of the energy storage
- The length of the engagement.

Thus, various scenarios need to be studied and performance optimized with respect to given metrics.

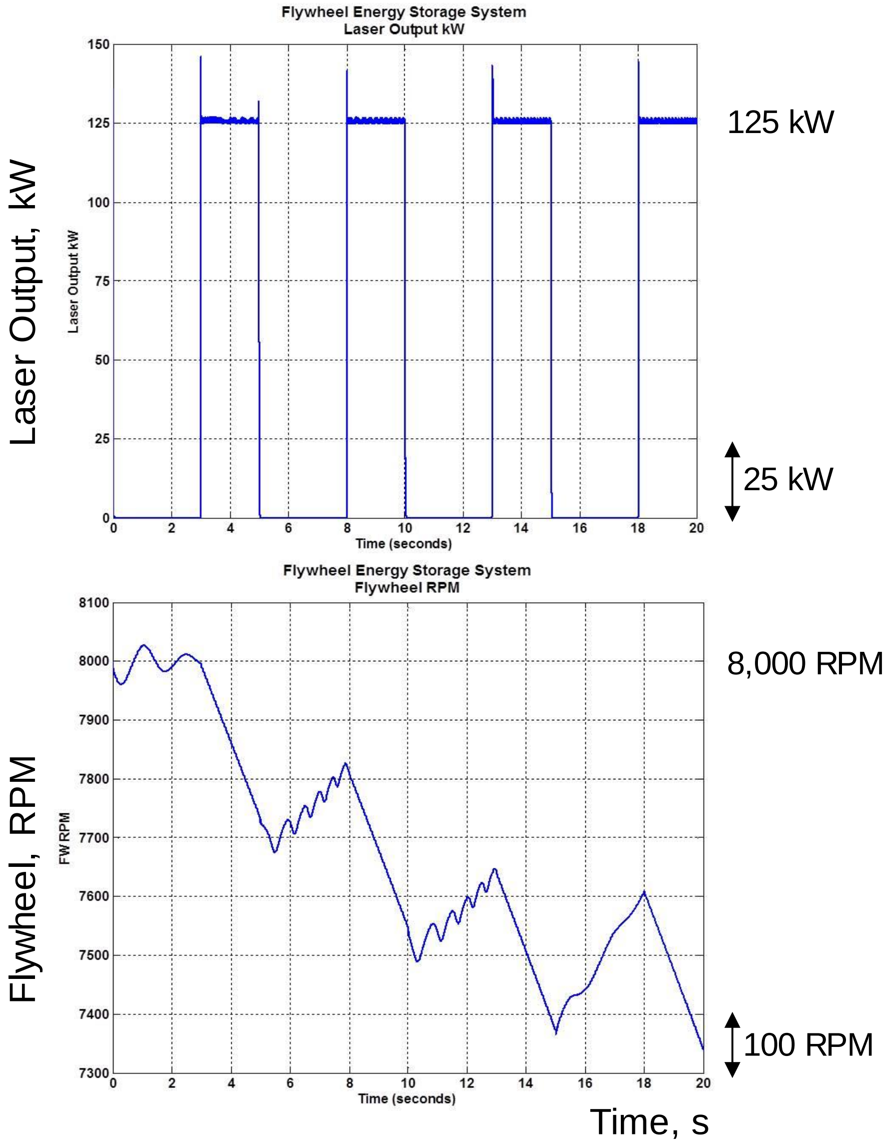


Charging

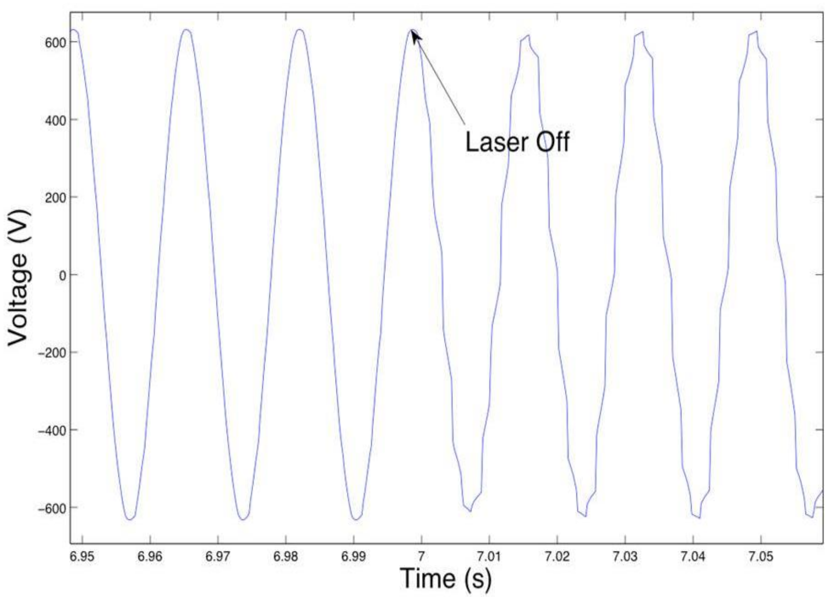


Discharging

Example of FESS Performance:
125 kW Laser, 40% Duty Cycle, 12 Shots/min



Impact on Ship's Power Quality



Similar results are obtained for the other storage technologies. These models allow the optimization of energy storage to support the pulsed Laser load within the given concept of operation.

Conclusions

- The PA is another alternative option for the Energy Magazine (EM)
- Particularly suited for railgun
- Can be used as bus support (UPS, etc.) or for load leveling function when not firing the railgun
- It should be evaluated along other EM options (batteries, capacitors, flywheels)
- Like all other EM options, its stability characteristics should be taken into account

SUMMARY REMARKS

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8/14/17

Rotating Machines Show Promise

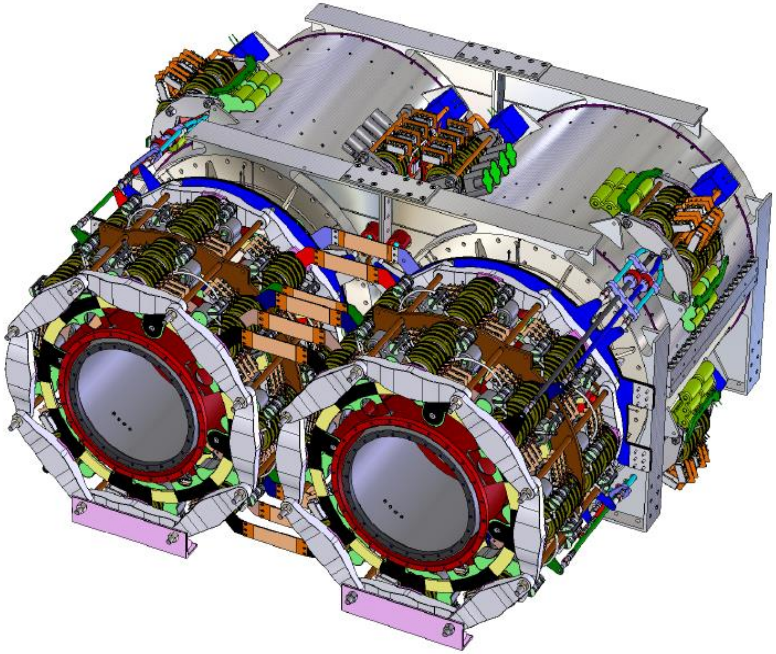
- The need to accommodate large transient loads and mission systems is increasing.
- Each energy storage technology has merits, and multi-dimensional solutions are likely.
- Pulsed Alternators are versatile rotating machines with very high power and energy density supported by a firm technology foundation.
  - Generations of system and component level technology development
  - Design tools are benchmarked against multiple systems

Pulsed Alternators Gaining Attention

- Pulsed Alternators were the power supply of choice for Army mobile platforms.
  - But US research is this area has been idle for the last decade
- Focus of pulsed-power research in China for the past 20 years
- Two privately funded research groups have recently investigated using a pulsed alternator for plasma research.
- A small commercial company is developing plans to use a pulsed alternator for an application in the oil and gas industry. The PA offers a compact, power and energy dense mobile platform for remote well sites.

A Technology Ready for Prime Time

- While PA research in the US has stalled, there remains an opportunity to leverage extensive DoD investment
- Solutions to many of the largest technical challenges have been developed and tested at a component level.
  - Composite arbors
  - Thermal management



What are the Next Steps?

- Need to capture interim technological advancements
  - Advanced switching and controls,
  - Thermal management,
  - Composite materials
- Need to update simulations for current SW platforms/ capabilities
- Need to transition expertise to future generations before it is gone