Enabling Technologies for High Speed HTS Motors/Generators

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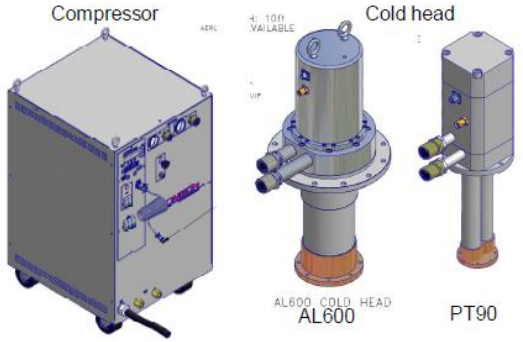
Enabling technologies

- Refrigerators
- Cryostats
  - Rotating coupling
- Thermal insulation
- Cables
- Sensors/protection (quench)

State of the art refrigerators

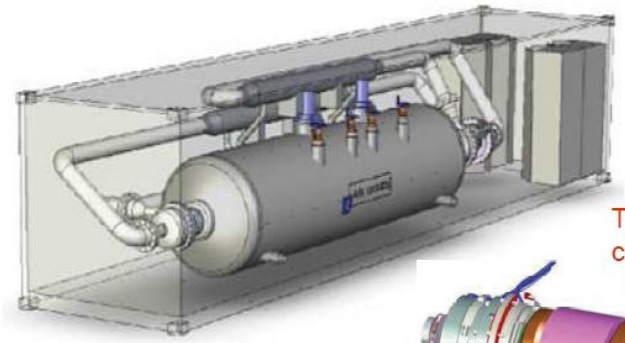
Stirling C&R SPC-4, 4 kW@80K

AISIN SEIKI 1 kW@77K Stirling cooler SC1501



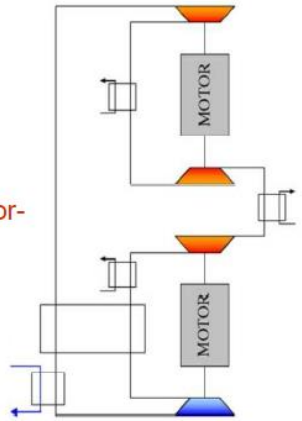
GM & GM-PT coolers made by CRYOMECH

NIST 500 W@30K Stirling-PT cooler



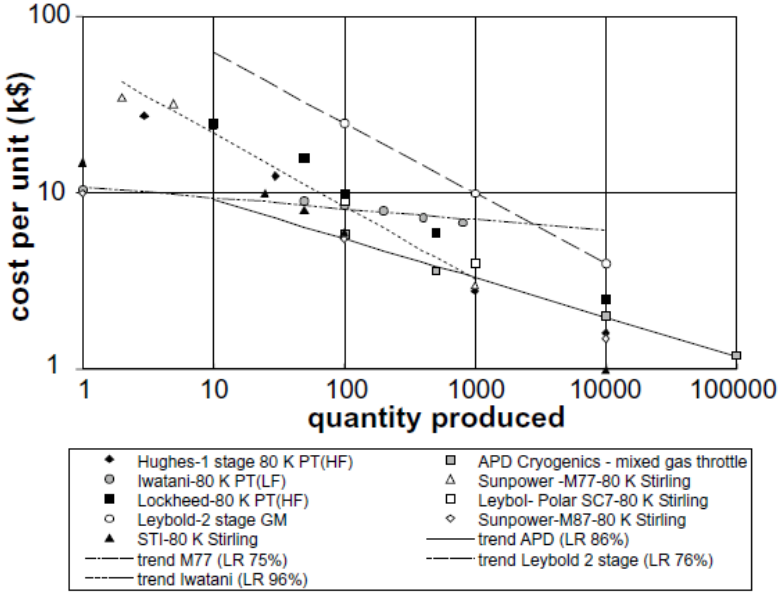
22 kW@72K turbo-Brayton cooler for LIPA II cables & FCLs made by AL

