Energy Storage and Flywheels for AF Applications

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Integrity ★ Service ★ Excellence

Overview

- **Functions of Energy Storage for Aerospace Systems**
- **Energy Storage Technologies**
  - **Overview**
  - **Superconductor-Magnetic-Energy-Storage (SMES)**
  - **Flywheel Energy Storage**

Acknowledgments:

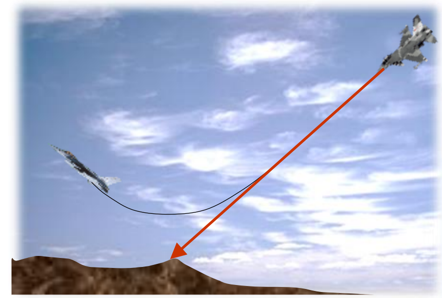
- Air Force Office Scientific Research (AFOSR)
  Dr. Harold Weinstock, STAR Team LRIR #14RQ08COR
- Aerospace Systems Directorate (AFRL/RQ)

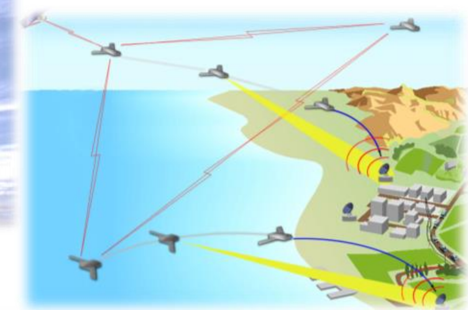
Functions of Energy Storage Devices for Aerospace Platforms

- **Energy Source for Propulsion**
  - Short Duration (minutes), Long Duration (hours)
  - Backup for Electric Motor Failure (MW, large energy)
- **Power, Energy, and Thermal Management**
  - Load leveling, transient fault management
  - Handle busbar overloads (actuator reverse)
- **Emergency Backup Power**
- **Energy Source for Next-Generation Electric Weapons:**
  - High Energy Lasers (HPM), High Power Microwave (HPM)

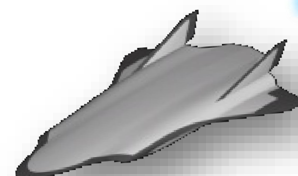
Needs that Drive Power and Control Division

- **Automated & Autonomous Systems**
  - **Auto Ground-air Collision Avoidance System (A-GCAS) – "another pilot and F-16 saved"**
  - **Flight Control automation**
  - **Operate in contested environments**

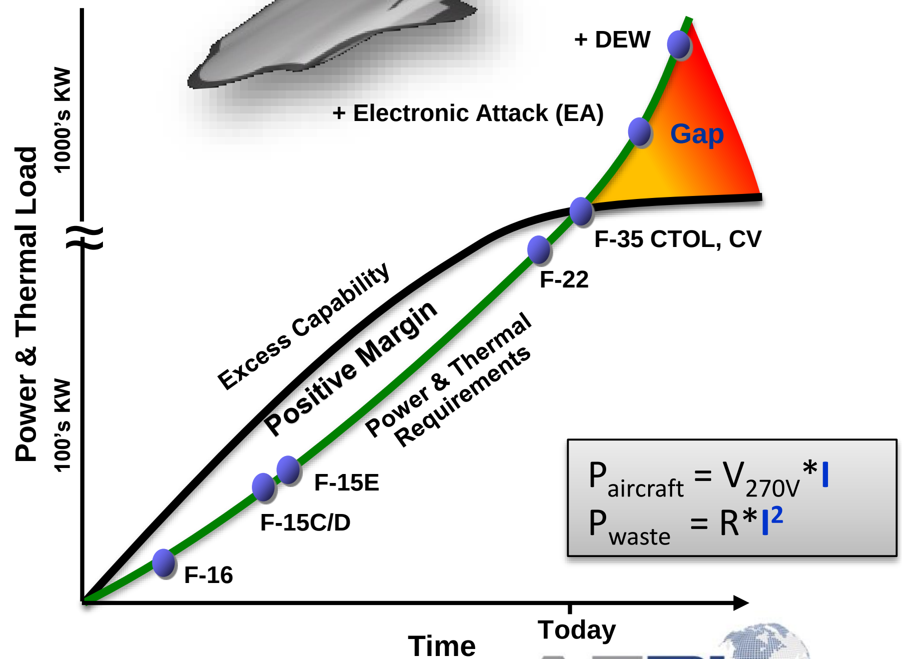




- **Hypersonics**



- **Aircraft Power and Thermal Management**
  - **Electrical power needs continue to grow**
    - **Mission avionics**
    - **Directed Energy**
  - **As power needs grow so will the generation of heat which needs to be mitigated**
    - **More effective thermal systems**
    - **Higher temperature electronics**
    - **Less heat through improved efficiency**



Power & Thermal – The Problem

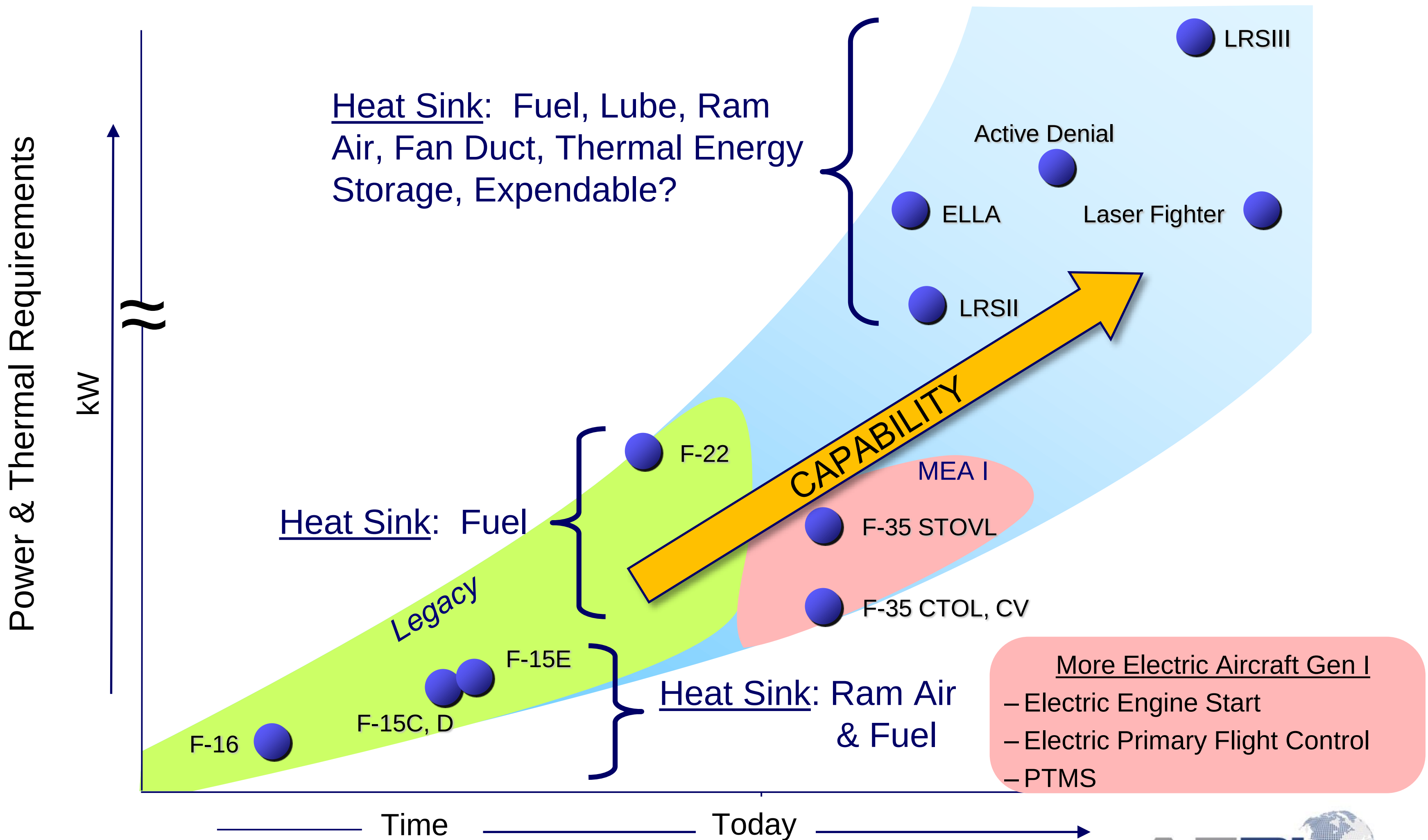
- **6th Gen mission systems need more electric power**
  - Advanced Radar systems
  - Special Mission Loads (DEW, EA, EW)
- **Power is increasingly flight critical**
  - 4th Gen → Flight control computer
  - 5th Gen → Added actuation power
  - 6th Gen → Mission systems
- **More power equals more heat**
  - Advanced LO aircraft have limited heat dissipation options
- **Efficient engines provide less fuel for heat sink**
- **High power extraction can affect engine operability**

Generate this much electric power in a fighter

System engineering indicates solutions to 6th Gen weapon system challenges require highly coupled propulsion, power, & thermal

Increased Capability Drives Onboard Energy Requirements

Power & Thermal Management Requirements



Approved for public release – 88ABW-2016-3118, 20160105

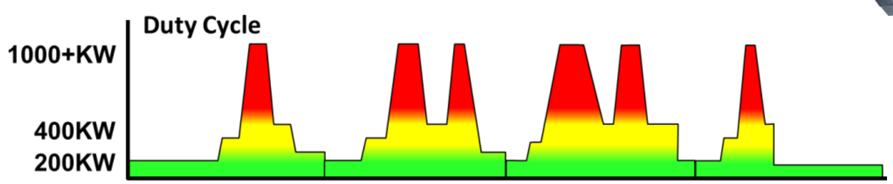
5^{th} vs. 6^{th} Gen Aircraft

- **5^{th} Gen aircraft today have ~250KW installed electrical power capability**
- **6^{th} Gen aircraft concepts desire 1000KW peak**

