THERMOACOUSTIC POWER CONVERSION

Robert Keolian

SONIC JOULE
ACOUSTICAL HEAT ENGINES

(Penn State retired)

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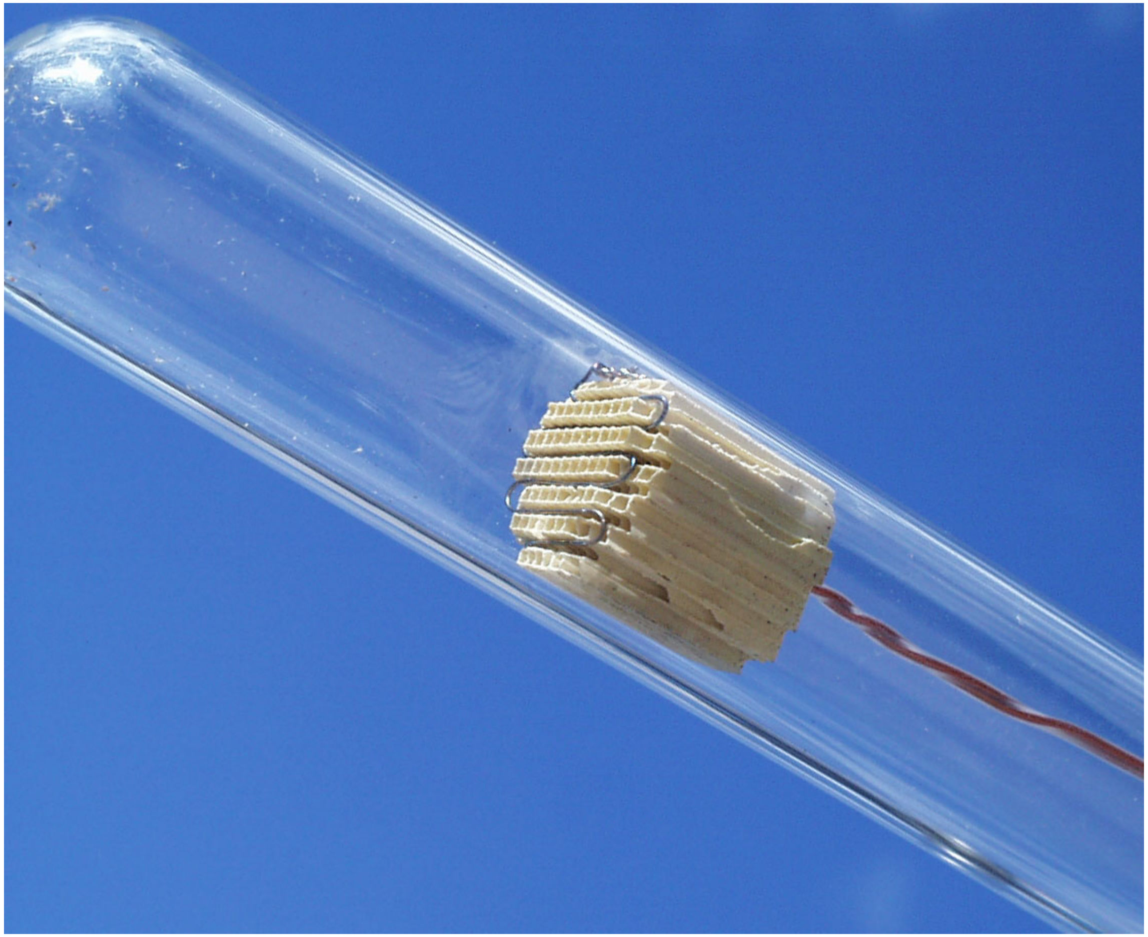
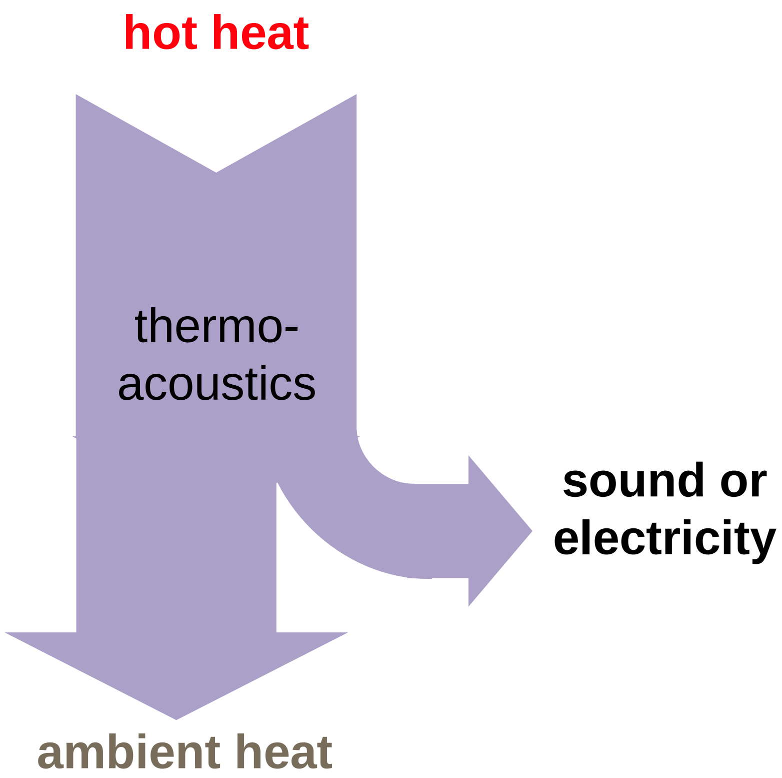
Simple Thermoacoustic Demonstration Engine