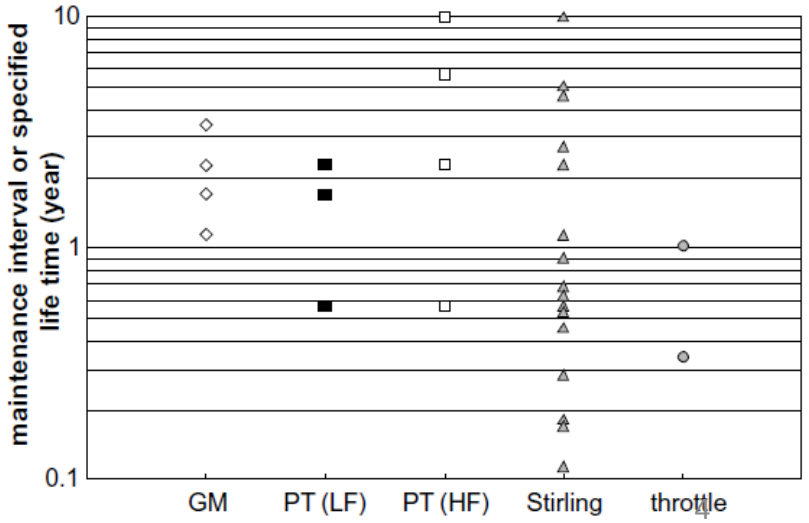
Turbo-motor-cmpressor



Refrigerators-I

- Issues
  - Cost, cost , cost
    - Cost decreases with economies of mass production
  - Reliability
    - Reciprocating devices ~ 2000-9000 hours MTBM
    - Turbomachinery has good characteristics

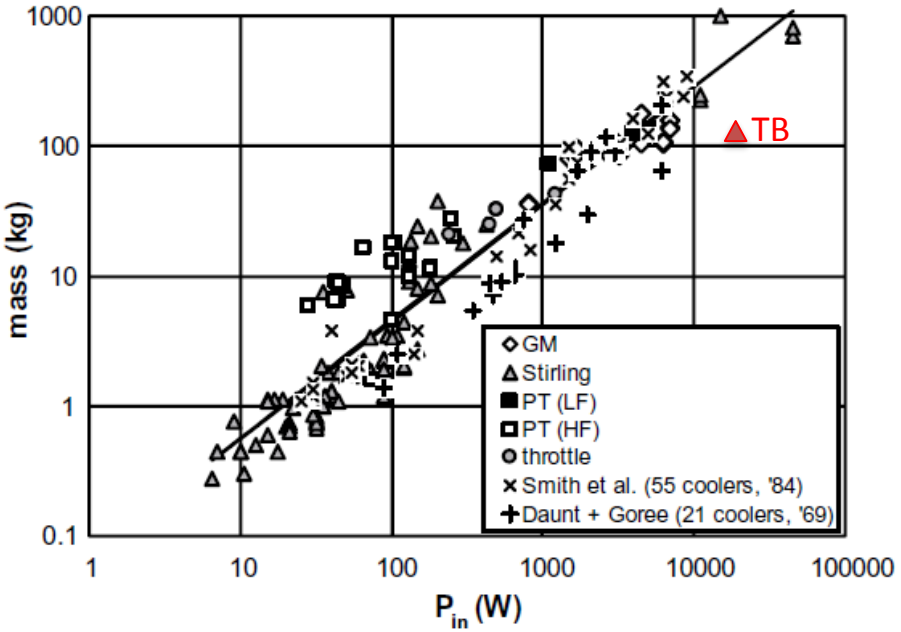


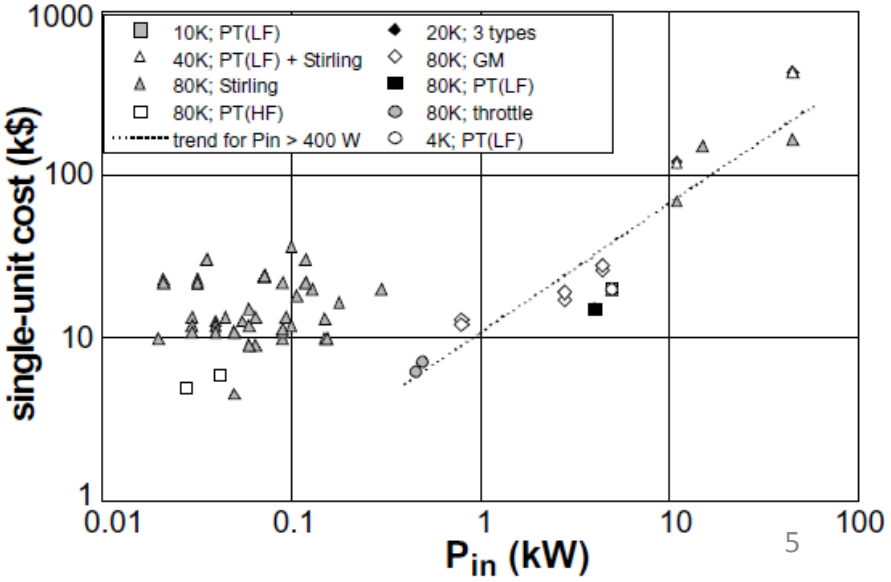


van ter Brake (2002)