6^{th} Gen =

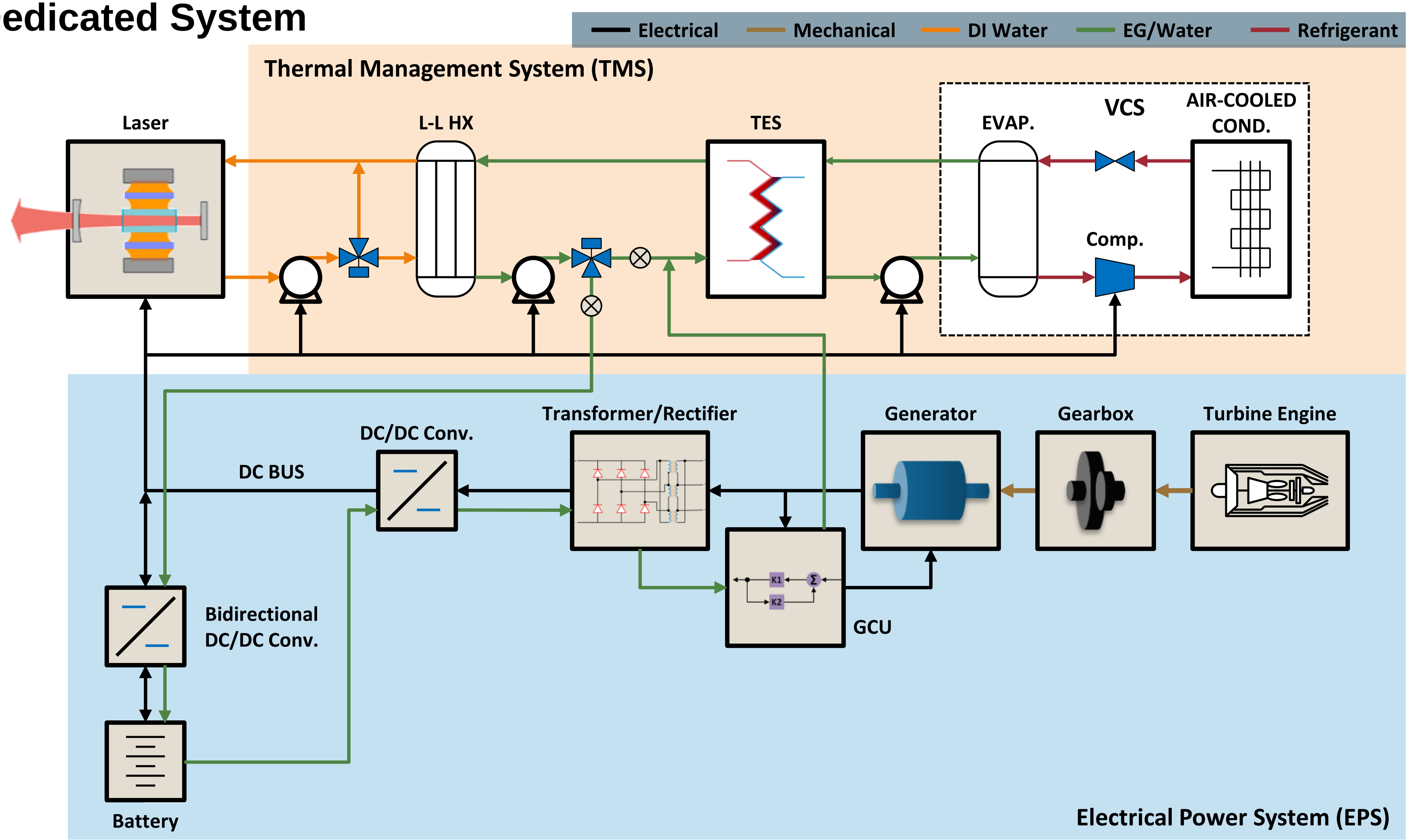
5^{th} Gen =

Mission system duty cycles are highly variable



Notional MegaWatt Pod Architecture

Dedicated System



0.2 MJ Systems:
Integrated Vehicle and Energy Management (INVENT)

More Electric Aircraft

Current More Electric Aircraft

Boeing 787

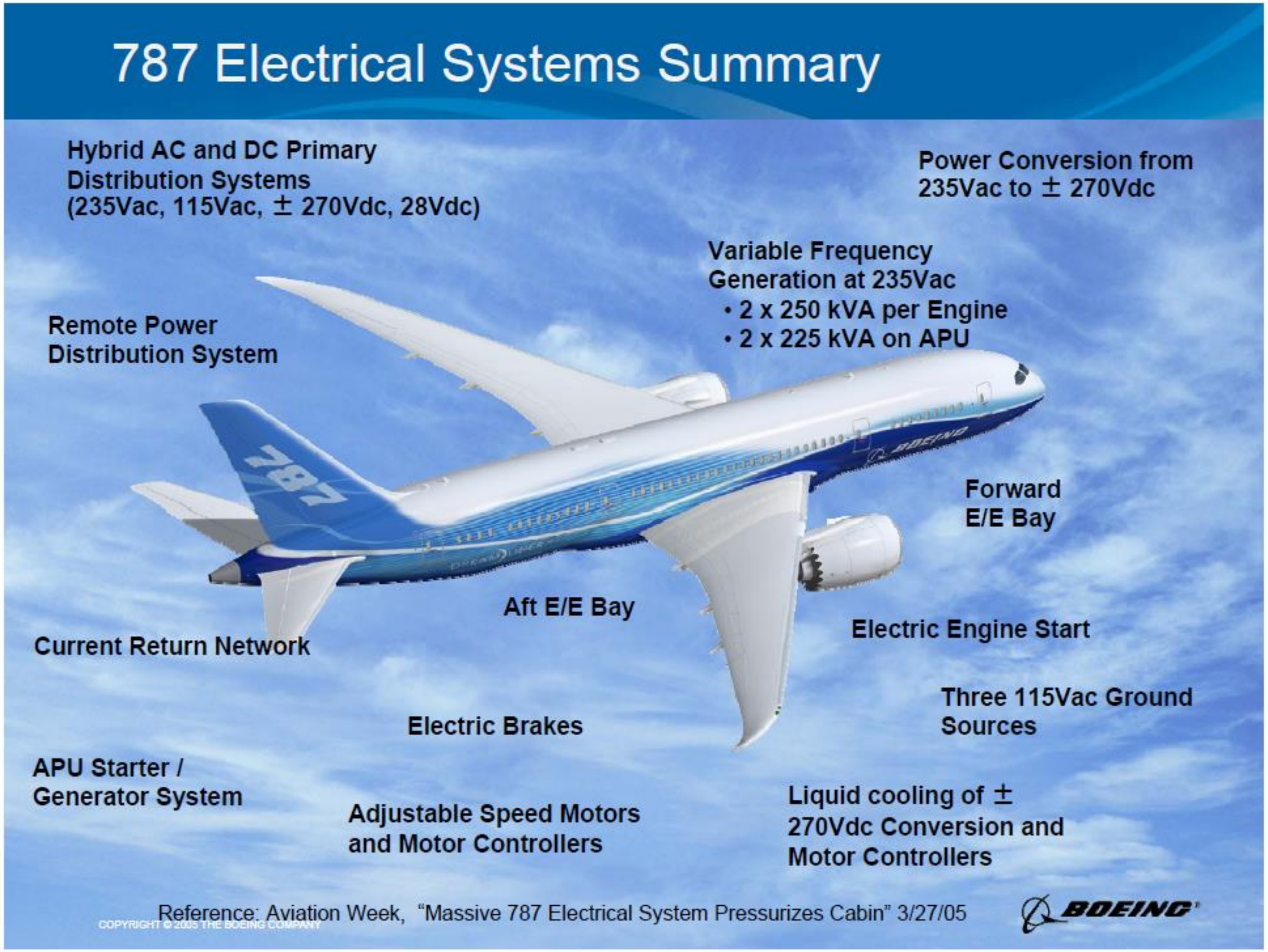
~ 2 MW Electric Power

Airbus A380

F-35 Fighter

~ 0.1 MW Electric Power

Boeing 787 Electrical Systems



INVENT Energy Management

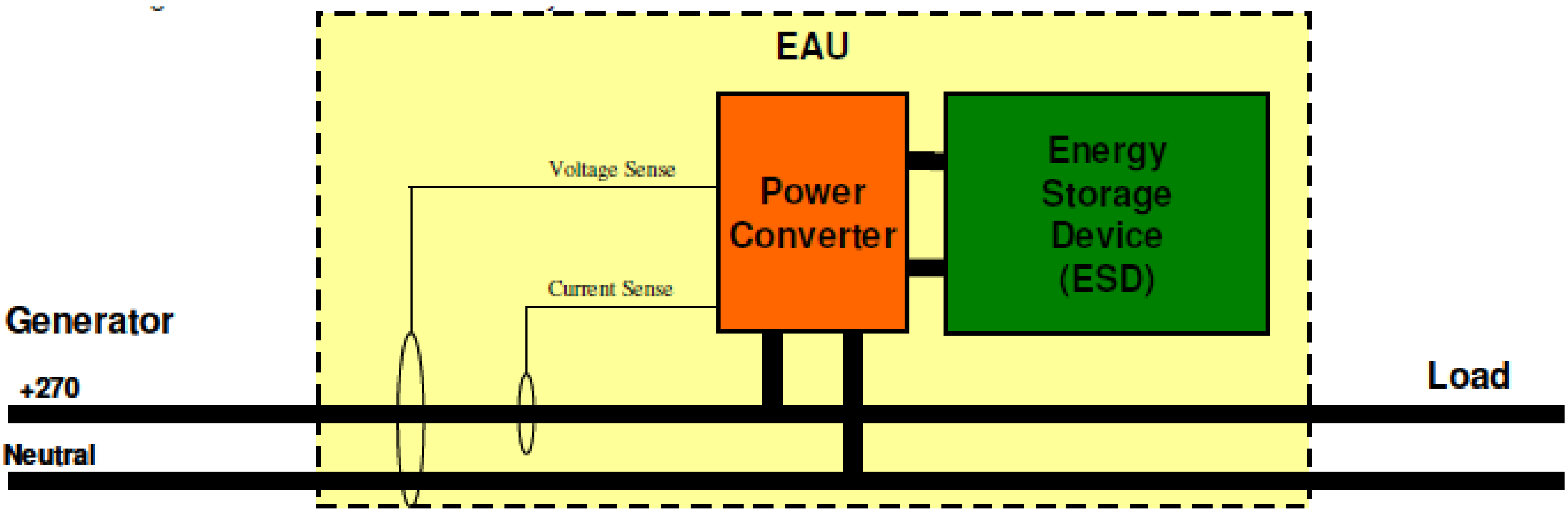


Figure 3. Proposed EAU layout

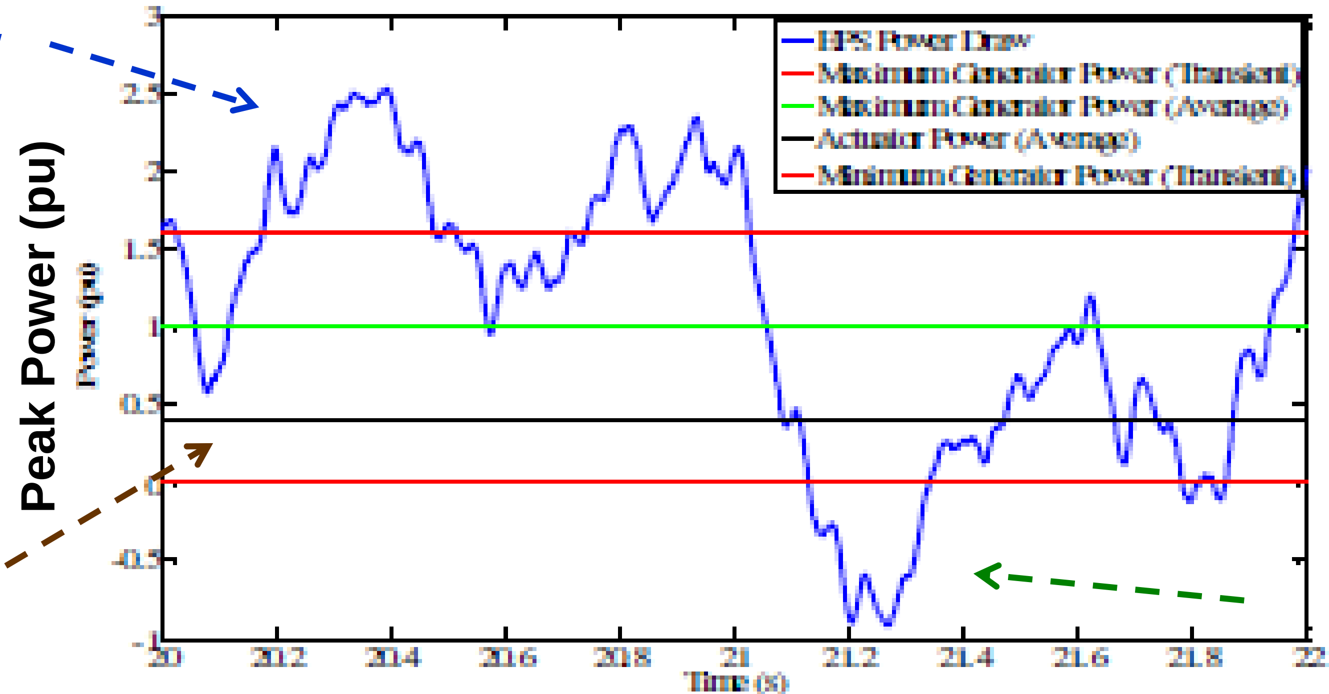
Electrical Accumulator Unit: stores and controls power coming back onto the bus off of the load

Loads: electromechanical actuators (EMA), electrohydrostatic actuators (EHA), directed energy weapons (DEW), advanced radar

J. Wells, et al, "Electrical Accumulator Unit for the Energy Optimized Aircraft," SAE International Journal of Aerospace, v. 1(1): pp. 1071-1077, 2008

Power Fluctuations on Modern Electric Aircraft (MEA)

Power Draw



Avg Load

Power back onto bus

pu = power/avg power

Representative Transient Power Profile

- **Power**: Pulsed transients of 150 kW can occur in about 10 ms
- **Regenerative Power**: up to 150 kW ‘waste heat’
- **Duty Cycles:** 25-100%
- **Switching frequencies:** 0-20 kHz

J. Wells, et al, “Electrical Accumulator Unit for the Energy Optimized Aircraft,” SAE International Journal of Aerospace, v. 1(1): pp. 1071-1077, 2008

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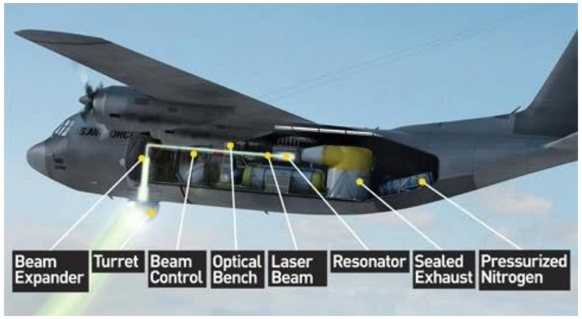
Energy Storage Needs
5 - 70 MJ

- Directed Energy
- Hybrid-Electric Propulsion
- Railgun Launch
- Thermal/Power Management

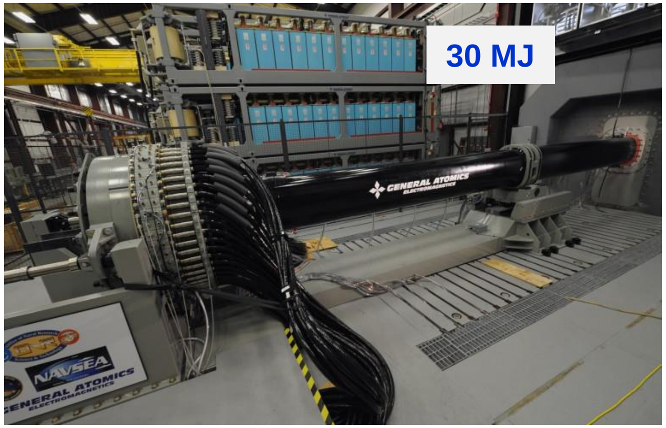
DOD Applications of High Power Energy Storage Devices



http://defense-technologynews.blogspot.com/

HEL Directed Energy

- 70 MJ Li-Battery (2,500 lbs, 1.0 MW)
- 12 laser shots, takes 15 min to recharge



Railgun Launch

- 30-250 MJ Battery per shot in ~ < 0.1 Sec
- ~ 50 lb shell achieves Mach 7-8 !,
- Navy range = 250 miles

EADS Electric Trainer

- 69 MJ Li-Battery (0.57 gal_{equiv}, 507 lbs)
- Range ~ 100 miles

Aircraft Electrical-Accumulator-Unit

- 0.5-5 MJ, ultra-fast charge/discharge for energy control/management

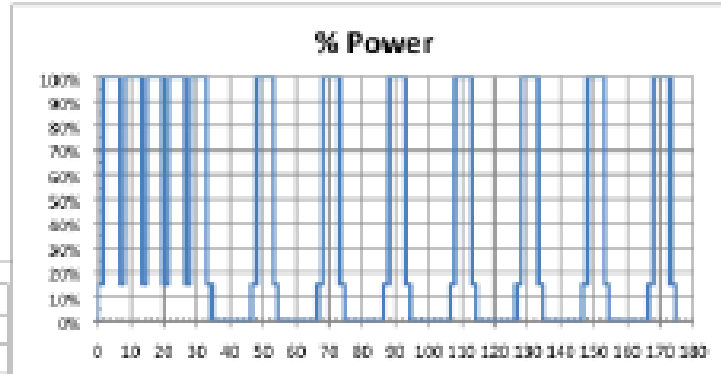
Hybrid Power for Laser Weapons

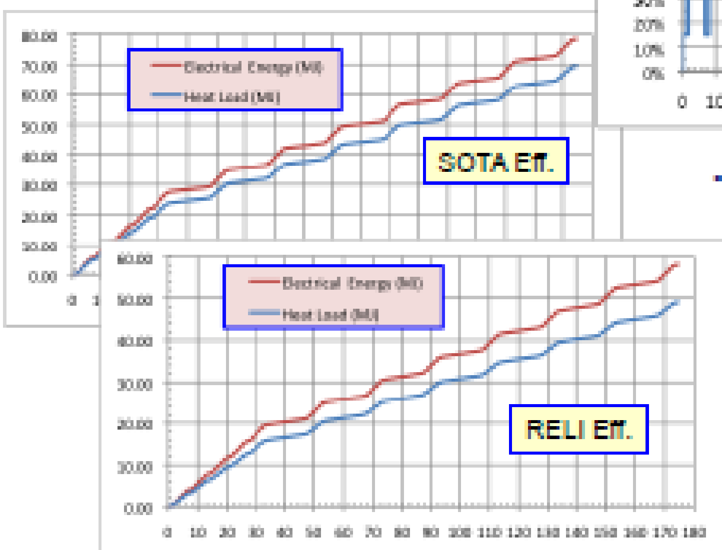
DEPS 2010 Conference Proceedings , General Atomics Aeronautical
Distribution "A": Approved for public release; Distribution unlimited

58 MJ Electrical Energy

Timeline for "Goal" 150-kW LWS Scenario

- Total Electrical Energy~80MJ
  - 6.6 MJ per shot
- RELI Improvements reduce to ~58 MJ Electric (<5 MJ / Shot)





- Twelve shots over ~156 Seconds
  - Five, 5-second Shots With 1.5-second Dwell Between Targets
  - Seven, 5-second Shots with 20% Duty Cycle
  - 60 Second Magazine … 10-15 Minute Recharge

Timebase in Seconds

GENERAL ATOMICS AERONAUTICAL

DEPS 2010 Conference Proceedings , General Atomics Aeronautical
Distribution "A": Approved for public release; Distribution unlimited

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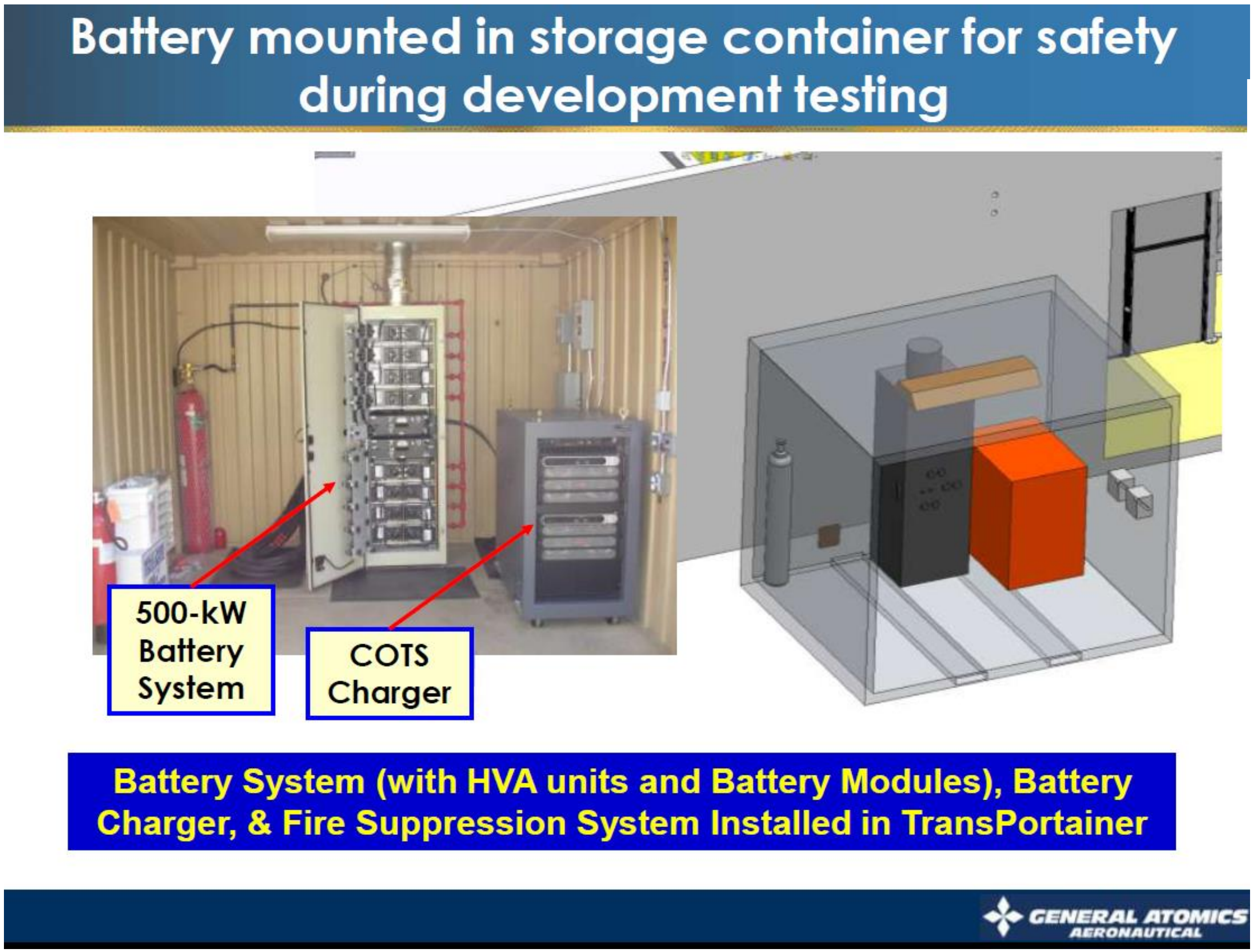
500 kW Li Batteries for DE Power



- Energy: 58 MJ useable,
- Discharge time: 30-60 sec
- Recharge Time: 10-15 min
- Weight: 1500 lb (= 800 lb device + 700 lb fire suppression)
- Cost $0.5-1 M

DEPS 2010 Conference Proceedings , General Atomics Aeronautical
Distribution “A”: Approved for public release; Distribution unlimited

37 MJ System*
Li Batteries Chevy Volt

Charge time: 6- 6.5 hrs
Weight: ~ 170 kg
Cost: ~ $13K

* Actual = 58 MJ, however useable = 38 MJ

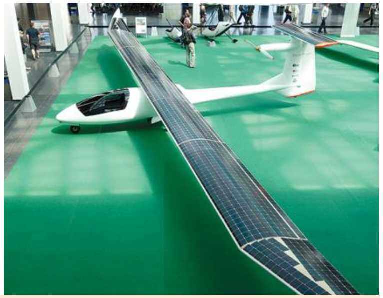
http://gm-volt.com/2010/07/19/chevrolet-volt-battery-warranty-details-and-clarifications/

IEEE Spectrum, 2 Aug 2013
"10 Electric Planes to Watch"


Solar Impulse


Anteres 23E


Taurus Electro G2


Sunseeker Duo


LZ Design


Archeoptryx

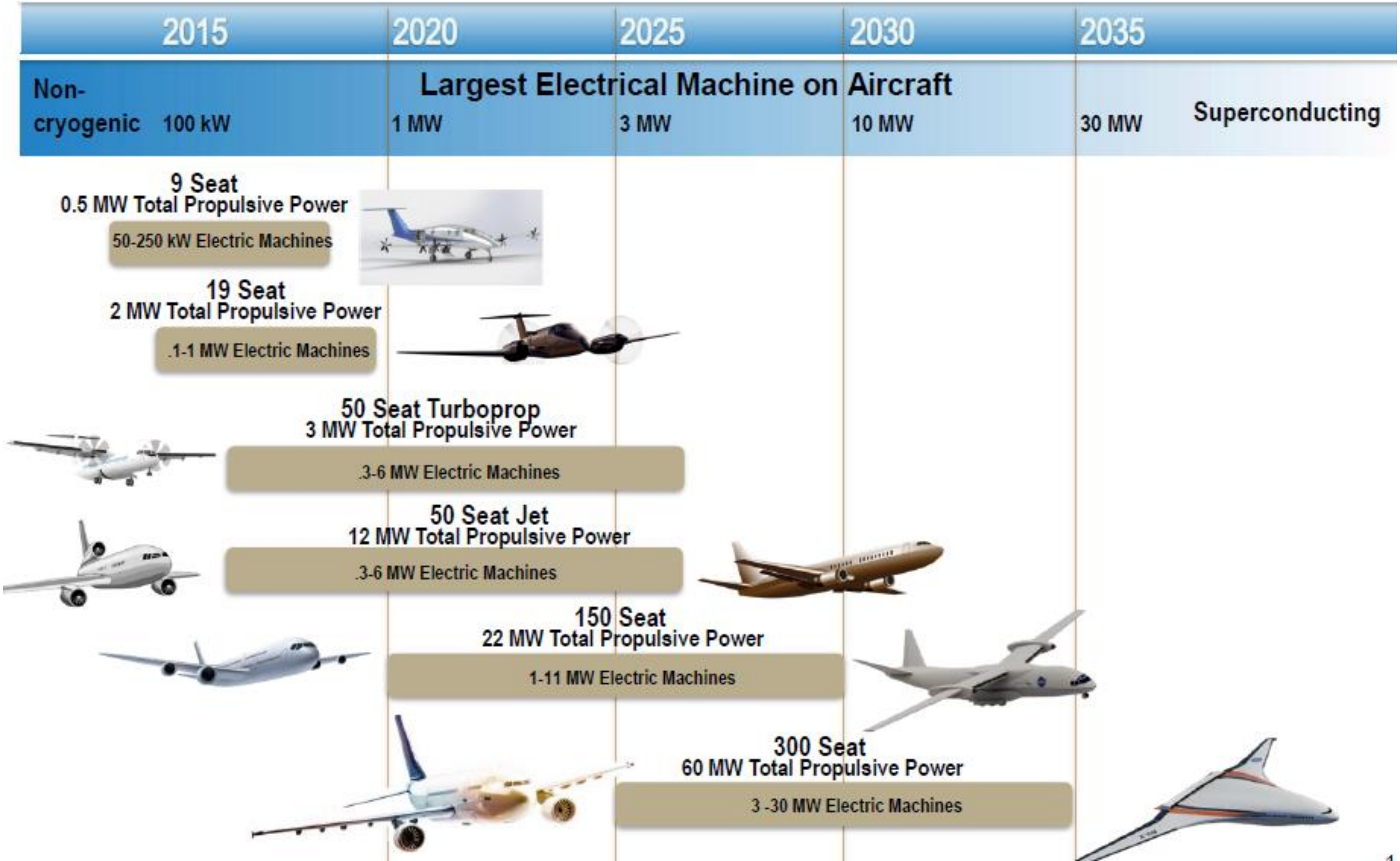
Cri-Cri E-Cristaline

Yuneec e430


Long ESA


Eurosport Crossover

Commercial Aircraft Hybrid Electric Propulsion



M. Madavan, IEEE-ECCE 2015, NASA

Commercial Aircraft Hybrid Electric Propulsion

Projected Timeframe for Achieving Technology Readiness Level (TRL) 6

Technologies benefit more electric and all-electric aircraft architectures:

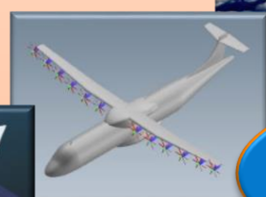
- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

>10 MW

- Turbo/hybrid electric distributed propulsion 300 PAX

5 to 10 MW

- Hybrid electric 150 PAX
- Turboelectric 150 PAX



2 to 5 MW class

- Hybrid electric 100 PAX regional
- Turboelectric distributed propulsion 150 PAX
- All electric 50 PAX regional (500 mile range)

1 to 2 MW class

- Hybrid electric 50 PAX regional
- Turboelectric distributed propulsion 100 PAX regional
- All-electric, full-range general aviation

kW class

- All-electric and hybrid-electric general aviation (limited range)

M. Madavan, IEEE-ECCE 2015, NASA

Power Level for Electrical Propulsion

Today | 10 Year | 20 Year | 30 Year | 40 Year

NASA Updates, 2016

NASA FY 2017 Budget for Aeronautics

- **Total Budget increase $3.7B in 10 years !!!** (proposed)
- Only one of 7 sub-areas with a significant increase

Actuals FY 2015	FY 2016	FY 2017[1]	Notional FY 2018[2]	Notional FY 2019	Notional FY 2020	Notional FY 2021
$642M	$640M	$790M	$846M	$1,060M	$1,173M	$1,287M

NASA's FY 2017 budget provides $790 million to the Aeronautics Research Mission Directorate to implement its visionary strategy. The Aeronautics budget is supplemented by $3.7B in mandatory funding over ten years to accelerate the realization of low carbon air transportation as part of a multiagency plan for a 21st century clean transportation system.