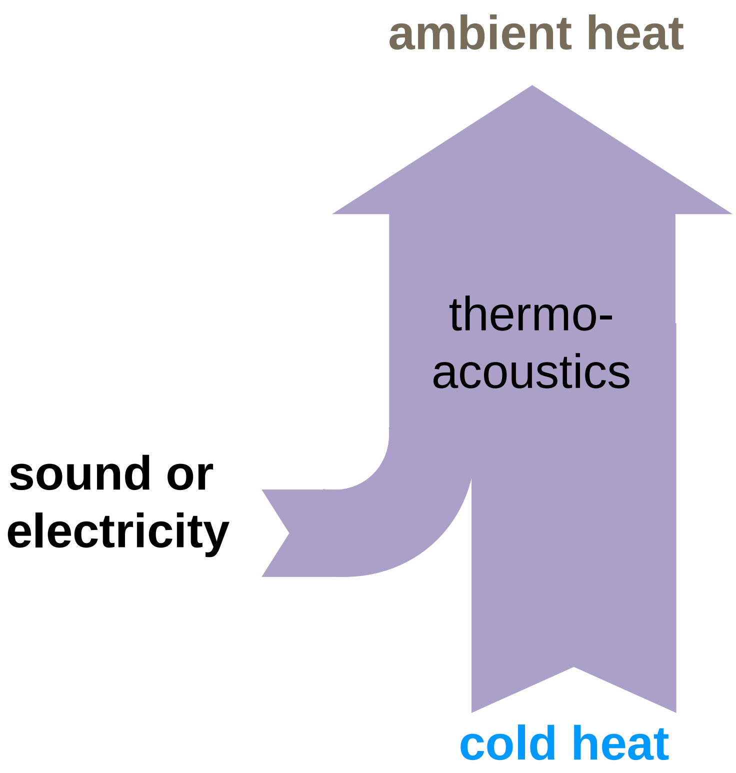


- Older style "stack" based standing wave device
- Style of state of the art 18 years ago