Refrigerators-I

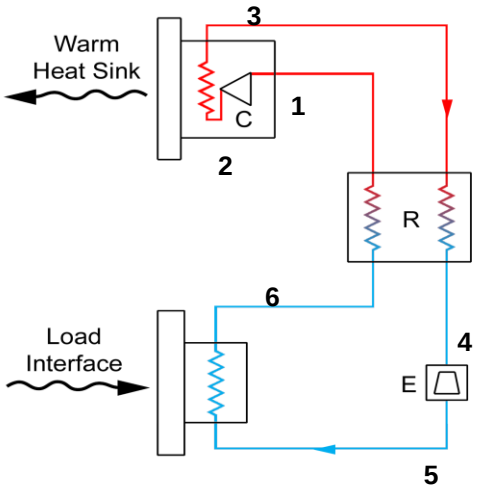
- Issues:
  - Mass/cost related to compressor power, insensitive to cooling temperature or power



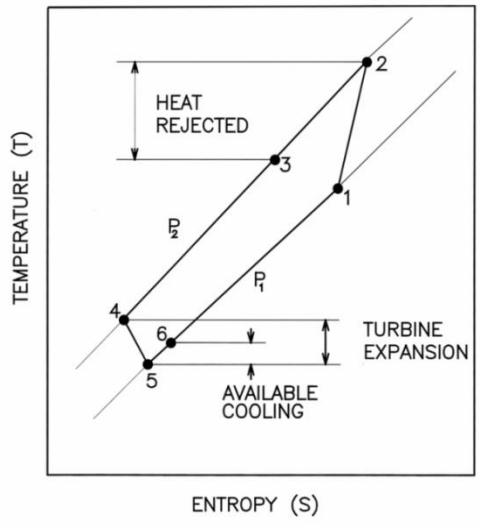


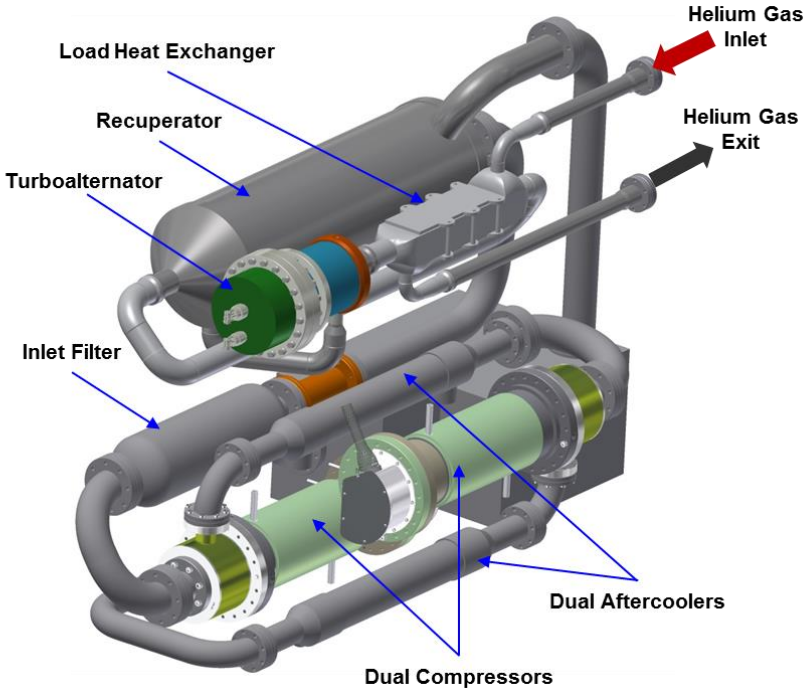
van ter Brake (2002)