$150M/yr increase

$400M/yr increase

http://www.nasa.gov/sites/default/files/atoms/files/fy_2017_budget_mission_directorate_fact_sheets.pdf?linkId=21122570

- **"Electric Plane being Developed by NASA" ABC morning news** ~ Jun 2016

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Electric-Aircraft: YUNTEC Int. *e430*

2 passenger aircraft
http://yuneeccouk.site.securepod.com/Aircraft. html

4-Passenger Aircraft @ 100 kW

Specifications	**Combustion Engine (typical)**	**All-Electric (glider-style)**
Fuel Cost @ 100 kW	~ $50/hr	~ $3/hr
Drivetrain Efficiency	~ 15 % (?)	~90 %
Fuel @ 100 kW	9 gal/hr	90 MJ/hr
Fuel Weight	70 lbs	150-300 lbs (Li-Polymer)

Impacts:

- **Flight Efficiency:** ↑ 25% or more
- **Fuel Cost :** ↓ 10x
- **Maintenance:** only a few parts
- **Ownership Cost :** extremely low
- **Noise:** ultra-quiet
- **CO_2 emission:** potentially zero
- **Other:** vertical lift, distributed, etc..

Electric, Combustion Comparison 4 Passenger: 120-150 kW

Pipestrel G4 Taurus

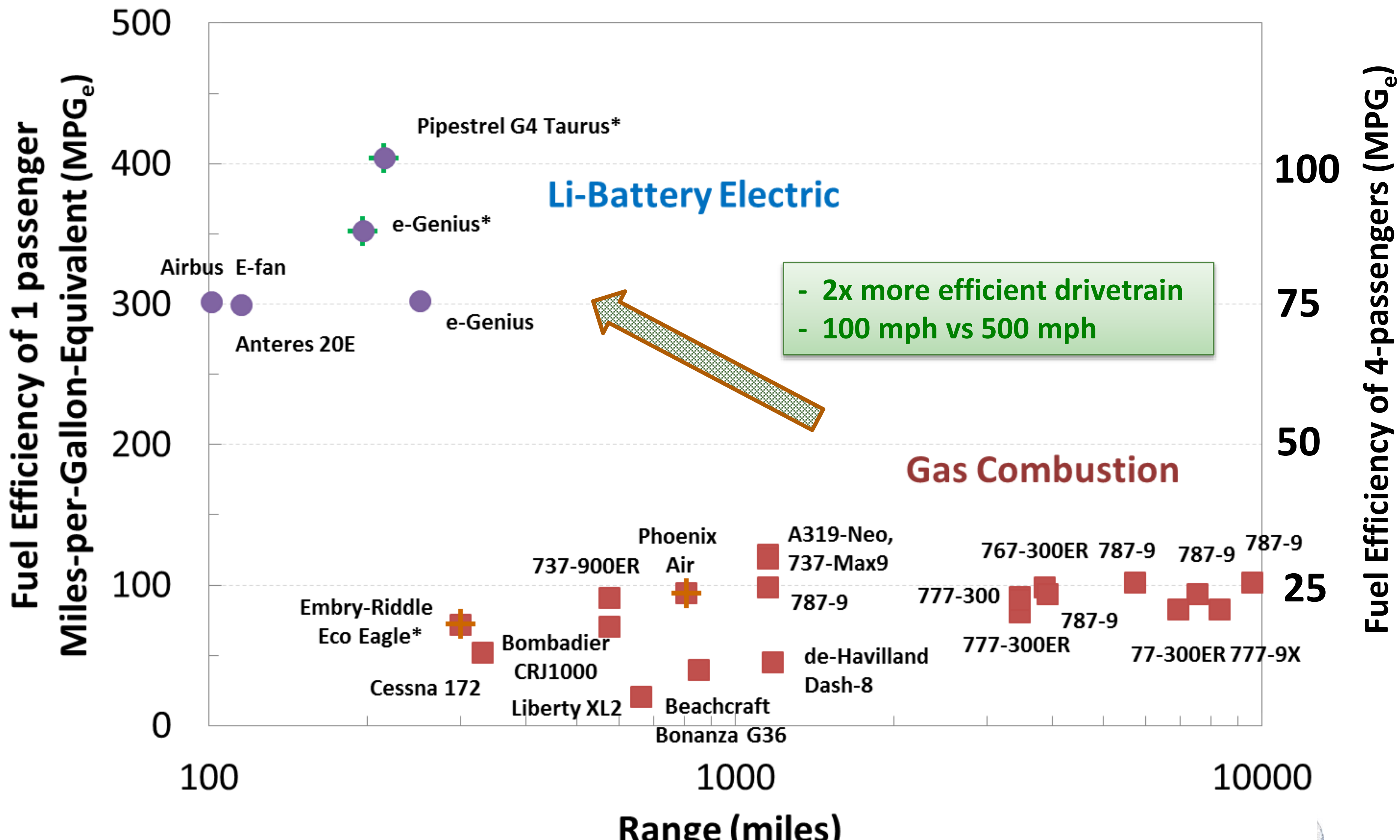
Fuel Efficiency ~ 100 mpg_e
Battery Energy Burn = 1.07Gal_e/hr
(Electric = \$2.36 gal_{equiv} @ ¢7/kW*h)
Fuel Cost = \$2.52/hr

Cessna 172 Skyhawk

Fuel Efficiency ~ 12 mpg
Fuel Burn ~ 8 Gal/hr
(AvGas \$5.60/gal)
Fuel Cost = \$45-50/hr

http://cafefoundation.org/v2/main_home.php
http://www.wired.com/autopia/2011/08/pipistrel-taurus-g4-electric/, http://wikipedia.com, other

Aircraft Propulsion Efficiency
Electric, Gas Combustion Compare



* NASA-Café Foundation 2011 class-winner

Beachcraft King Air 250, 10 passenger, 0.63 MW

- **Aircraft Specifications**

http://beechcraft.txtav.com/en/

Max. Takeoff Weight (MTOW)	12,500 lb
Usable Fuel Weight	3,645 lb
Useable Load	3,760 lb
Maximum Payload	2,170 lb
Maximum Baggage	550 lb
Engine Power Rating	634 kW

- **TEDP Electric Drivetrain*,** conventional SOA, cryo TRL 1,2 or projected

	Generators	AC to DC Inverters	Power Cables	DC to AC Inverters	Motors	System Integr/ Cool	Total
Cu-Wire/Conv Weight (lb)	341	265	782	265	341	113	2,113
Efficiency	95%	97%	99%	97%	95%		85%
Cryo/Supercon Weight (lb)	34	26	15	26	34	56	191
Efficiency	99.80%	99.70%	100%	99.70%	99.80%		99%

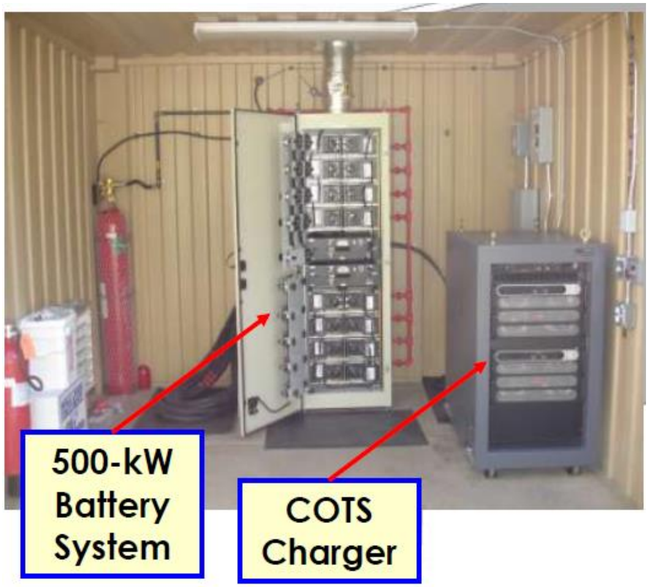
- Weight Problem

* Same component power densities as slide 40

MW-class energy storage

- **MW-class Devices:**
  - **MW-power energy-storage-device** (ESD) needed for future Aircraft
  - good **power transient capability** and **energy storage capability**
  - "Depending on the control loop, **a superconducting-magnetic energy storage (SMES) device can respond very rapidly (MWs/milliseconds)"**

Li-Battery Pack
500 kW, 70 MJ
- 800 lb
- 700 lb fire suppression



SMES Magnet
1.08 MW, 0.16 MJ
- 9.9 lb
- 3,990 A @ 270V
- 14 YBCO Subcoils in //
- Cool with ~ 1 liter liquid He per day

Northrup Grumman.DEPS proceedings (2010), SAFT update 2015

6.4 MW-Class Hybrid-Electric VTOL Aircraft – Electric Drivetrain Requirements

3.2 MW

De Havilland Dash 8
- 38 Passenger
- 36,660 lb MTOW
- 1.6 MW x 2

6.4 MW Electric Drivetrain Requirements?

Boeing V-22 Osprey
- 52,800 lb MTOW
- 4.6 MW x 2

Electric Drivetrain: Electric Generators through System Integration, Cooling

	Combustion-only weight (lb)	Present SOA Power Density (kW/kg)	Weight (lb)	Future Conventional? 3x Improve Power Density (kW/kg)	Weight (lb)	Cryoelectric, TRL = 2,3 10x Improve Power Density (kW/kg)	Weight (lb)
Combustion Motors (3.2 MW*2)	3,741	3.77	3,741	3.77	3,741	3.77	3,741
Electric Generators (3.2x2)		3.2	4,409	9.6	1,470	32	441
DC to AC Power Inverters (3.2MWx2)		6.0	2,352	18	784	60	235
AC to DC Power Inverters (0.64MW*10)		6.0	2,352	18	784	60	235
Electric Motors (0.64MW*10)		4.5	3,135	13.5	1,045	45	314
Power Cable (6.4 MW) (Cu-bird est.)			13,116		6,558	(30x)	437
System Integration, Cooling, (?) (all est.)			2,000		1,000		200
Electric Drivetrain Weight (lb)			27,364		11,641		1,862
Total Machine Weight (lb)	3,741		31,105		15,381		5,603
Fuel Weight (Max.)	6,039						4,177
Typical Payload (lb)	7,511		7,511		7,511		7,511
Machine+Fuel+Payload (const, lb)	17,291		38,616		22,892		17,291
Aicraft Wt (max.)	36,660		36,660		36,660		36,660
Range Max, fuel-estimate-only (miles)	1,174		0		0		812

Machine+Fuel+Payload ≤ 17,291 lb (upper limit)

Summary: > 5x higher power densities than SOA needed to allow useful fuel loads

Photos: en.Wikipedia.org

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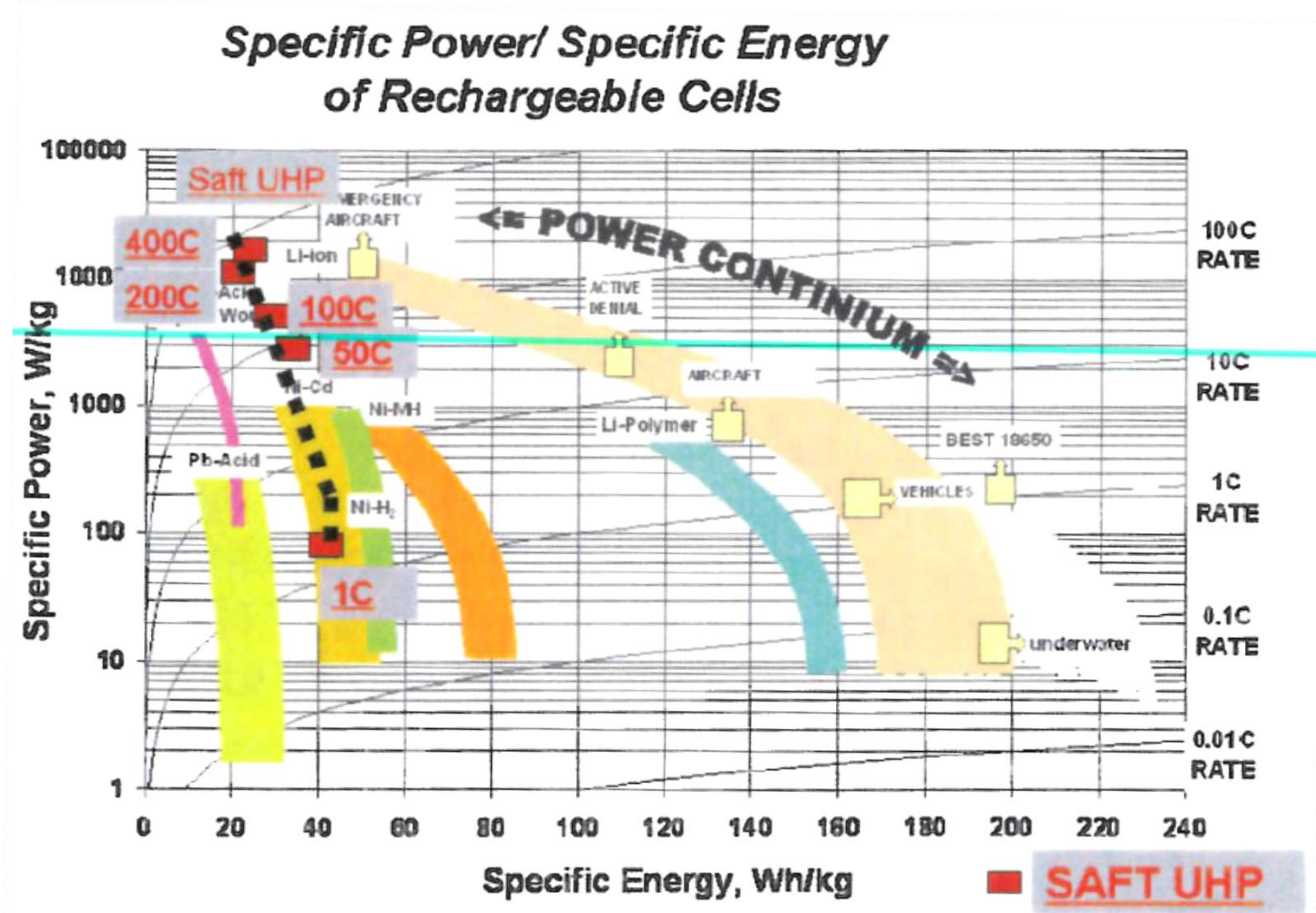
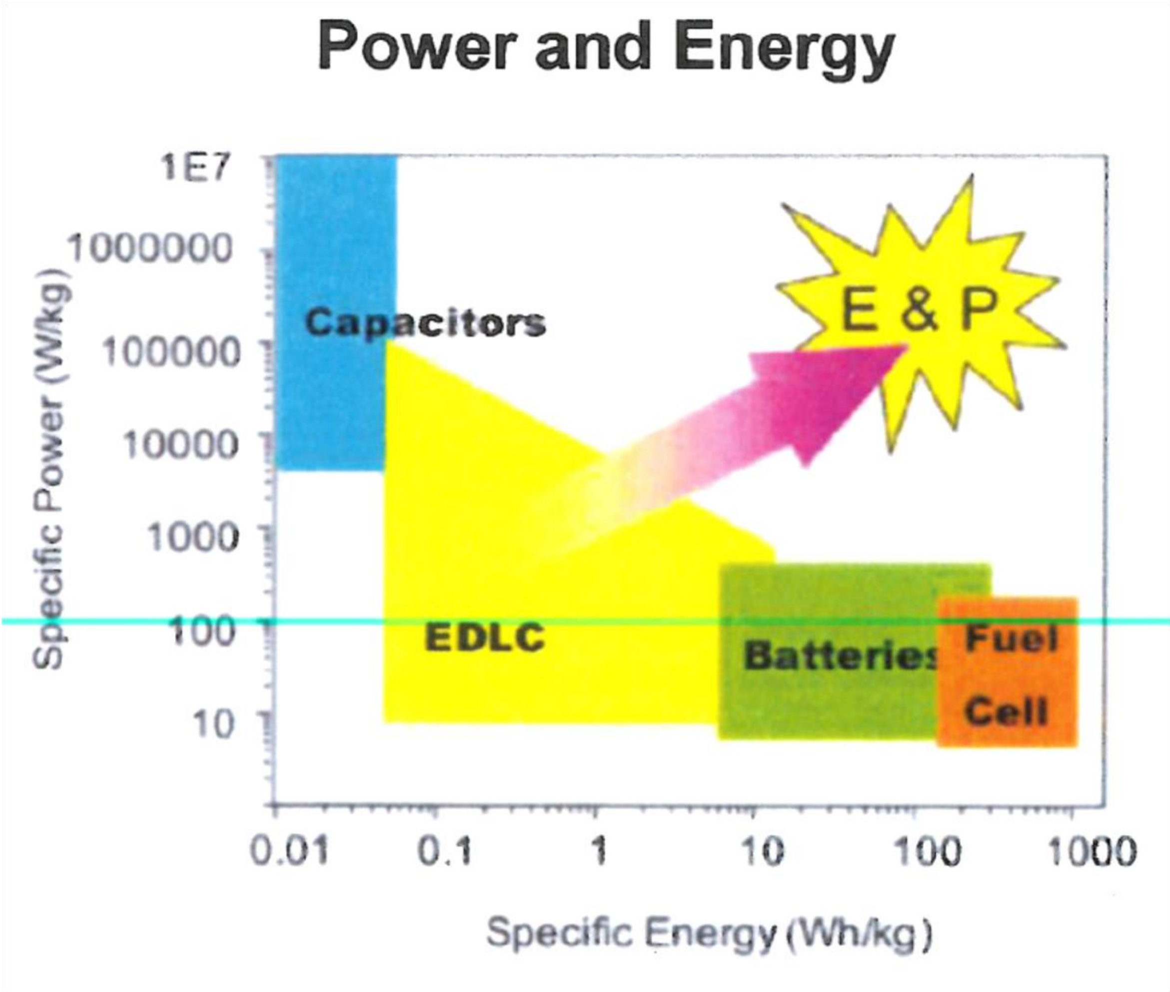
- **Energy Storage Technologies for Aerospace Needs**

Ragone Chart



E. Shaffer (Army RDECOM), "Power and Energy Tutorial", DEPS Nov 2010

Ragone Chart



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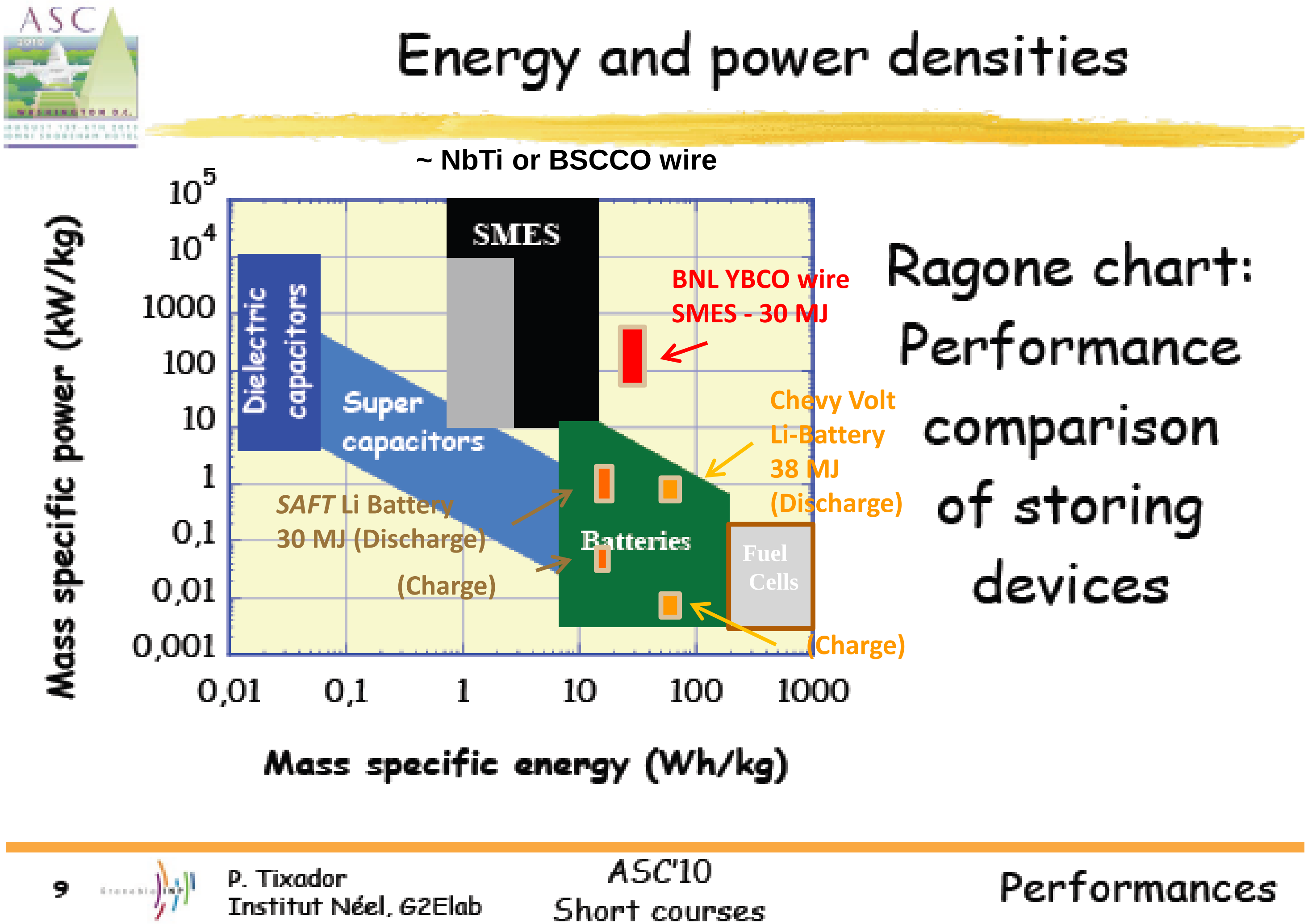
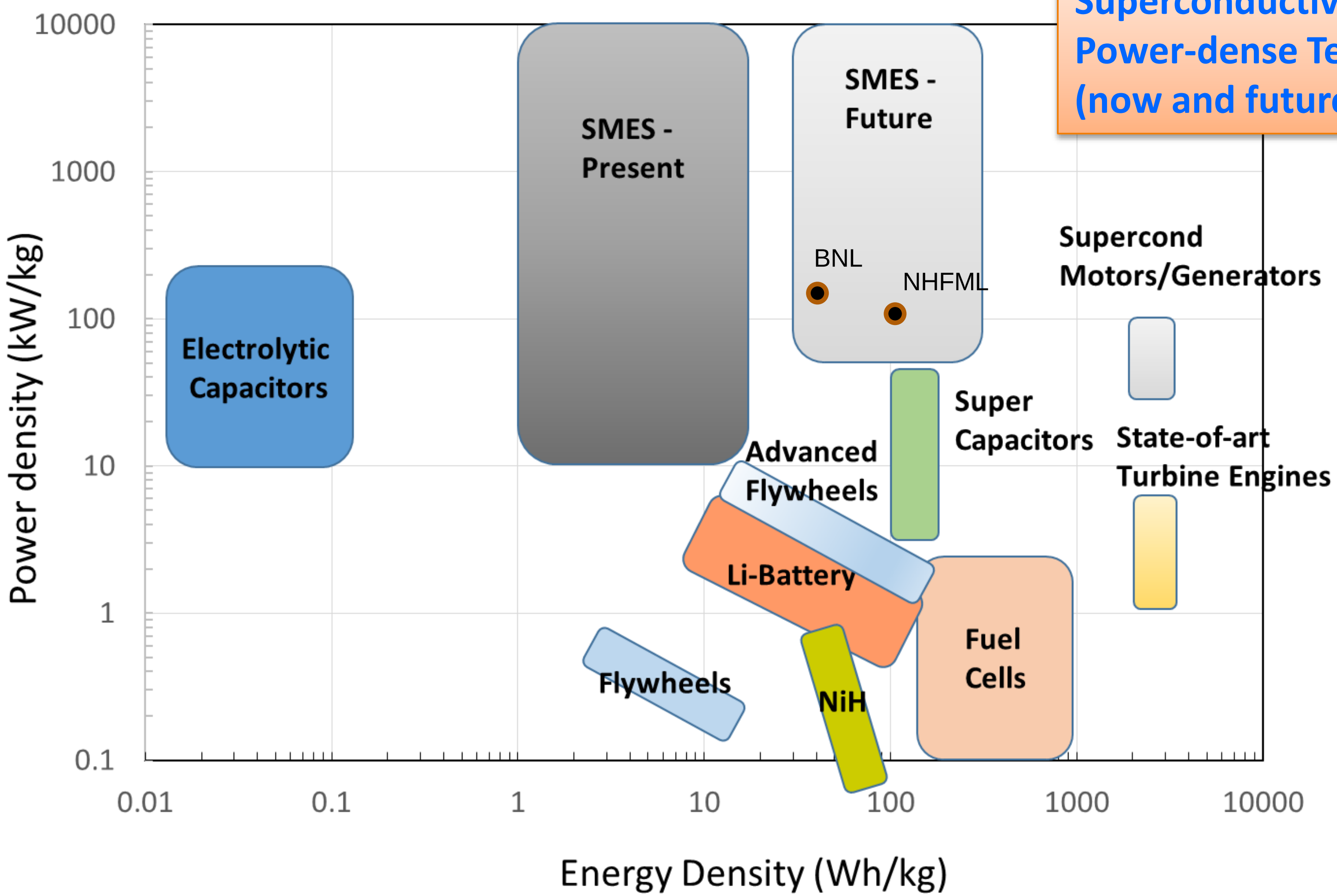
Ragone Chart



Base chart from ASC '10

Ragone Chart Updated, Power Density and Energy Density



Superconductivity most Power-dense Technology (now and future projected) !!

Energy Density

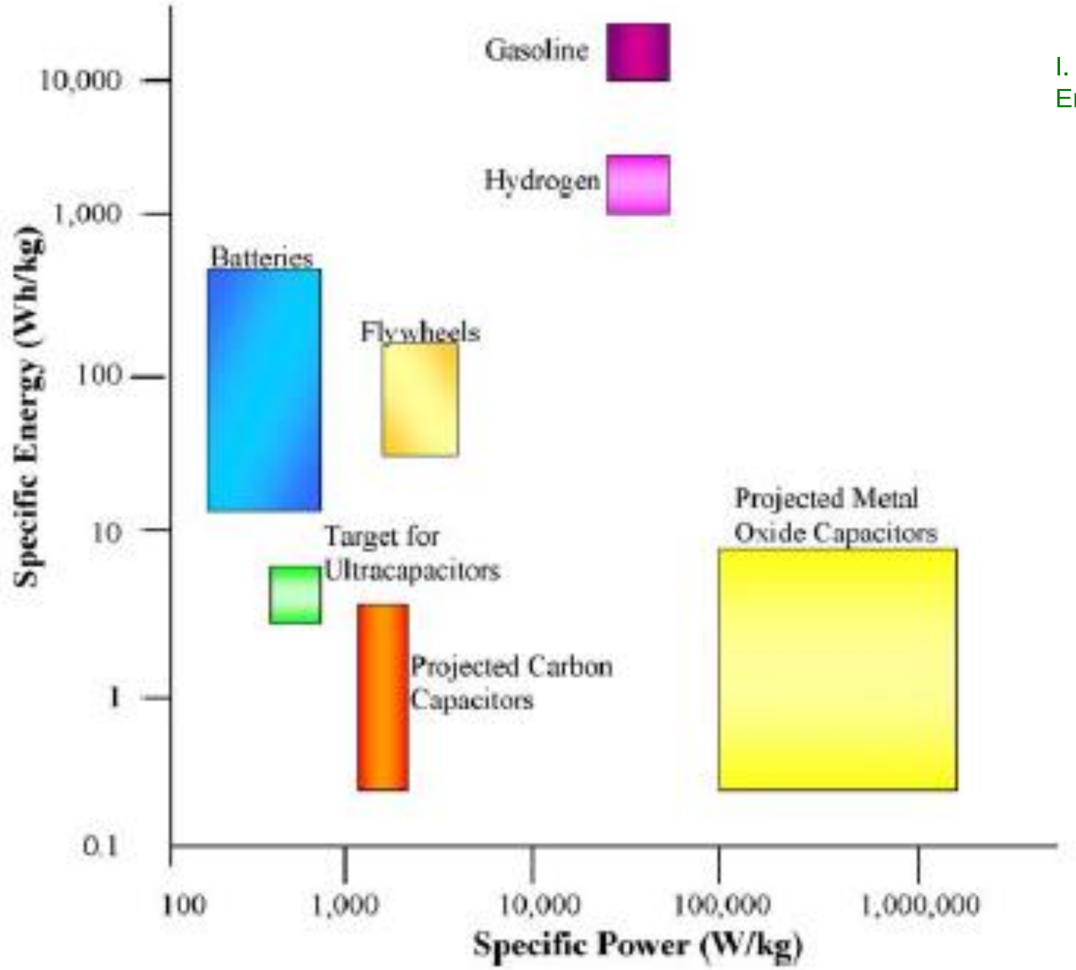


Fig. 10. Comparison of specific power and energy storage potential of each storage technology [7].

I. Hadjipaschalis, et al, Renew. Sustain. Energy Rev. **13**, 1513 (2009)

Energy Storage Power Ratings

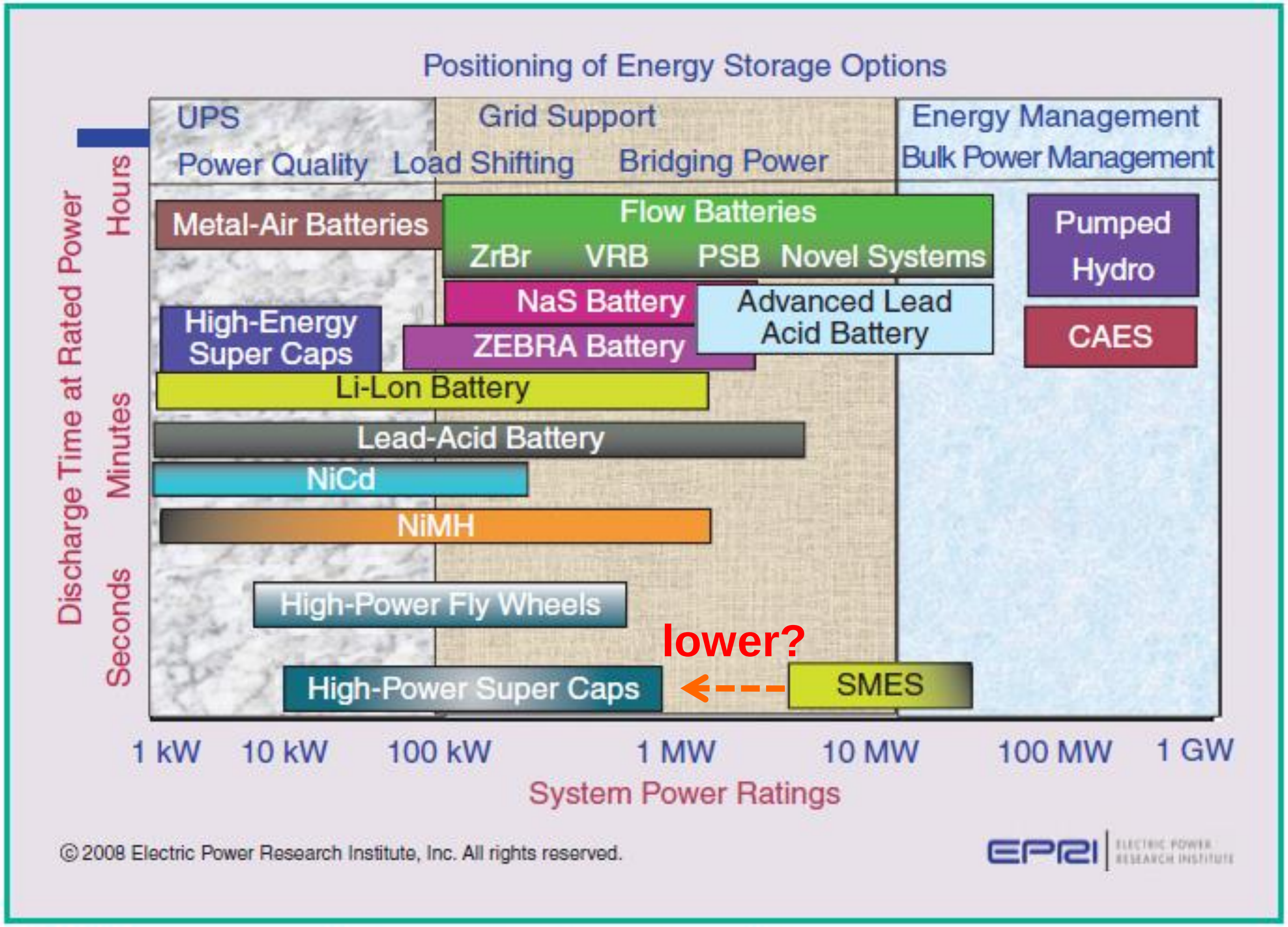


figure 2. Storage technology application comparison.

IEEE Power and Energy Magazine, pp. 32-41, jul/august 2009

What is SMES ?

- **"Superconducting Magnetic Energy Storage" (SMES)** is electrical energy stored in any inductor device (L), e.g. magnet coils, that require energy/work to be charged

Energy stored in inductor = $\frac{1}{2} * L * I^2$

Energy density in magnetic field = $\frac{1}{2} * (B^2/\mu)$

- Energy of circulating currents is stored for up to 10 yrs with < 0.0001% loss!
- Only energy needed is for refrigeration, e.g. @ 4.2K = 2 kW cool power

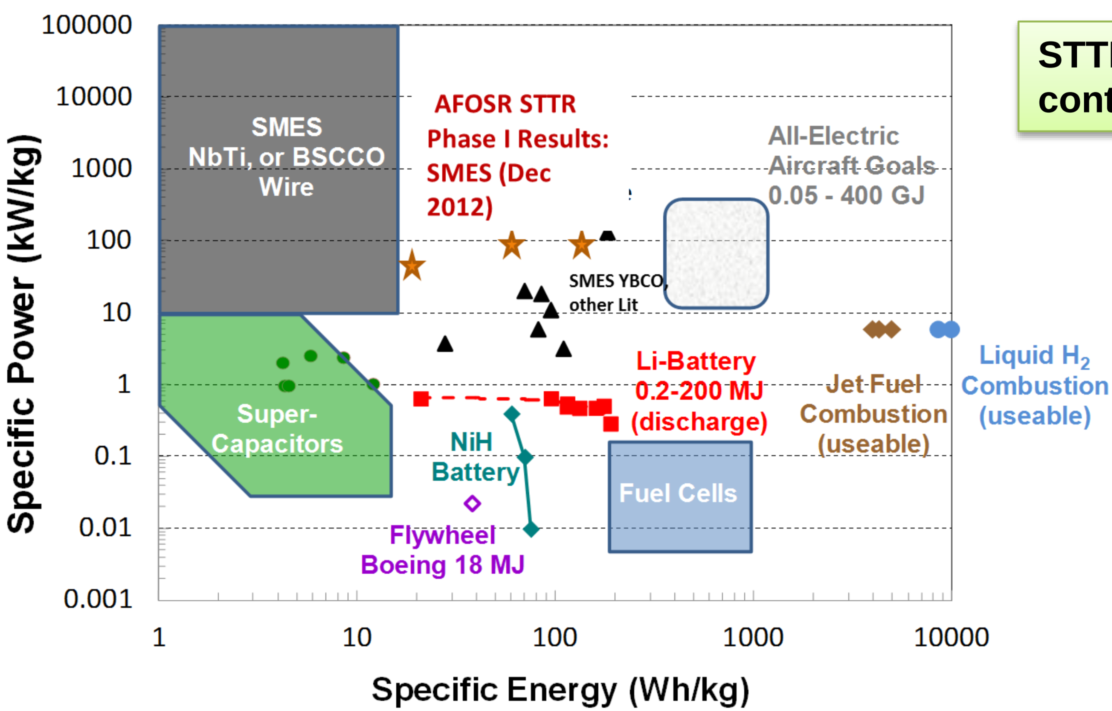
http://www2.portagehealth.org/index.php?p=service_detailservice&service_id=1689

MRI Scanner, E = 0.1 to 30 MJ

Issues, Background Info

- SMES first developed in the 1980's
- **Employed in the power grid in the 1990's for instantaneous energy and power management, at 40 MVA power levels (TRL = 9)**
- "Depending on the control loop of its power conversion unit and switching characteristics, **the SMES system can respond very rapidly (MWs/milliseconds).**"

L. Chen, et al, *IEEE Trans. Appl. Power Delivery*, v21(2), 699 (2006)



STTR results are for 70 MJ devices, continuous power

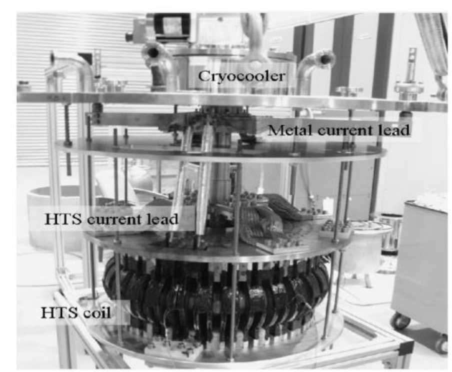


Figure 1: Example of a Toroidal HTS SMES System with Pancake Coil Construction[1]

A.R. Kim, IEEE TAS **20(3),** 2010

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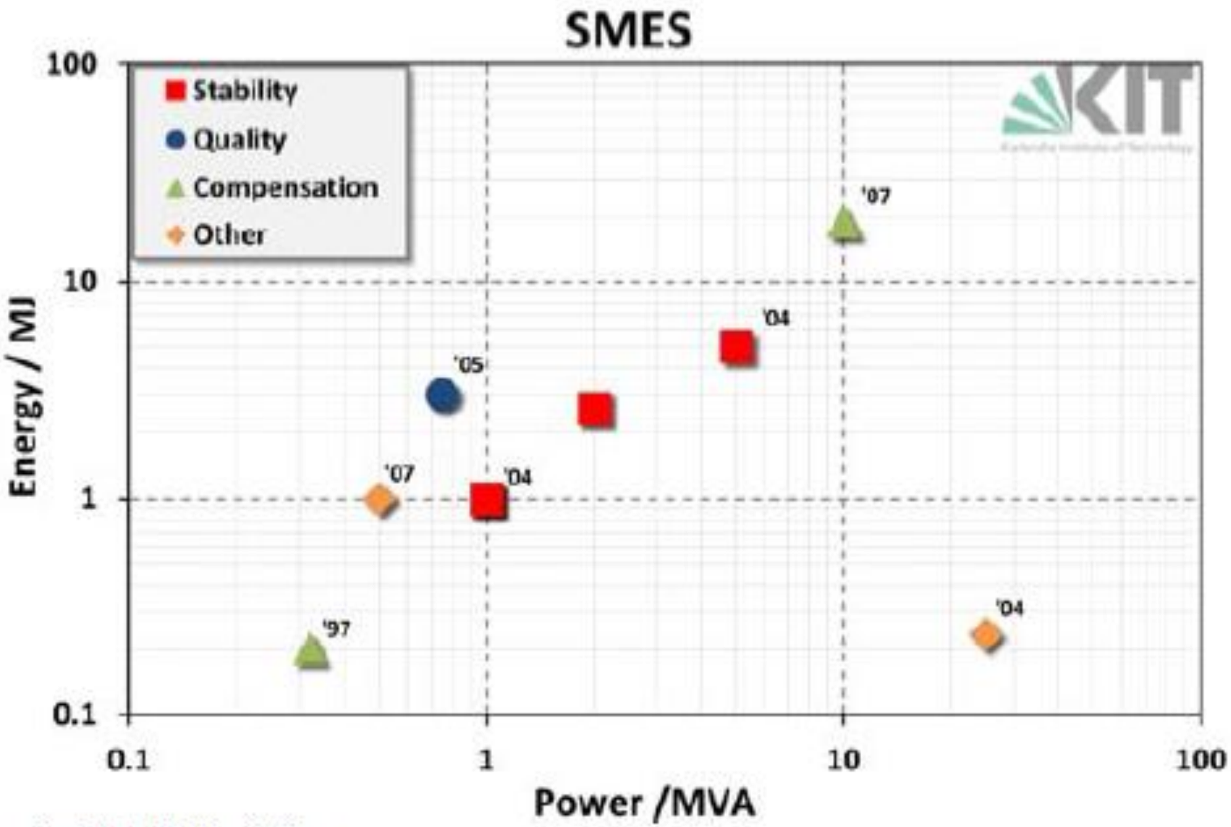
State-of-the-Art SMES



Source: www.itep.kit.edu/HTS4Application

Maximum Energy 20 MJ with LTS up to now

SMES Design Criteria

- SMES Design Criteria for Aerospace Systems
  - Energy and Power Densities (mass specific)
    - Weight
    - Volume
  - Efficiency (charge/discharge cycle)
  - Operability and Logistics
  - Development, Parts, Assembly Cost, Life Cycle Acquisition
- Limiting Factors for Maximum Energy Density
  - J_e vs H properties
  - Lorentz Forces – Virial Theorem
  - AC losses during charge/discharge – filament size, switches
  - Stray magnetic fields
  - Cable and magnet design
  - Stability and Quench protection
  - Minimize/eliminate wire joints

SMES Support Systems Needed

- Current Leads to ambient temperature
- Persistent Circuit Switches
- Cryovessel
- Cryocooling Technologies
- Power Electronic Circuits
- Quench-Protection/Mitigation

SMES Design Criteria Summary

	0.2 MJ INVENT	5-50 MJ Directed Energy	0.2-2 GJ Electric Drive Aircraft
High Duty Cycle	10	4	1
AC Loss	10	8	1
High Efficiency	7	8	10
Low Weight/Volume	5	8	10
Operability/Logistics	9	7	6
Cost	7	9	10

Rating Scale: 10 is highest and 1 is low for importance (approximate)

AFRL/RQQ Basic Research: SMES Devices cont.