Turbo-Brayton Cryocoolers



C – Compressor
R – Recuperator
E – Turbine

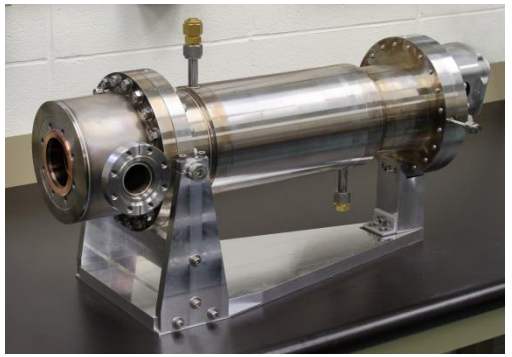




- **Features**
  - **Miniature high-speed turbomachines with non-contact bearings**
    - Ultra-high reliability, Long life, Low/no vibration
  - **Remote and distributed cryogenic heat transport**
  - **Operation independent of orientation**
  - **Flexible packaging and integration**
  - **Efficiency and mass/size scale well to high capacities and low temperatures (unlike GM or Stirling machines)**

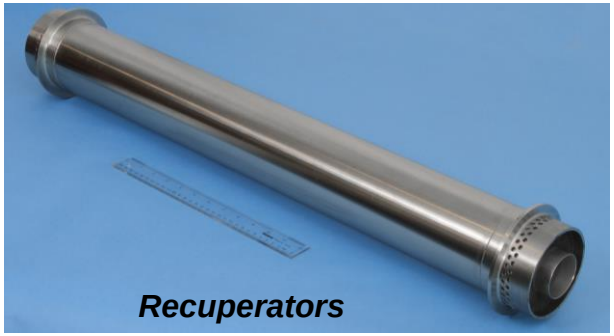
Key Cryocooler Components

- Centrifugal compressors
  - Circulate cycle gas and provide pressure ratio
  - High efficiency
  - Shaft supported by non-contacting gas bearings
- Turbines
  - Refrigeration is provided by expansion of cycle gas
  - Fluid or electrical dissipation/recovery of expansion work at warm end of cryocooler
  - High efficiency
  - Shaft supported by non-contacting gas bearings
- Recuperative heat exchangers
  - Used to improve cycle efficiency
  - Need to have high thermal performance and low pressure drop



Compressors

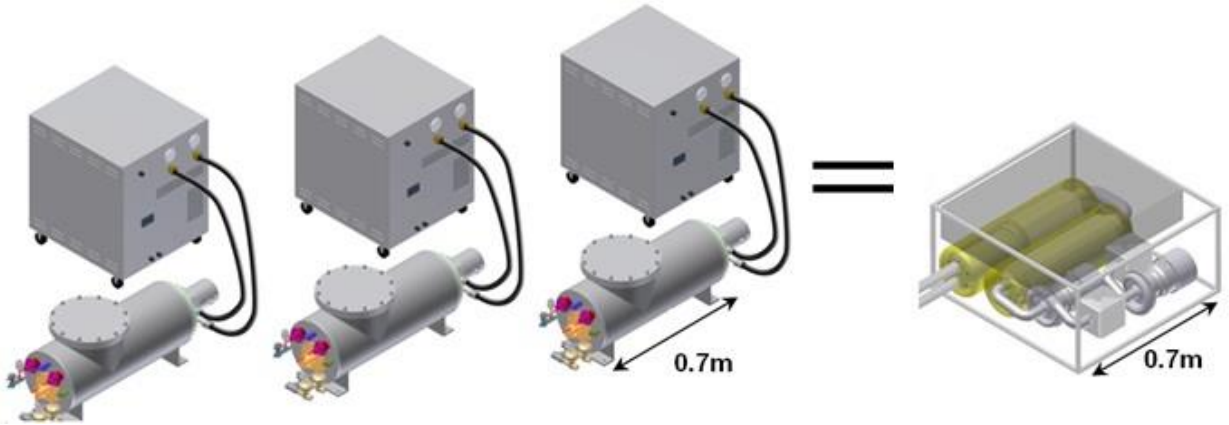
Turbines



Recuperators

Competing Technologies at High Capacity (1 kW at 50 K)

	Best Competitor	Turbo-Brayton	Turbo-Brayton Benefit
Cooling	1kW @ 50K	1kW @ 50K	**Same Cooling**
Units Needed	3	1	**1 Unit**
Input Power	47 kW	26 kW	**1/2 the Power**
Weight	800 kg	110 kg	**7 Times Lighter**
Volume	1 m^3	0.2 m^3	**5 Times Smaller**
Maintenance	Every 10,000 hrs	Never	**Maintenance Free**
Production Price	>$300k	<$250k	**20% Less Expensive**



It takes 3 Current Commercial Systems (Cryomech GM AL600 + Cryozone Circulator) to equal 1 Turbo Cryogenics unit.

EERE goals for refrigerators (2007)

Technology Attributes		Near-Term Goals (present – 2007)	Mid-Term Goals (2008 – 2011)	Long-Term Goals (2012 – 2015)
Cryogenics	Carnot Efficiency	12% @ 65 K	20% @ 65 K	30% @ 65 K
	Reliability	95%	99%	> 99.9%
	Cost	$100/W @ 65K	$60/W @ 65K	$25/W @ 65K

Navigant Peer review 2007

Road map for cryostats

- Ideally, thermal insulation without vacuum
- If vacuum, ideally, closed system without active pumping
- Non-metallic cryostats for armature winding
- Maintaining good vacuum challenging

Technology Attributes		Near-Term Goals (present – 2007)	Mid-Term Goals (2008 – 2011)	Long-Term Goals (2012 – 2015)
Cable Cryostats*	Heat Leak	2 W/m	1 W/m	< 0.5 W/m
	Cost	$500/m	$300/m	$100/m

Navigant Peer review 2007

Non-refrigerator cryogenic issues

- Rotating coupling for high speed HTS rotor
  - Ferrofluid and clearance seals
    - Coolant leakage
    - Lifetime issues
    - Power dissipation
- Potential solutions:
  - Stationary HTS field winding
    - Flux switching rotating machinery
    - Rotating resistive armature winding, stationary field HTS field winding

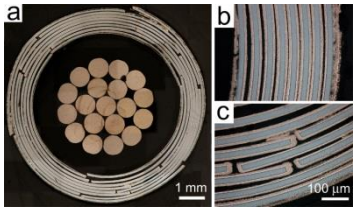
Quench detection/protection

- Conventional means to detect quench are challenging
  - Electrically noisy environments (especially in stator)
  - High temperature, low quench propagation velocity
- Metrics:
  - Sensing within < 200 ms (12 line-cycles @ 60 Hz)
- Options
  - Voltage taps
  - Fiber optics
  - Unconventional sensors

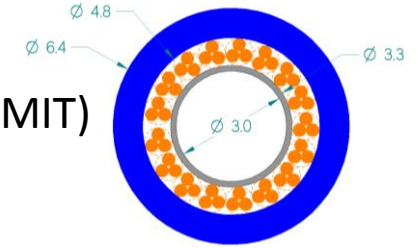
Cables?

- How to make medium to high current cables
- How to integrate cooling with cable
- Integrating cooling into cables (MgB_2) while avoiding breakdown (LH2 cooling)

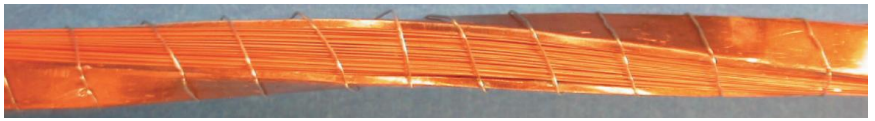
CORC (ACT)



MgB_2 CICC (MIT)



Twisted Stack-Tape Cable (MIT)



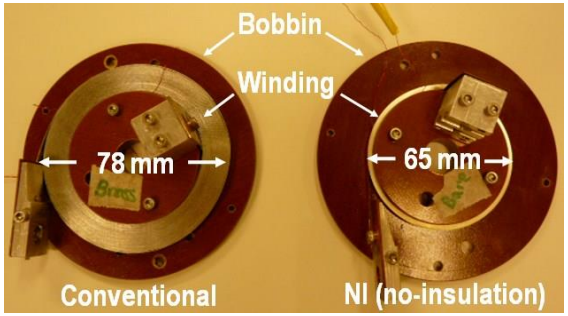
Conventional HTS power transmission cables

Roebel Cable (KIT)

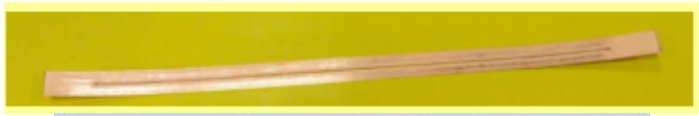
No insulation winding for rotor

- Developed for high field NMR magnets
- Much higher current density than conventional winding
- Can address protection/detection issues with YBCO tapes

No-insulation winding



Partially slit tapes



Prototype enabler demonstrations?