Primary Goal: Determine whether SMES is a viable energy storage alternative for air and space applications

Goals for this study

- Investigate maximum energy density winding geometries for 2nd Gen YBCO tape, and MgB_2 and Nb_3Sn wire. (NbTi will be included at a later date)
  - Find solenoid SMES winding configurations that **maximize specific energy density** for a given energy.
  - Investigate the scaling-law dependence of energy density, winding volume, radius, as a function of total energy stored

Motivation

- An approximation of the size, geometry, cost, and performance of potential SMES configurations is useful in giving direction to future studies on SMES for Air Force applications.

Limitations for this study

- Winding volume of generic wire is the **only** consideration.
- We consider ***only the critical current constraint.*** The virial theorem limit is considered as an upper bound after the fact.
- Only a solenoid geometry is considered. 4.2K is the primary temperature focus.

AFRL/RQQ Basic Research: SMES Devices cont.

Mathematical Problem Summary

For a given energy E maximize

$$\varepsilon = \frac{1}{2}L(a,b,l)I^2(B_{peak}(a,b,l))/V(a,b,l)$$

Governing Equations

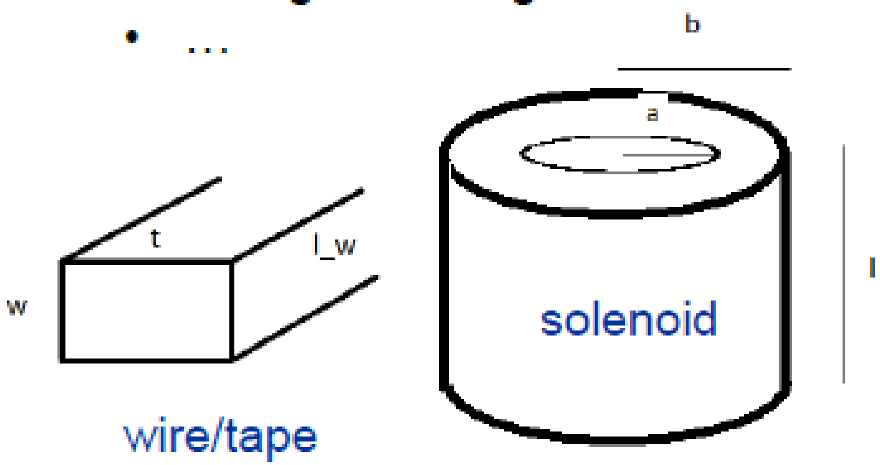
- $E = \frac{1}{2}LI_{op}^2$
- $L = 3.1496 \times 10^{-6}\frac{r^2N^2}{6r+9l+10(b-a)}$
  - Wheeler's approximation
  - Limiting Case Error
    - Pancake coil: less than 8%
    - Infinitely long solenoid: 11%
    - $6r \cong 9l \cong 10(\mathrm{b}-\mathrm{a})$: 1%

Constraints

- $I_{op} \leq fI_c(B_{peak})$ where $f = 0.7$ is an engineering safety factor
- $V = \pi(b^2 - a^2)l = l_{wire}wt$

Constraints not yet fully considered

- Stress/strain
- Stray field
- Charge/discharge rates
- …



Implementation

- **Mathematical Problem Summary**
  - **For a given E maximize** $\frac{1}{2}L(a,b,l)I^2(B_{peak}(a,b,l))/\mathrm{m}(V(a,b,l))$
  - **With the constraints:**
    - $V = \pi(b^2 - a^2)l = l_{wire}wt$
    - $I_{op} \leq f I_c(B)$ **where** $f = 0.7$
- **Computational Approach: Explore the parameter space for the smallest volume configuration that satisfies the constraints for a given energy.**
- **…or, for a given energy, find the solenoid that works with the least amount of wire.**

Loop over values of l (solenoid length)

↓

Loop over values of b (outer radius)

↓

Loop over values of a (inner radius)

↓

Inductance $L = L(a,b,l)$

Compute for a particular *E*:

Operating current: $I_{op} = \frac{\sqrt{2E}}{L}$

Calculate peak B on the windings

Look up $I_c(B)$

↓

If $I_{op} > fI_c(B)$ then discard and continue

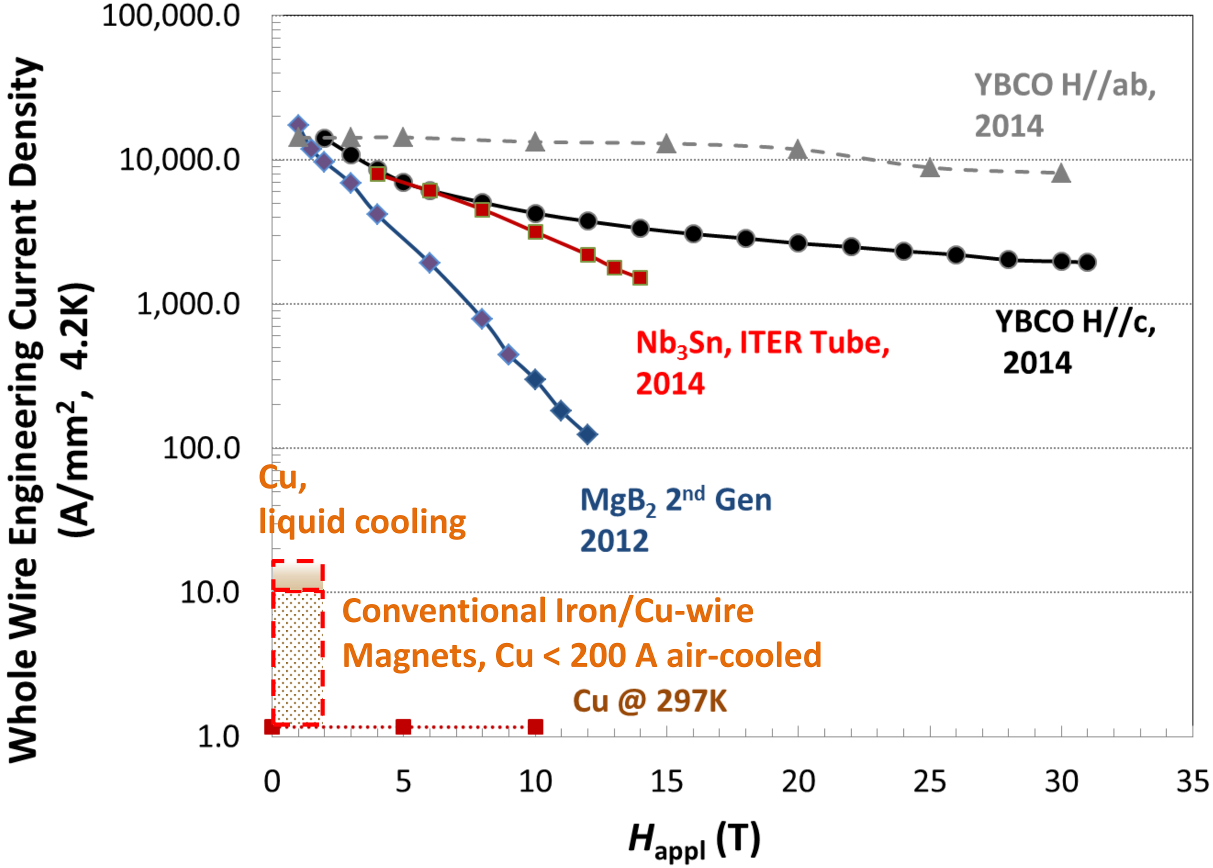
Else

Record design and continue

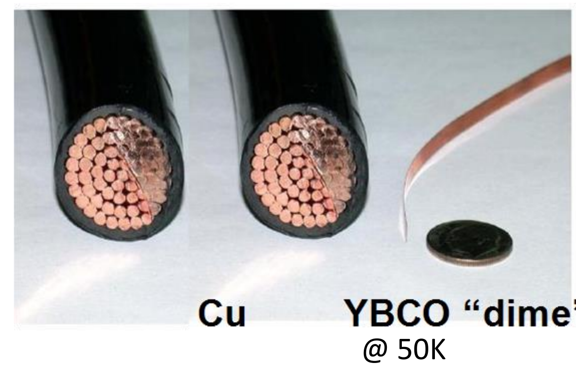
Superconductor Wires, Km-length and < $40/meter

Superconductors: 1,000-10,000x higher current densities than metals !!

Cu-wire: no change in > 100 years, 15% heavier than steel !!

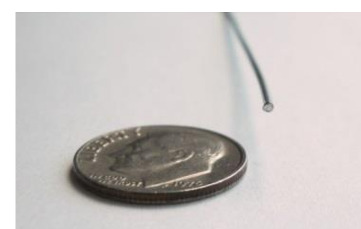


800A Wires (0.22 MW @ 270V)



MgB_2 ~ 0.8 mm_{OD} Wire

8,000 A @ 20K



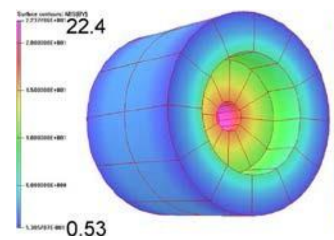
AFRL

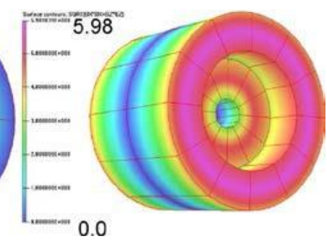
Comparison of Modeling Methods to Published Experiment

TABLE I
MAIN DESIGN PARAMETERS

Target Design field (optimistic)	~22 T
Number of coils (radial segmentation)	2 self supporting
Stored Energy (both coils)	~110 kJ
Inductance (both in series)	4.6 H
Nominal Design Current	~220 A
Insulation (Kapton or stainless steel)	~0.025 mm
J_e (engineering current density in coil)	~390 A/mm^2
Conductor	2G ReBCO/YBCO
Width	~4 mm
Thickness	~0.1 mm
Stablizer	~0.04 mm Cu
Outer Solenoid Parameter	
Inner diameter	~100 mm
Outer diameter	~160 mm
Length	~128 mm
Number of turns per pancake	~240 (nominal)
Number of Pancakes	28 (14 double)
Total conductor used	2.8 km
Target field generated by itself	~10 T (@4.2 K)
Inner Solenoid Parameter	
Inner diameter	~25 mm
Outer diameter	~90 mm
Length	~64 mm
Number of turns per pancake	~260 (nominal)
Number of Pancakes	14 (7 double)
Total conductor used	0.7 km
Target field generated by itself	~12 T (@4.2 K)
External Radial support (overband)	Stainless steel tape

HTS nested solenoids under development for muon collider applications for BNL. Solenoids were tested individually. Measured and calculated (in red) B values compared below.



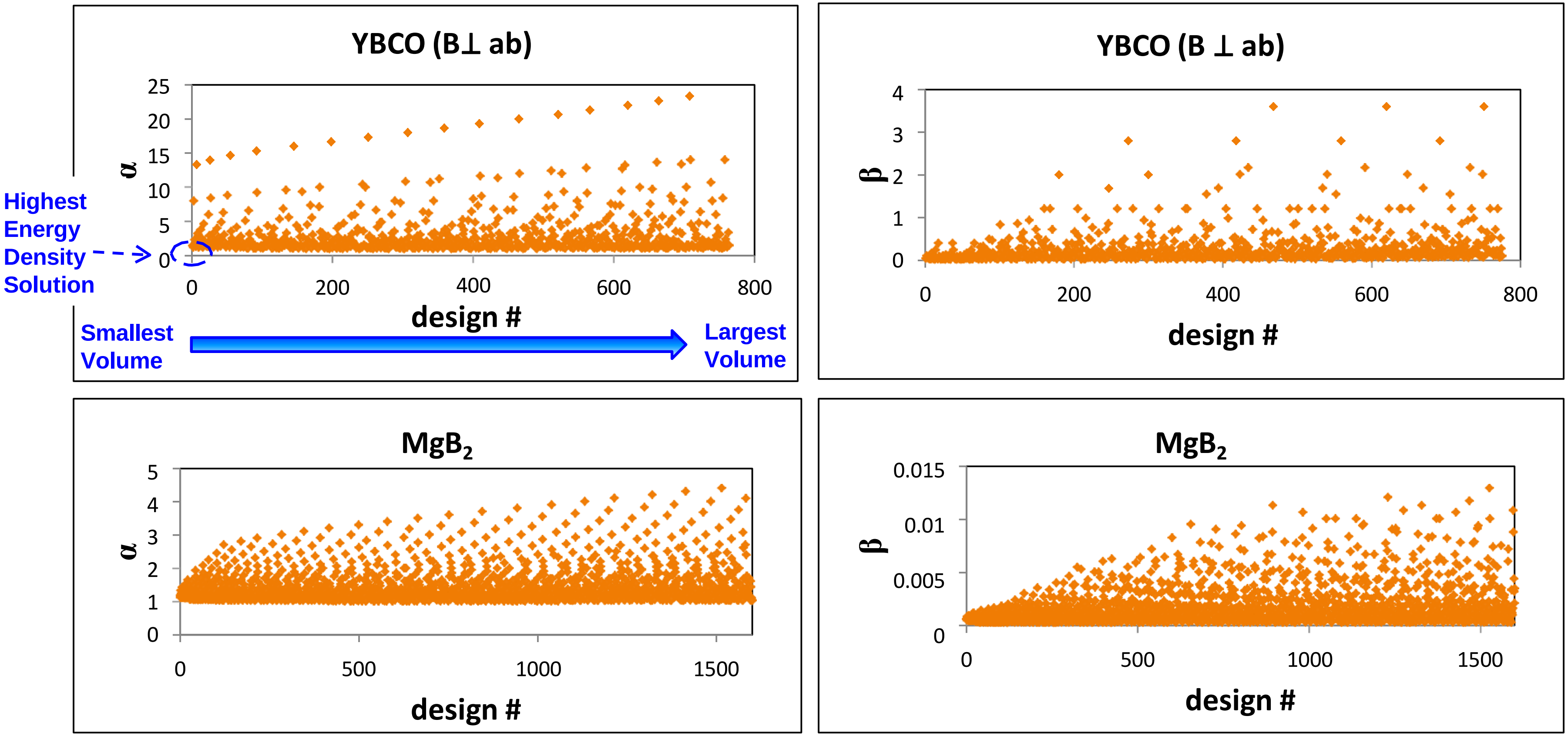


	L(H)	I(A)	E(MJ)	B(T) peak	B(T) central
inner	0.32	285	0.013	16.2	15.8
	0.32	284.44	.013	15.56	15.22
Outer (12 pancakes)	0.93	250	0.029	9.2	6.4
	0.93	249.99	.0291	9.23	6.49

Slight difference in B filed may be due to approximate reported dimensions

R. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1884–1887, Jun 2011
R. Gupta et al., *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun 2014

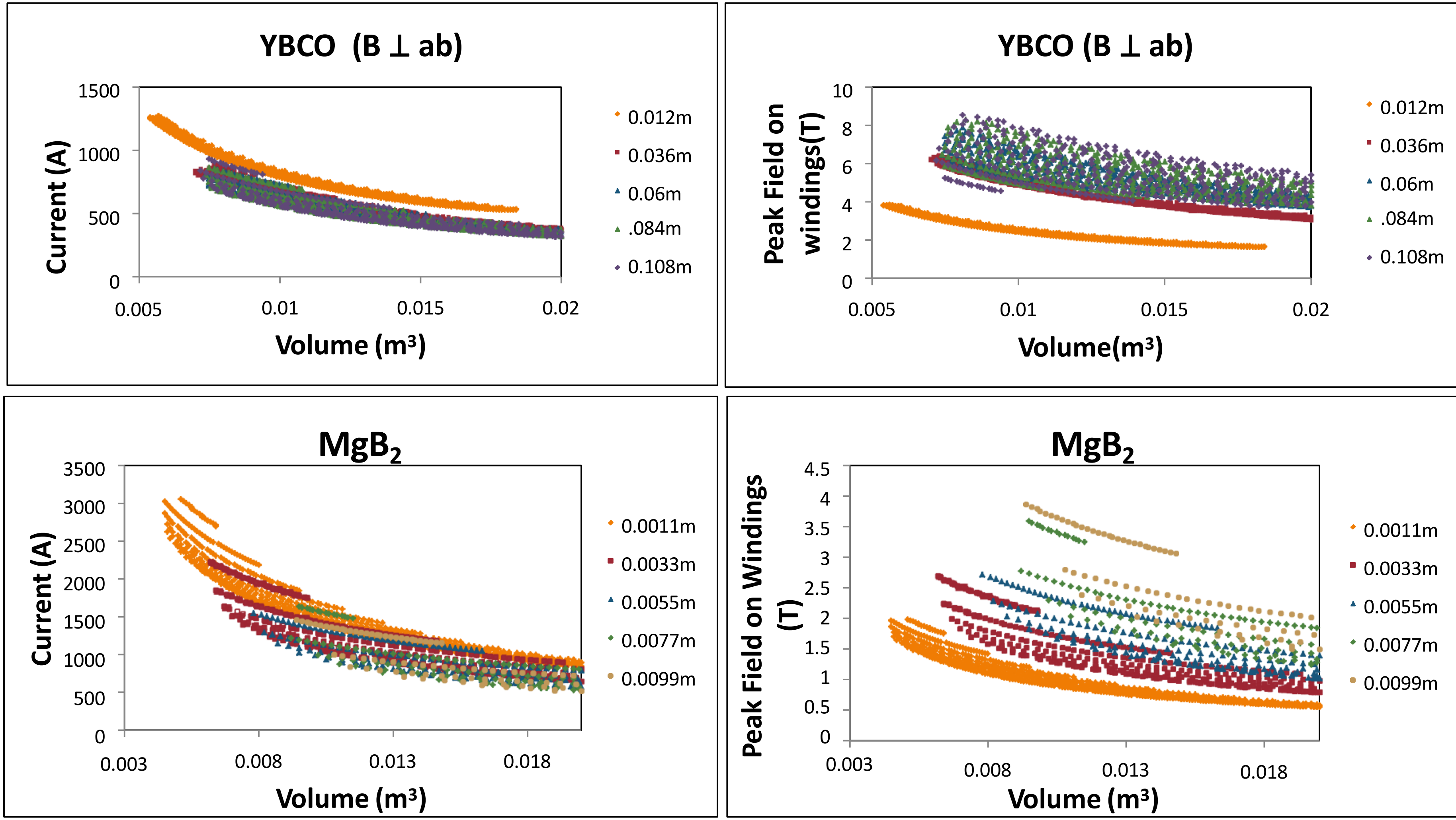
3MJ, 4.2K: Geometry



Plots show solenoid parameter ratios $\alpha = b/a$ $\alpha = l/a$ vs design number sorted by increasing volume. Optimum coil geometry **tends** to be a pancake (Yuan et al., 2010) with $\alpha \sim 1.8$ for YBCO and
$\alpha \sim$ 1.2 for MgB_2 and Nb_3Sn.