- To reduce costs, cryo-refrigerators need either new concepts or mass production
- Rotating couplings could be developed separately from machines (high-speed clearance seals will always leak a little)
- Scale-up quench-tolerant, no-insulation rotor winding for a ~ 1 MW motor
- Quench sensors can be developed separately from machines
- Cables can be developed separately from machine, ~ 3 kA level, 6~15 kV voltage
- Investigate "safety" of H_2 cooling for MgB_2, with realistic cables
- HTS to resistive transformer to couple current through cryostat boundary (eliminating current lead losses)

Refrigerators

- Several designs reach high efficiency (15~25% of Carnot)
  - Reduce parasitic losses by reduced cryogenic loads
    - HTS only in field winding to minimize ac loss
    - However, substantial gains if armature winding is SC
  - However
    - Size of refrigerators are large
    - Costs are large

Typical refrigerators

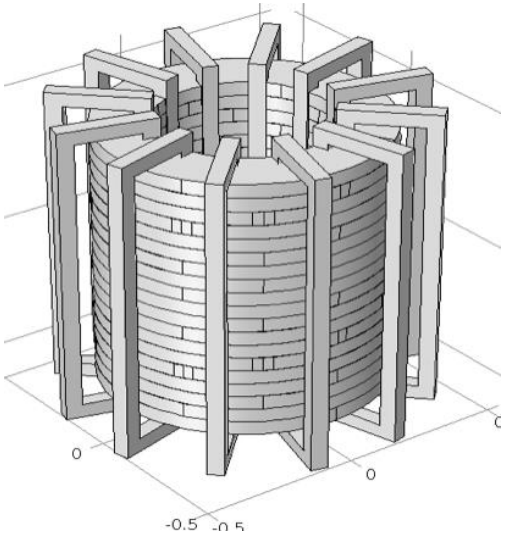
	Refrigeration Temperature (K)	Working Fluid	Capacity (Supplier Units)	Approximate Refrigeration (W)	Cycle	Expander	Plant Cost	Capital Cost per Watt $$$		Input Power (KW)	Input Power/ Cooling Pwr (W/W)	% Carnot
Large Scale GM Systems												
Leyblod 120T	65	He	130 W	130	GM	Recip	$20,200	$155.38	3.1	6.5	50.0	7.23%
Cryomech AL200	65	He	150 W	150	GM	Recip	$19,600	$130.67	3.6	5.5	36.7	9.86%
Helium Gas Systems												
PSI Model 1620	65	He	1200 W	1200	Claude	Recip	$400,000	$333.33	3.8	105	87.5	4.13%
Stirling Cycle												
Stirling Cryogenics LPC04	80	He	4200 Watts	4200	Stirling	Recip	$400,000	$95.24	8.9	45	10.7	25.67%
SPC-4T	20	He	300 Watts				$400,000		8.9	45		
Large Scale Recondensing Systems												
PSI	80	??	11,500 Watts	11,500	Brayton	Turbine	$800,000	$69.57	4.8	167	14.5	18.94%
Liquid Air Plants												
Cosmodyne GF-1	80	N_2	4 T/Day	8,400	Brayton	Turbine	$700,000	$83.33	1.9	372	44.3	6.21%
Cosmodyne Aspen 1000	80	N_2	1000 nM^3/Hr	64,969	Brayton	Turbine	$2,650,000	$40.79	1.9	1400	21.5	12.76%
GEECO EDLP-20TN	80	N_2	20 T/Day	42,000	Brayton	Turbine	$1,790,000	$42.62	1.9	933	22.2	12.38%
GEECO EDLP-40TN	80	N_2	40 T/Day	84,000	Brayton	Turbine	$2,750,000	$32.74	1.6	1773	21.1	13.03%

DOE Review

~ \$4-5/W_{in}

Addressing through Topologies

- Gramme-ring (toroidal stator)
  - Individual cryostats for stator



- Flux switching machines
  - Both armature and field windings stationary