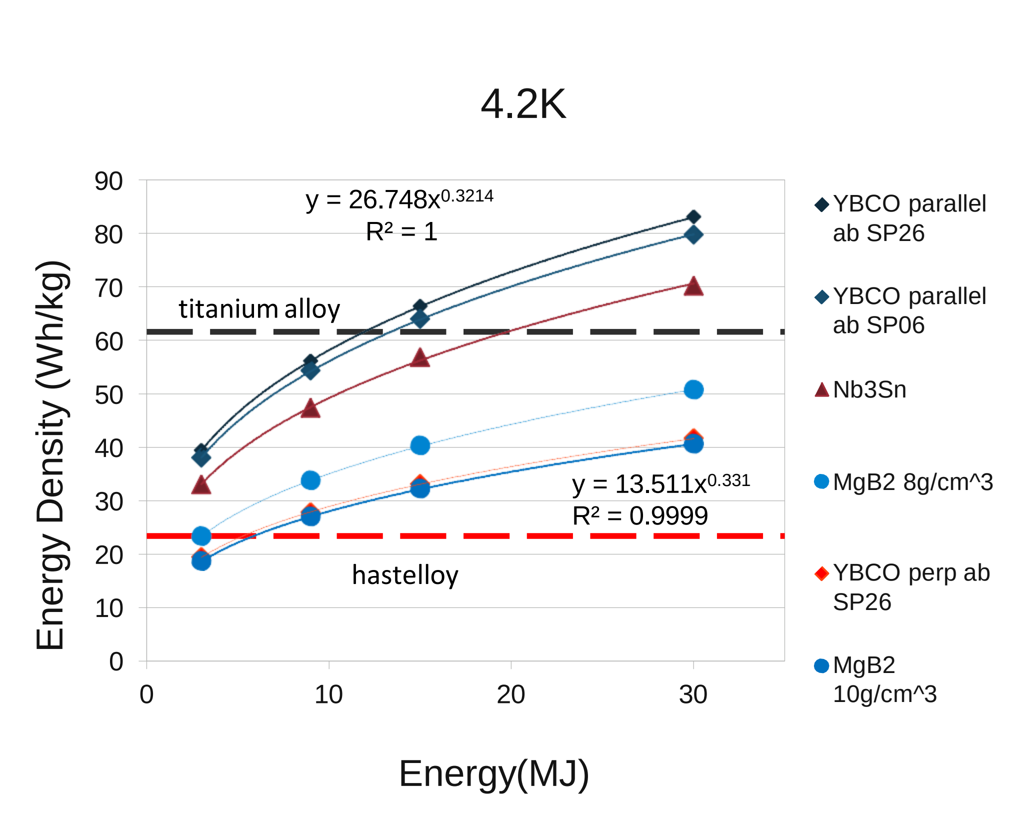
W. Yuan et al., *IEEE Trans. Appl. Supercond*, vol. 20, no. 3, pp. 1379-1382, Jun 2010

3MJ, 4.2K: Fields and Current



Color indicates height of solenoid design. Pancake designs tend toward high currents and low magnetic fields.

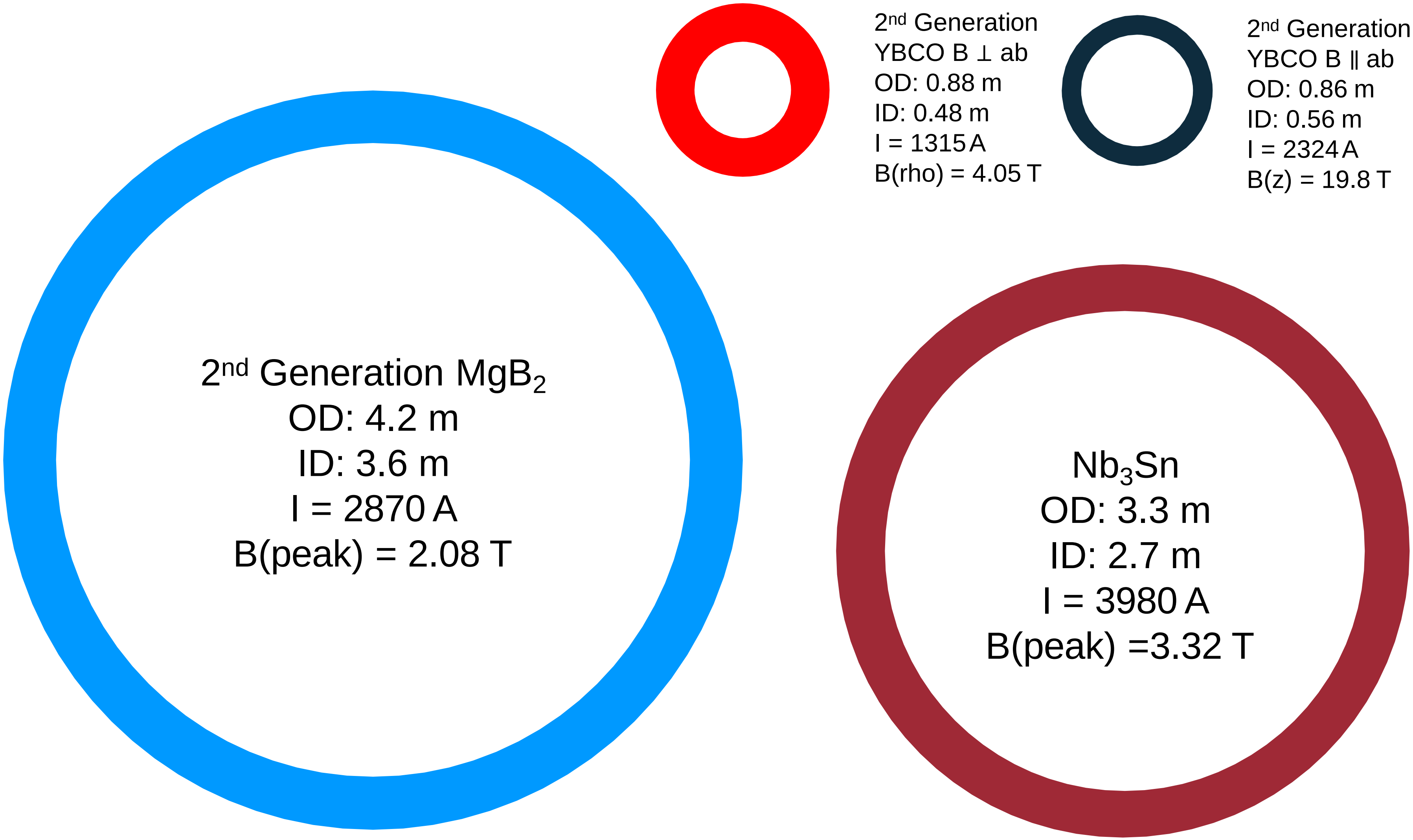
Largest Energy Density Designs



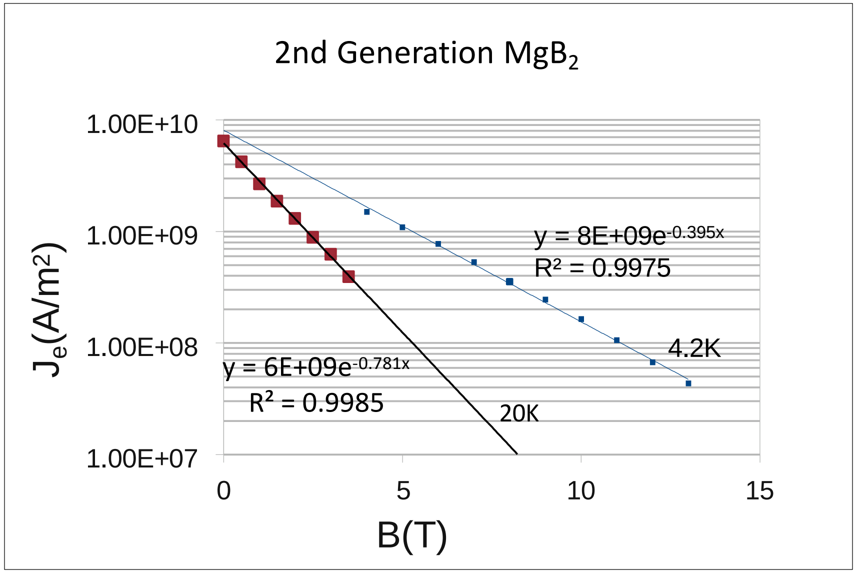
Wire type	Peak Magnetic Field(T)	Current(A)
Nb_3Sn	~3	~3900
MgB_2	~2	~2900
YBCO ‖ ab	~21	~2300
YBCO ⊥ ab	~4	~1300

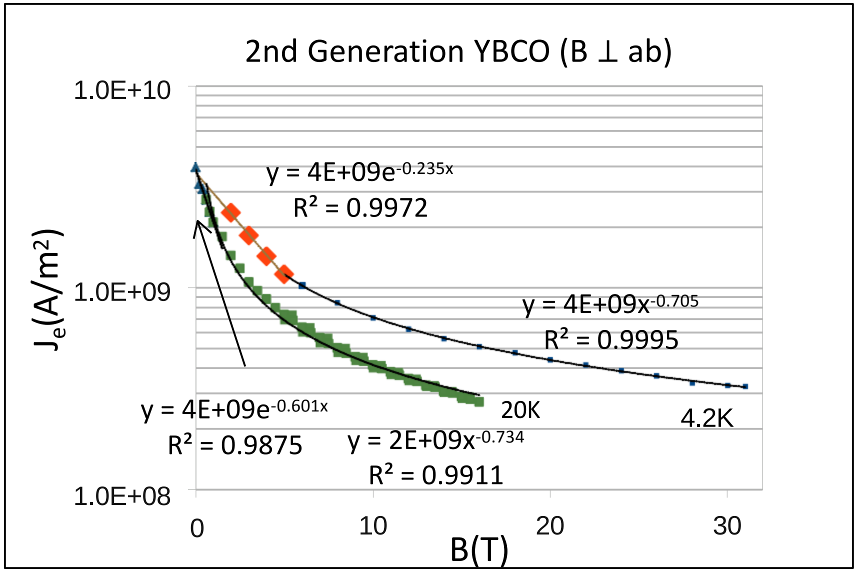
- Each data point represents a highest energy density design for a particular energy.
- Energy density scales as $\varepsilon \sim E^{1} \rightarrow m \sim E^{2}$ (Hassenzahl 1991) regardless of superconductor wire type. ***The J_e(B) constraint puts an upper bound on the energy density for a given energy, but not on the energy density itself.***
- Currents and fields for a particular wire type always arrive at the same approximate value.

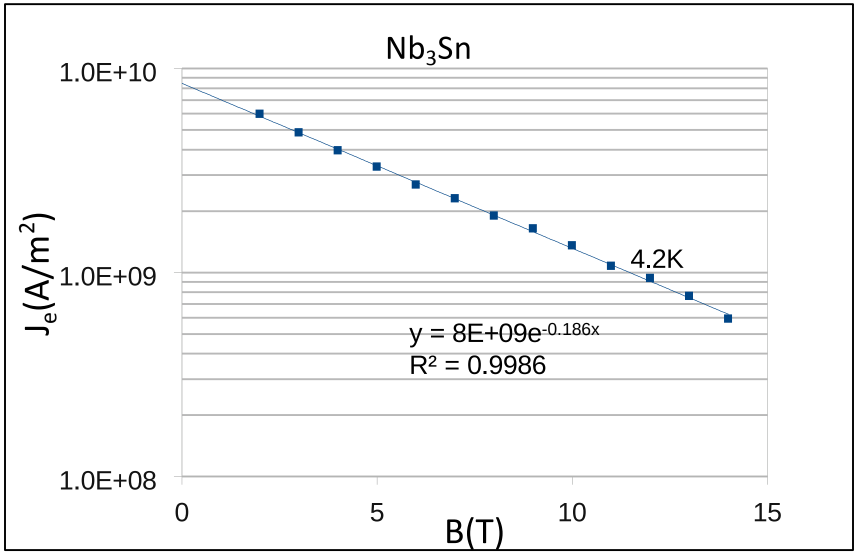
3MJ, Largest Energy Density Designs (4.2K)



Wire Performance and Data Parameterization





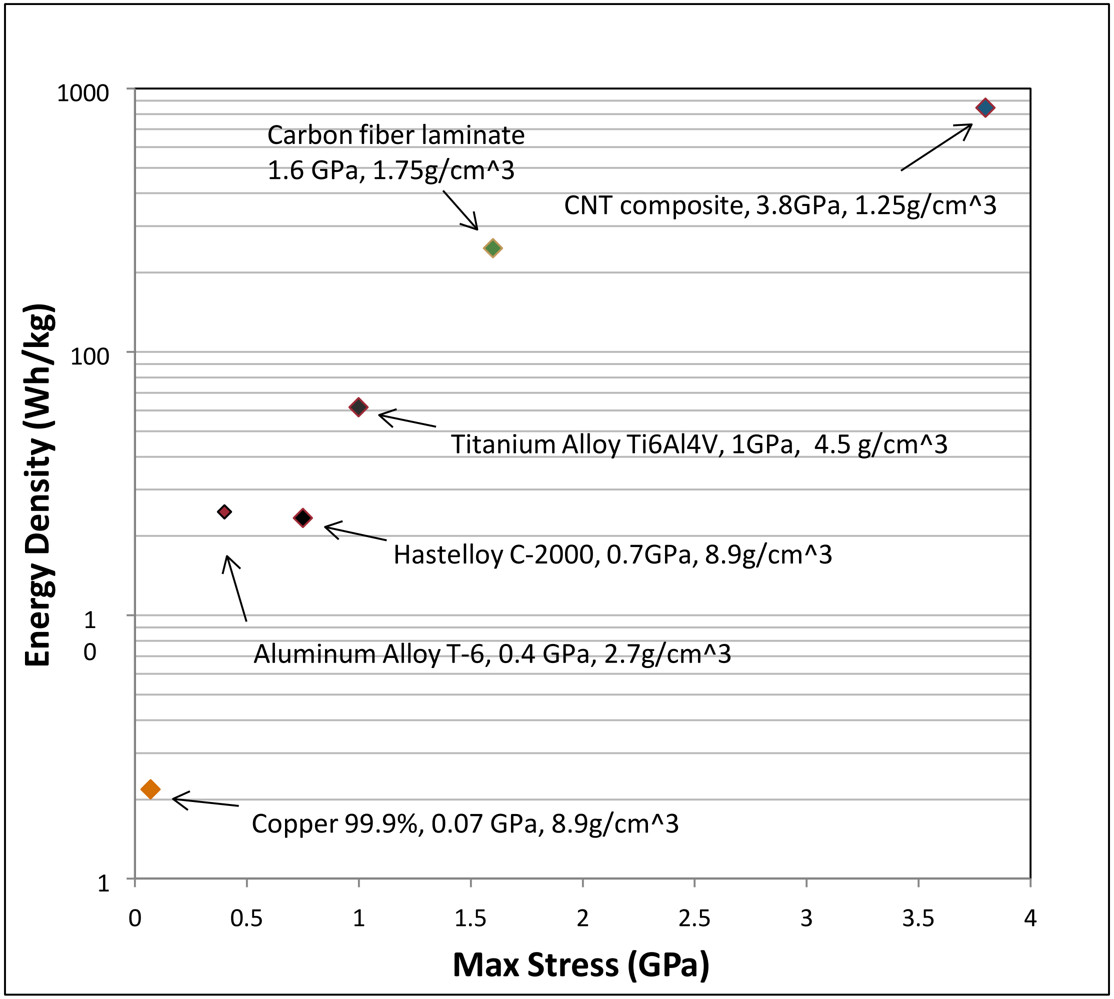


- YBCO curves are fit, piece-wise, to power law and exponential curves. All others fit well to a single exponential curve.

References:

- M. Sumption, Cryogenics 52 (2012) 91-99
- M. Tomzic, Hyper Tech MgB2 EUCAS 2013 presentation, "The Markets that are Opening for MgB2 Superconductors" p 17
- A. Xu et al., Supercond. Sci. Technol. 23 (2010) 014003
- V Braccini et al., Supercond. Sci. Technol. 24 (2011) 035001

Virial Theorem Limit



Virial Theorem

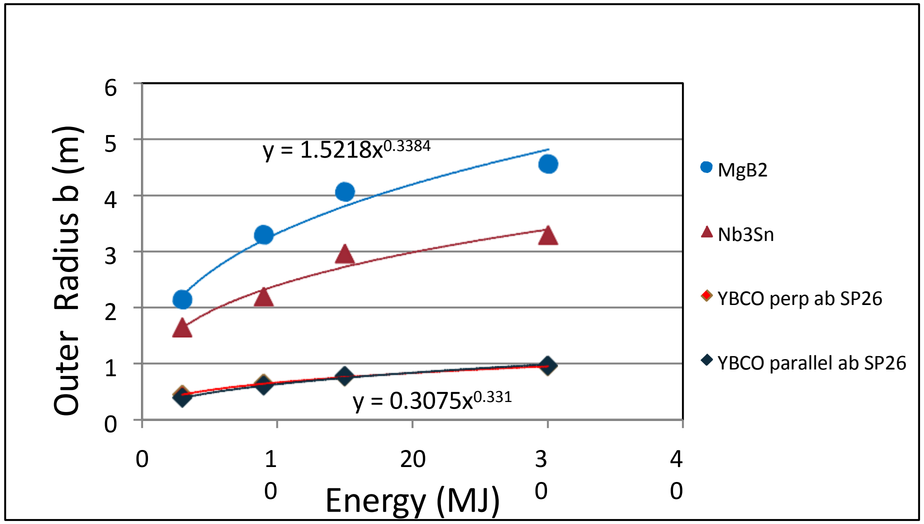
$$\epsilon = \frac{3600 * Q_{max}}{\rho_s * \sigma_{max}}$$

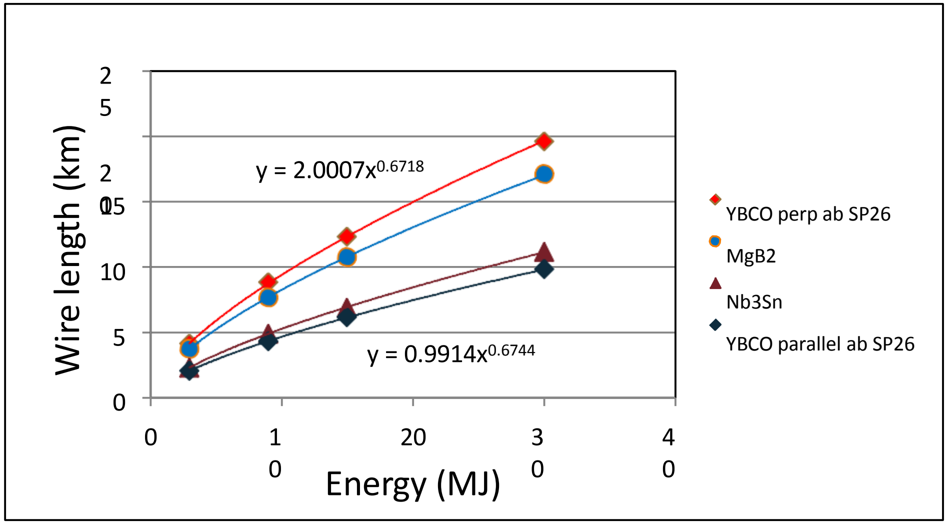
ε = Energy Density(Wh/kg)
ρ = denisty of supporting structure
σ_{max} = maximum stress (Pa)
Q_{max} = structure factor

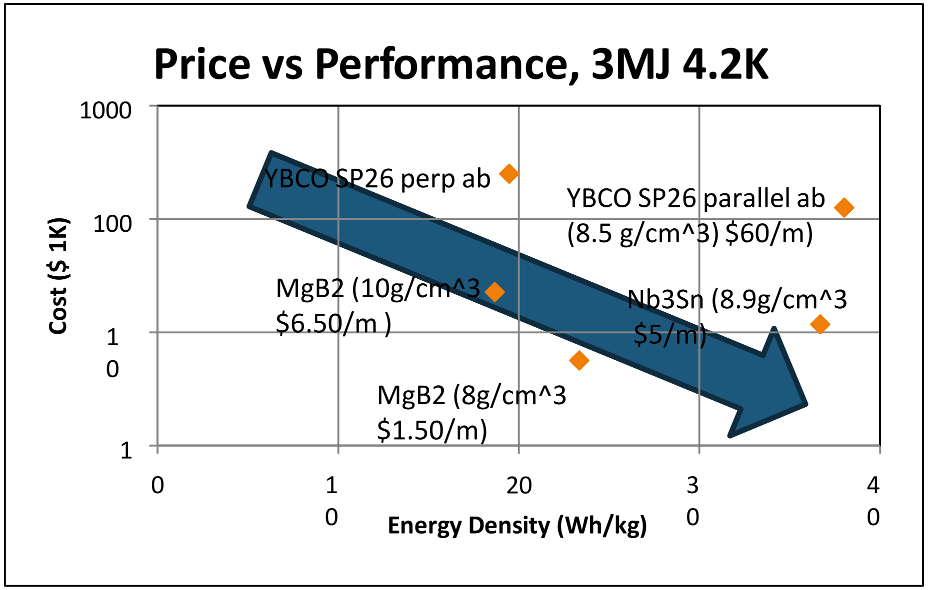
- 0.5 toroid
- 1.0 optimized solenoid
- 1-2 solenoid
- > 2 toroid field coil

CNT composite values taken from X. Wang, Mat. Res. Lett, iFirst 1-7 (2012)

Largest Energy Density Designs (4.2K)







- SMES designs for MgB_2 and Nb3Sn tend toward larger spatial dimensions than YBCO. Wire length grows as $E^{2/3}$
- From the length we can estimate cost of the wire. Depending on design requirements different wire type provides different cost options
.

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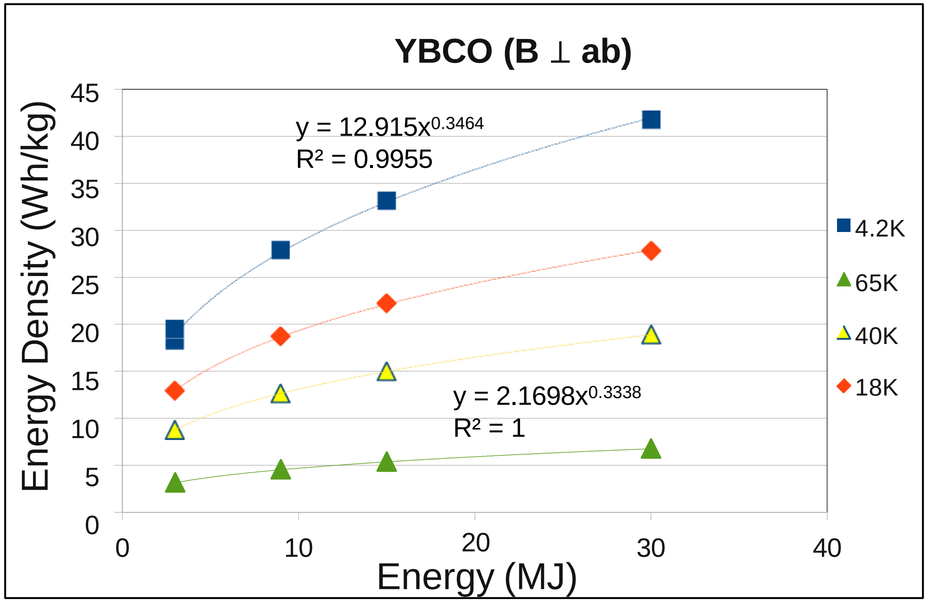
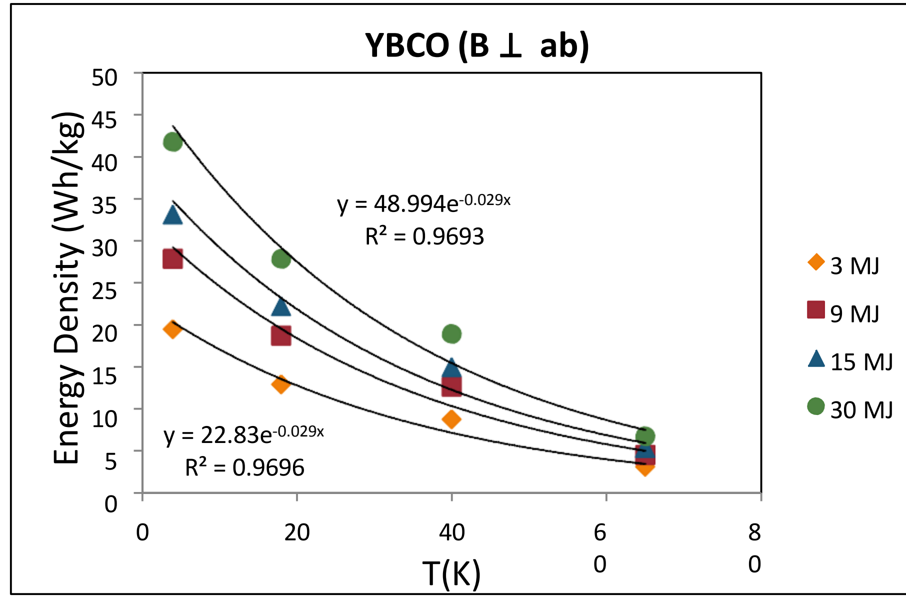
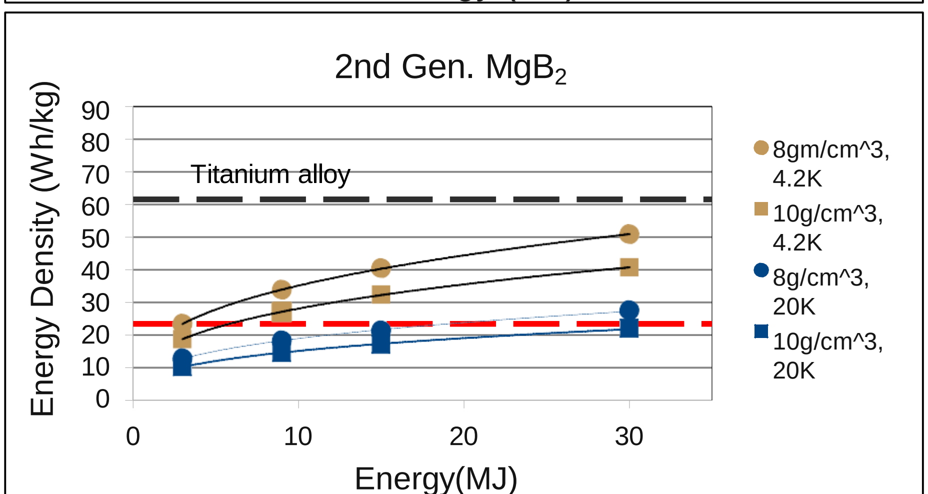
Temperature Dependence of SMES Designs

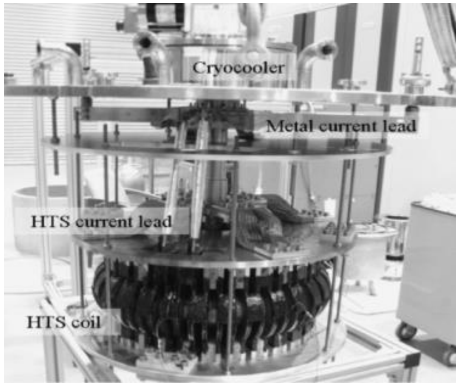




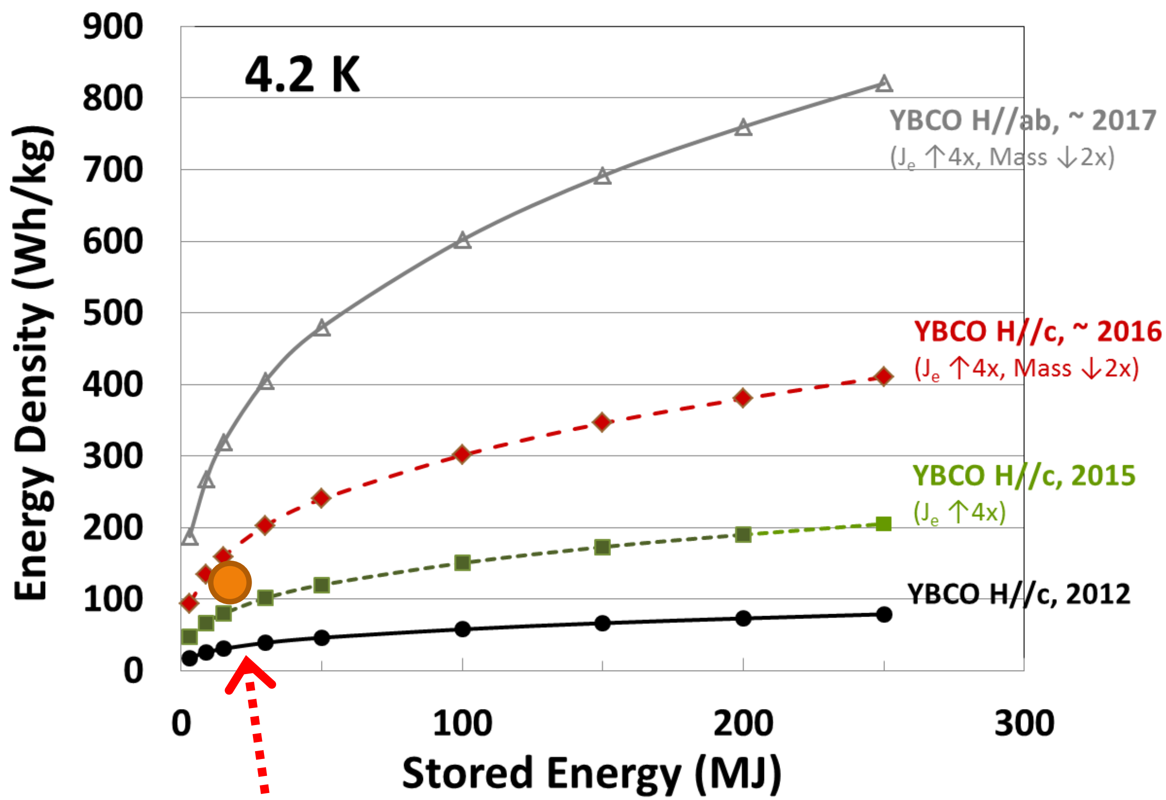


- Energy density scales as $E^{1/3}$ for a given temperature across a temperature range.
- For a given energy the maximum specific energy density falls off exponentially with temperature.

Computational Investigation of Superconducting Inductor Geometries for Energy Storage, RQQM



Upper limits of Energy Density
(ultra-thin solenoid magnet)



NHFML 7.1 MJ Magnet for YBCO wire Mass ↓ 2.5x

- Energy density scales as $\varepsilon \sim Jc^{1/3} * E^{1/3}$ ***regardless of superconductor wire type***.
- $J_e(B)$ properties of each wire type define upper limits to ε

Magnet Comparisons: YBCO to Cu-magnet

For a solenoid, B = const*n*I, and E = ½*L*I²

H_2O Cooling Lines

10 kW Magnet Power Supply

RQQM, Bldg 23 Rm 120

YBCO Solenoid = 16.2 Tesla

- **Weight = 9.9 lb**
- **Energy = 0.16 MJ (good for INVENT EAU)**
- **Cryo-cooler Power = 2 kW** (120V, ~ 20 A)
- Temp = 4.2 K, I = 285 A per coil (14 coils)
- Charge/Discharge ~ 0.3 sec (= 270V/L_{coil}~0.3 Henry)
- SMES Power = 1.08 MW
- SMES Energy Density = 11 Wh//kg
- SMES Power Density = 240 kW/kg
- 1 coil = 100 meters of 4 mm width tape

Cu-wire Magnet = 2.0 T (practical limit – lab)

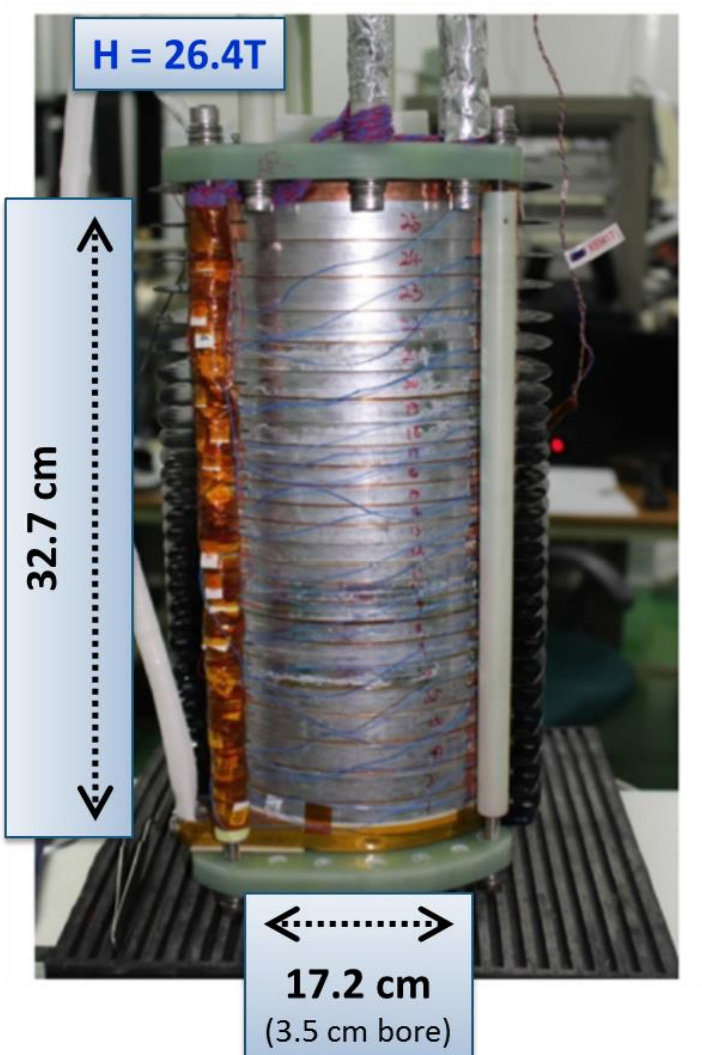
- **Weight = 3970 lb**
- **Energy = 784 J (E ~ const*B²)**
- **Max. Charge Power = Cooling Power = 10.6 kW** (140A, 76V)
- 2 T = limit for commercial systems, I = 140 A
- Cooling, Max. charge = 15.0 l*min⁻¹ H_2O
- Energy Density = 4.4×10^{-5} Wh/kg

Superconducting Magnet Energy Storage (SMES) for Aircraft

0.16 MJ for MW-Class Energy Management

- **Power = 1.1 MW @ 270V (charge or discharge 14 // coils)**
- **Mass ~ 30 lb magnet + cryovessel**
- **Cryocool power ≤ 2 kW**
- **Power Density > 50 kW/kg**

Superconducting Magnetic Energy Storage (SMES), 7.1 MJ



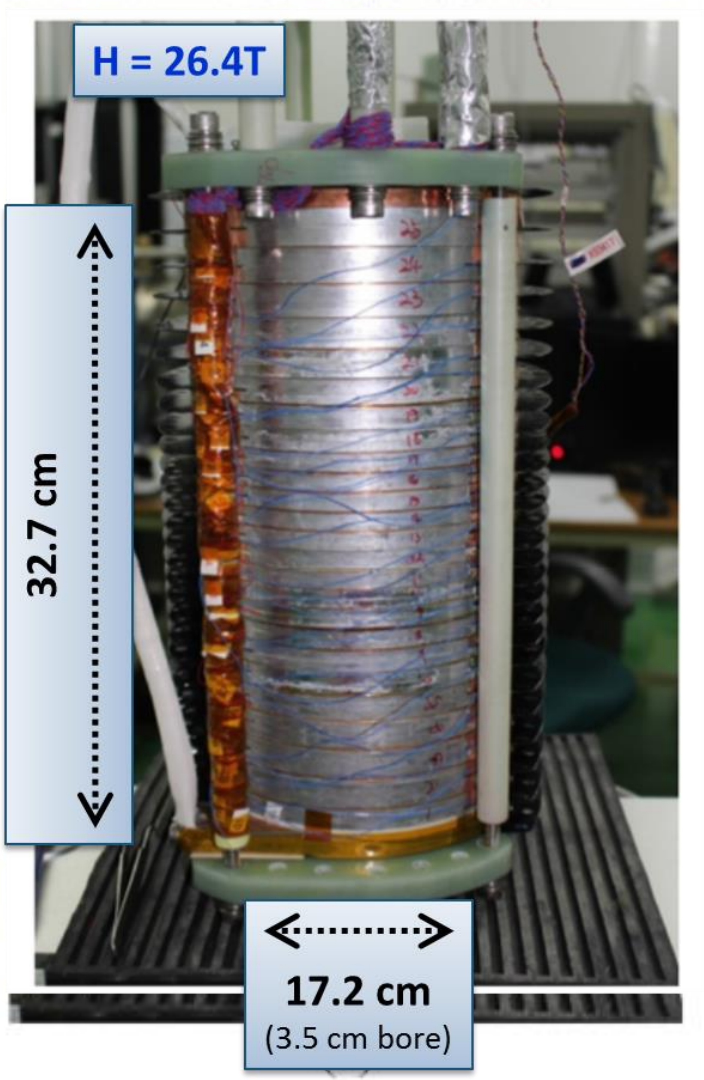
	Present (SUNAM, as made)	Possible SOA (Superpower Inc. tape)
Wire Length (4.1mm width)	11.2 km	
Wire Mass	51.6 kg	**14.7 kg**
Energy Density	**38 Wh/kg**	**134 Wh/kg**
Wire Cost	\$0.23M @ \$20/m	\$0.46M @ \$40/m
Inductance *L*	12.79 H	
Time Constant τ	947 s (15.8 min)	
I_c (4.2K)	242 A, Series 6,282 A, 26 coils parallel	
Power @ 270V	**1.70 MW**	
Power Density		**115 kW/kg**

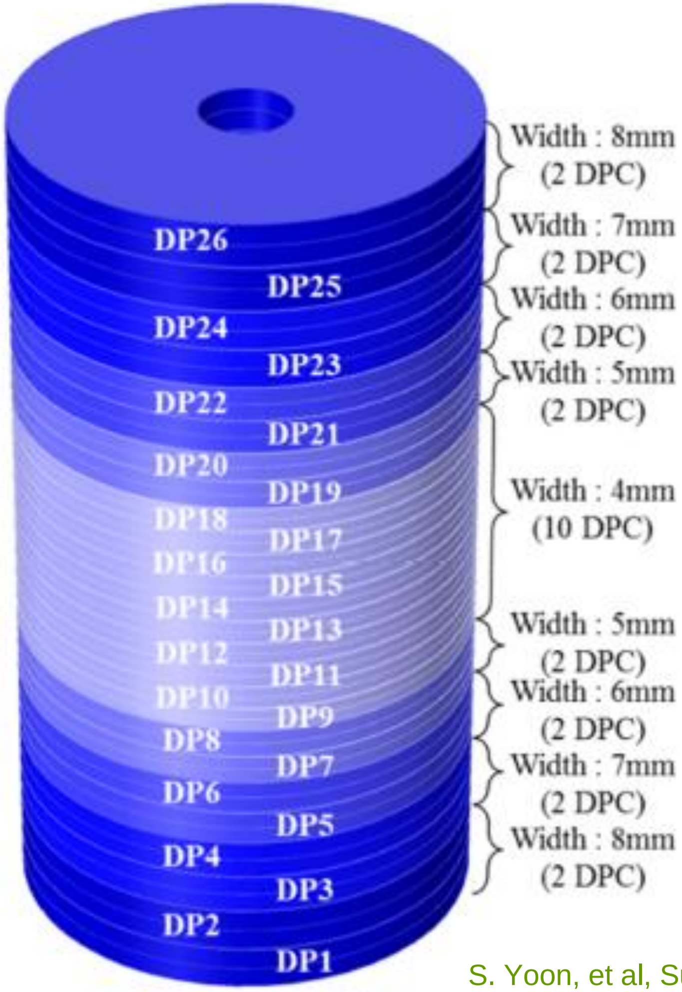
- As high as Li-batteries!

- 10-100x higher than Li-batteries!

S. Yoon, et al, SuST, 29, 04LT04 (2016)

Superconducting Magnetic Energy Storage (SMES), 7.1 MJ





(b)

S. Yoon, et al, SuST, **29**, 04LT04 (2016)

Superconducting Magnetic Energy Storage (SMES), 7.1 MJ

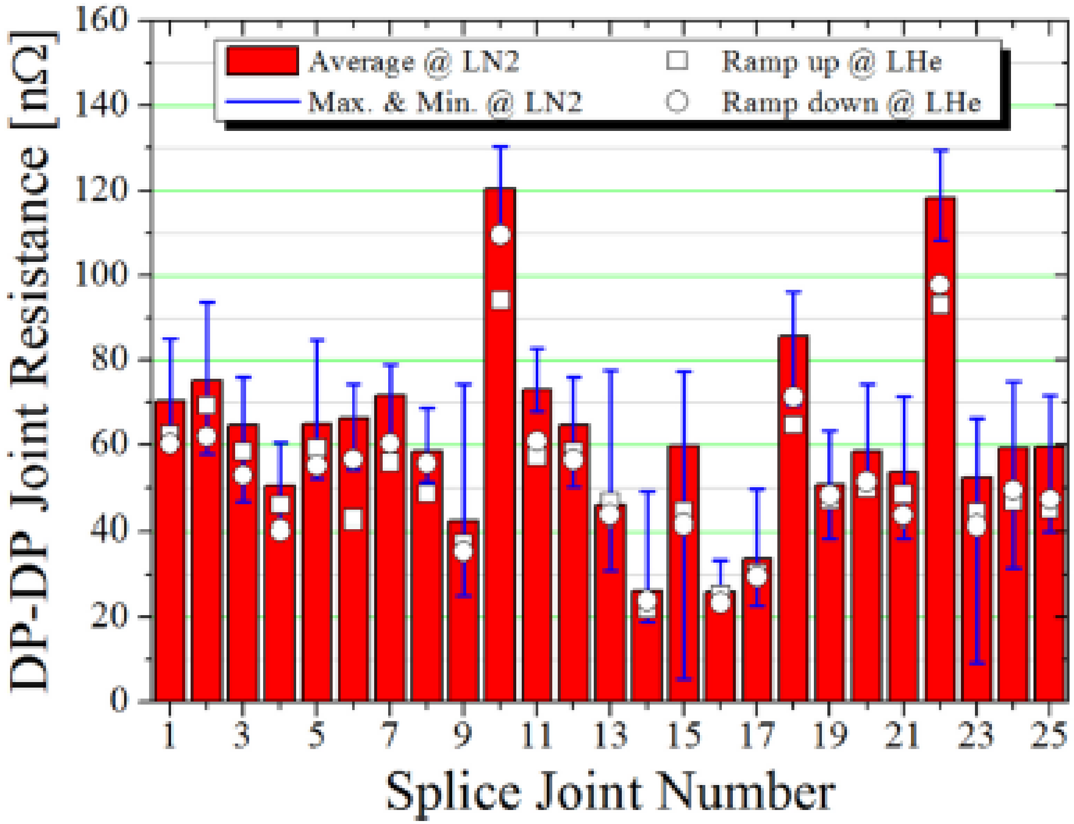


Figure 4. Test results of DP–DP splices in liquid nitrogen at 77 K (bars) and in liquid helium at 4.2 K (open symbols). The results at 77 K (bars) are an average from six measurements.

100 MJ Magnet,
< 1 Sec charge/discharge

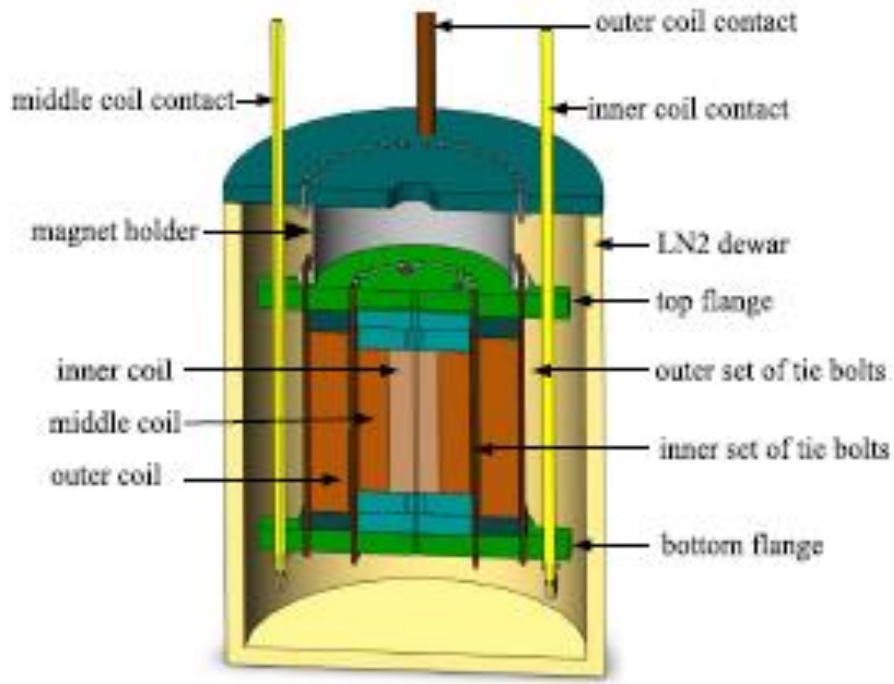


Fig. 1. Cutaway drawing of the 100-T magnet. The inner, middle, and outer coils are nested coaxially. The middle coil will be wound directly onto the outer surface of the inner coil. There is a gap between the middle and outer coils, so that the liquid nitrogen can flow between the coils. The height of the magnet is 700 mm, and the outer diameter is 650 mm.

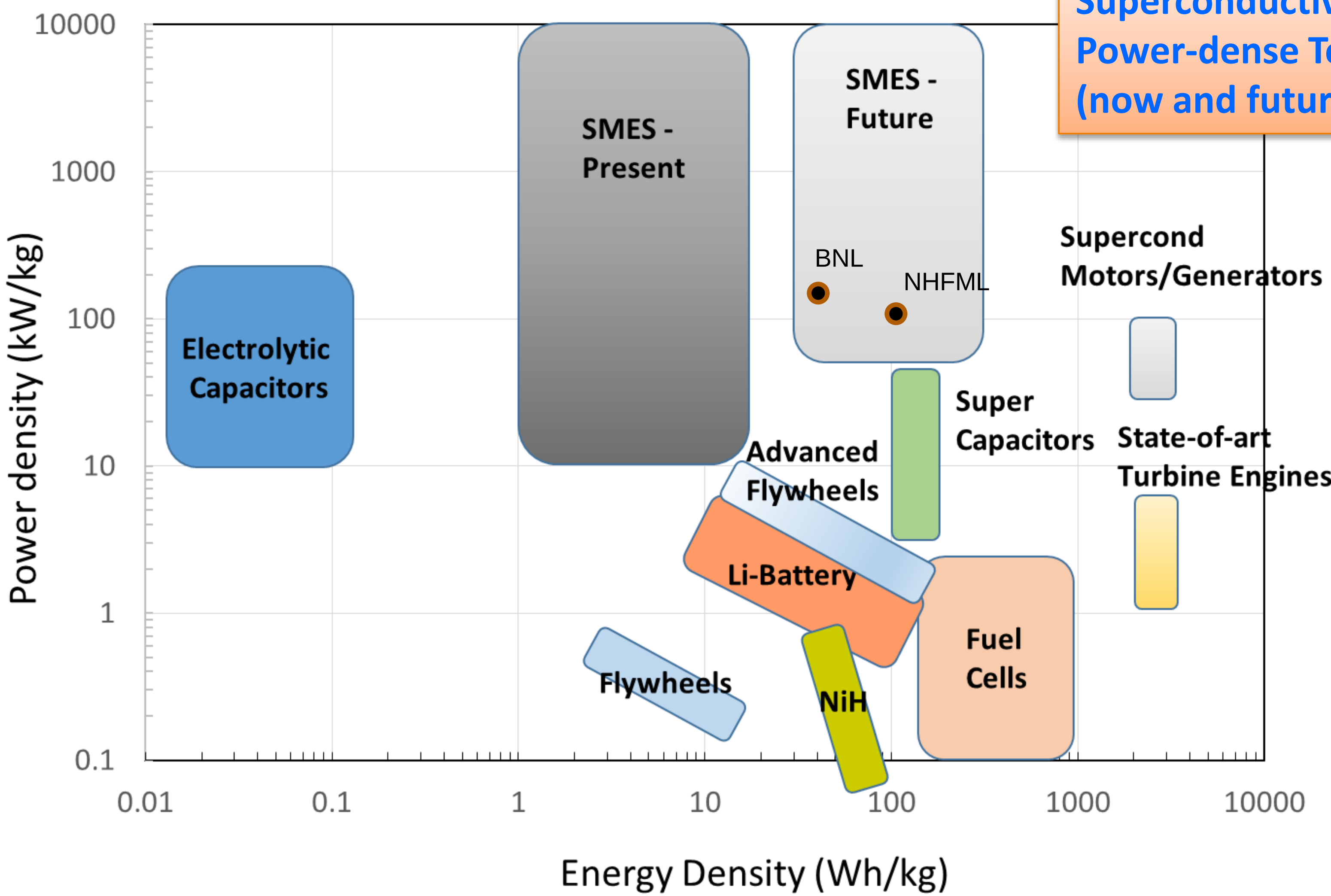
Energy	100 MJ	
Pulse Time	~ 10 mSec	
Mass	1860 kg	Cu-alloys ~ 8 g/cm3
Energy Density	15 Wh/kg	
Charge Time	0.488 sec	

- 3 coils,
- CuNb wire,Cu wires

T. Peng, IEEE Trans. Appl. Supercond. **26(4),** 4300504 (2016)

Ragone Chart, Power Density and Energy Density

Superconductivity most Power-dense Technology (now and future projected) !!



Flywheel Energy Storage

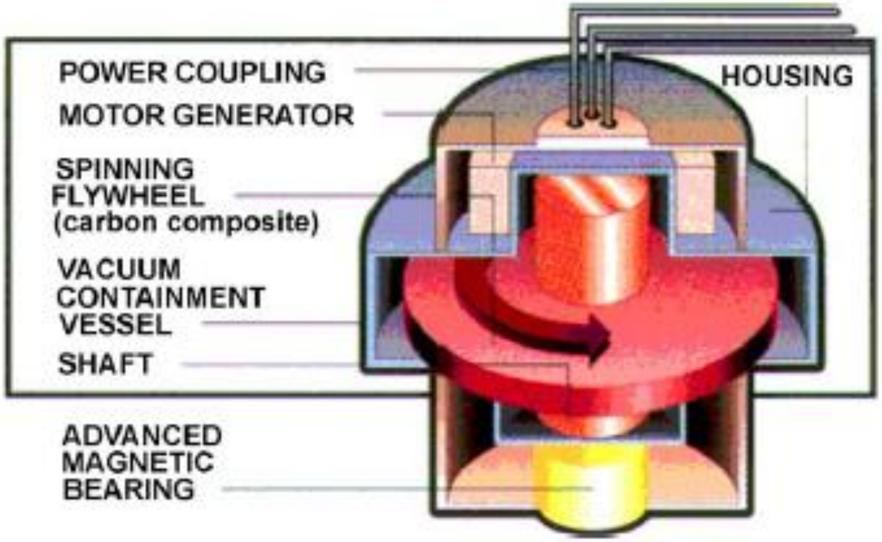


Fig. 1. Main components of a flywheel storage system [5].

I. Hadjipaschalis, et al, Renew. Sustain. Energy Rev. **13**, 1513 (2009)

Table 1
Comparison among three prominent energy storage systems.

Parameter	Lead–acid battery	Flywheel technology	Nickel–cadmium battery
Storage mechanism	Chemical	Mechanical	Chemical
Life (years in service)	3–12	>20	15–20
Life (deep cycles)	<1500 cycles	$<10^7$ cycles	<3000 cycles
Self-discharge rate	Very low	Very high	Very low
Technology	Proven	Promising (proven)	Proven
Tolerance of overcharge & deep-discharge	Very low	High	Low
Environmental concerns	Chemical disposal issues	Slight	Chemical disposal issues
Energy density	30 Wh/kg	5 Wh/kg steel 100 Wh/kg composite	15–50 Wh/kg
Power density	180 W/kg	1000 W/kg composite	50–1000 W/kg
Price/kWh	$50–100	$400–800	$400–2400

Flywheels for Space

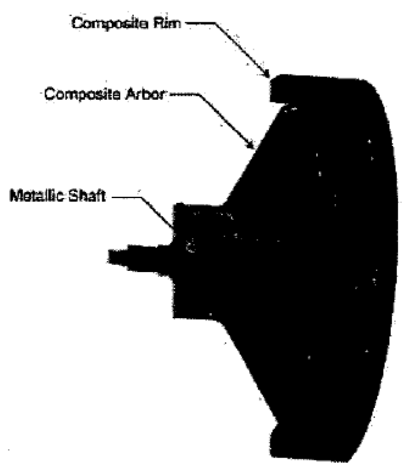


FIG. 1. CONCEPT DESIGN OF AN INTEGRATED FLYWHEEL

- High radial compressive stresses occur in the composite rim, leading to shortened performance life due to creep
- Metallic structures are speed limited to fatigue
- Overall, tip speed operation is limited with these designs, and the flywheel rim cannot benefit from use of high-strain composite materials

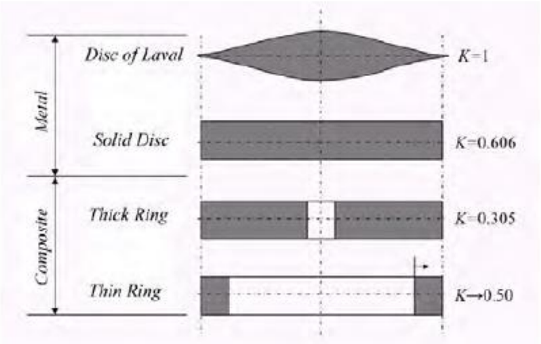


Fig. 2. Different flywheel shapes

$$E = \frac{1}{2} * I * \omega^2$$

- $I = \int r^2 \, dm$ is rotational inertia
- ω = maximum spinning speed, limited by capacity of material to withstand centrifugal forces

- R. Thompson, et al, 2002 37th IECEC Conference, 20055
- R. Peña-Alzola, Proc. 2011 Int. Conf. Power Eng, Energy Electrical Drives, 978-1-4244-9843-7/11/$26.00 ©2011 IEEE

Comparison of Energy Storage Systems

	ECB	FBESS	EDLC	SMES
Storage Mechanism	Chemical	Mechanical	Electrical	Magnetic
Peak power (kW)	Medium ($\approx 10^2$)	LS High($\approx 10^3$) HS Med ($\approx 10^2$)	Medium ($\approx$100)	High ($\approx 10^3$)
Efficiency (%)	80-85	90-95	>95	90
Pulse duration	> 1 hour	(VB) > 1 seg (VA)> 1 min	> 1 min	> 1 seg
Magnitude for SOC	Gravity, V, I y Z	Spinning speed	Voltage	Current
SOC measure reliability	Medium	High	High	High
Power density (kW/m^3)	Medium (10)	High (10^2)	High (10^2)	High (10^2)
Energy density (kWh/m^3)	High (10^2)	Medium (10)	Medium (10)	Low (1)
Useful life (years)	3-5	>20	10-20	~20
Technology maturity	Proven	Proven and promising	Proven and promising	Proven and promising
Temperature range	Limited	Less limited	Less limited	Controlled
Environmental concerns	Disposal Issues	Slight	Slight	Slight

- R. Peña-Alzola, Proc. 2011 Int. Conf. Power Eng, Energy Electrical Drives, 978-1-4244-9843-7/11/$26.00 ©2011 IEEE

Summary of Energy Storage Systems

	Li Batteries	Flywheels	SMES
Efficiency Charge/discharge	90-98%	> 90%	≥ 98%
# Cycles	1500-4000	> 10^7	> 10^{10}
Energy Density (cell)	10-300 Wh/kg	10-400 Wh/kg (?)	10-150 Wh/kg
Energy Density upper limits (?)	400-500 Wh/kg ?	> 400 Wh/kg ?	> 200 Wh/kg
Power Density	1-10 kW/kg	1-10 kW/kg	1-1000 kW/kg

Conclusions

- Our code shows good agreement with measured magnetic values of experimental coils.
- We observe that the winding mass scales as $M \sim const * E^{2/3}$ for different wire types and temperatures. This concurs with earlier work
- by Hassenzahl (1991) who showed that $M \sim B^{1/3} * E^{2/3}$ that. (This assumes a constant β).
- **Highest energy density SMES designs tend toward a pancake configuration** (Yuan et al., 2010). **However, the full parameter space still needs to be explored.** The pancake solution may be a local energy density maxima.
- Cost will play a big role in deciding future SMES investigation. As prices decrease MgB_2 may become more of a competitor.
- Additional constraints need to be considered including a more careful examination of internal stresses on the SMES, specific wire designs, etc.

References

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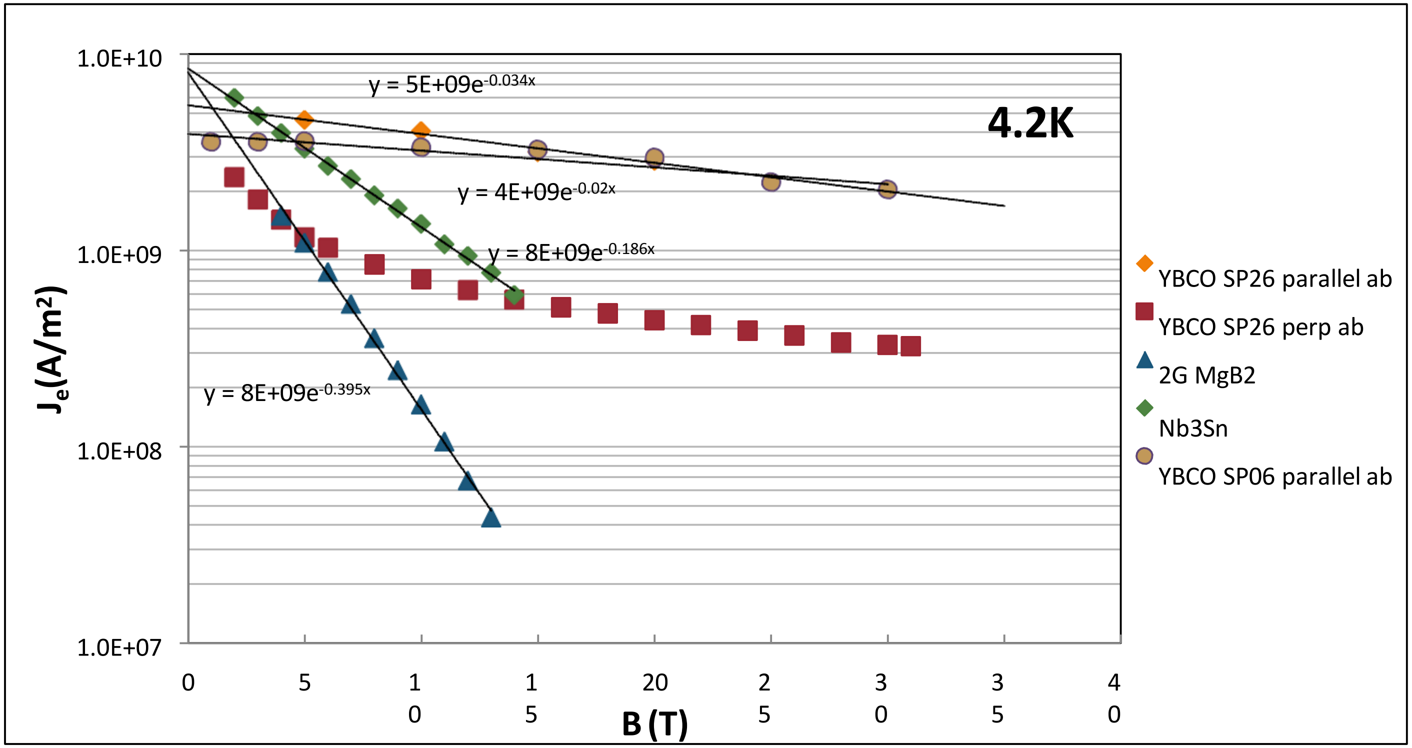
Wire Performance and Data Parameterization cont.



	Nb3Sn	MgB2	YBCO
Fill factor(%)	46.5	20	1 micron layer
Cross section dimensions	1.0954mm x 1.0954mm	1.0954mm x 1.0954mm	12mm x 0.1 mm
Density(kg/m^3)	8876	8000-10000	8500
Cost ($/m)	~5	~5-7 (1-2 projected)	~60