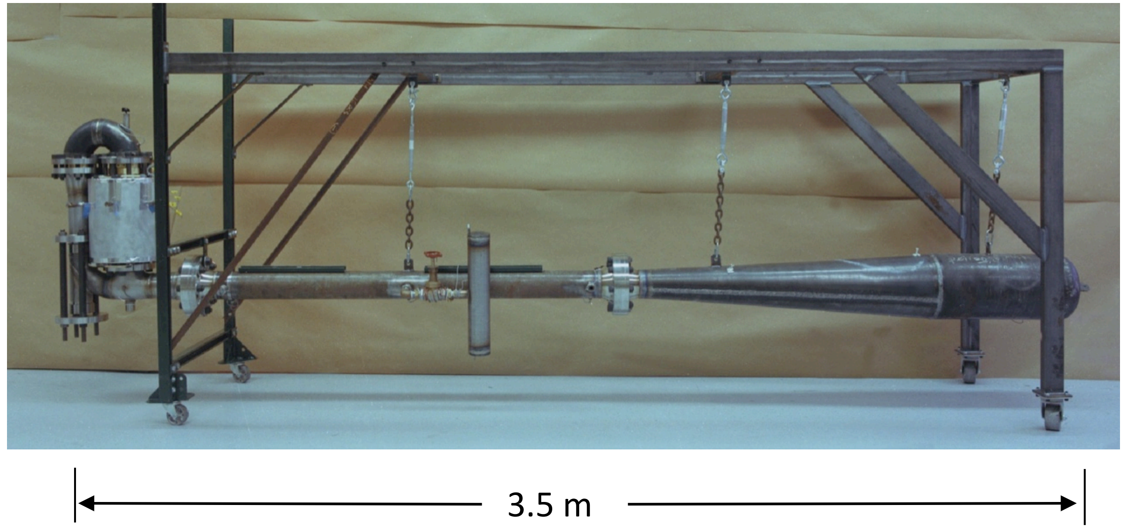
THERMOACOUSTIC GENERATOR



THERMOACOUSTIC REFRIGERATOR



Los Alamos National Lab Thermoacoustic-Stirling Engine



T_{HOT}	730 °C	270 °C
$T_{AMBIENT}$	15 °C	15 °C
Efficiency = W/Q_{HOT}	30%	10%
COPR (efficiency relative to Carnot)	42%	21%

First high efficiency device, in 1999

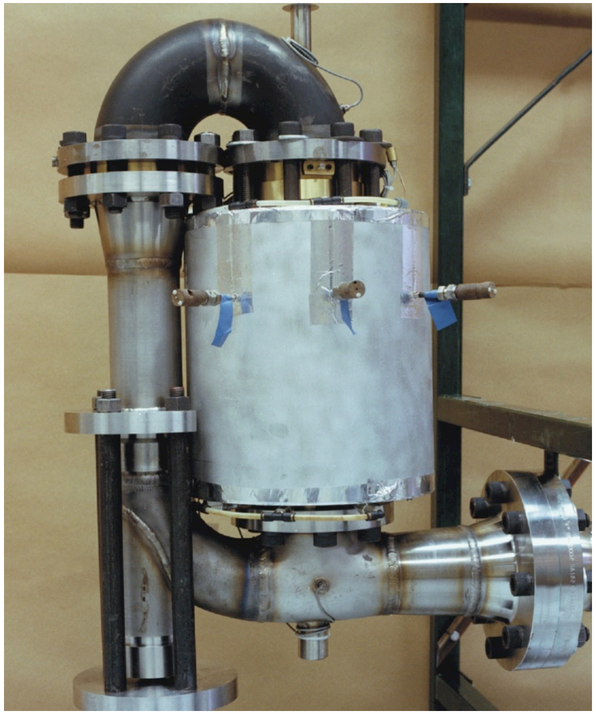
Developed up to 1700 W acoustic power

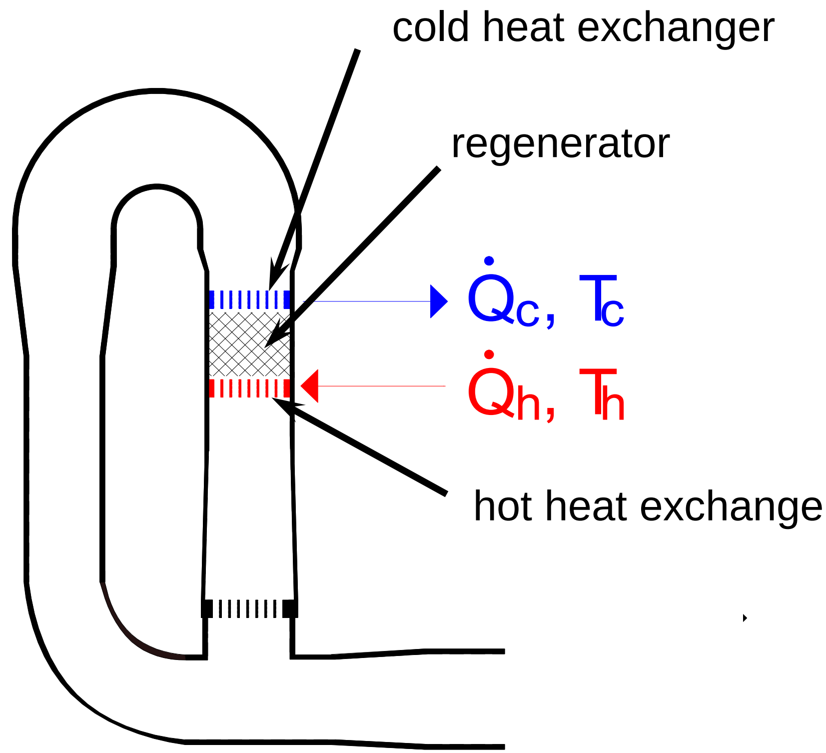
Mostly standing wave in long tube

Long length due to low 80 Hz operating frequency

Los Alamos

Inside the Thermoacoustic-Stirling Engine

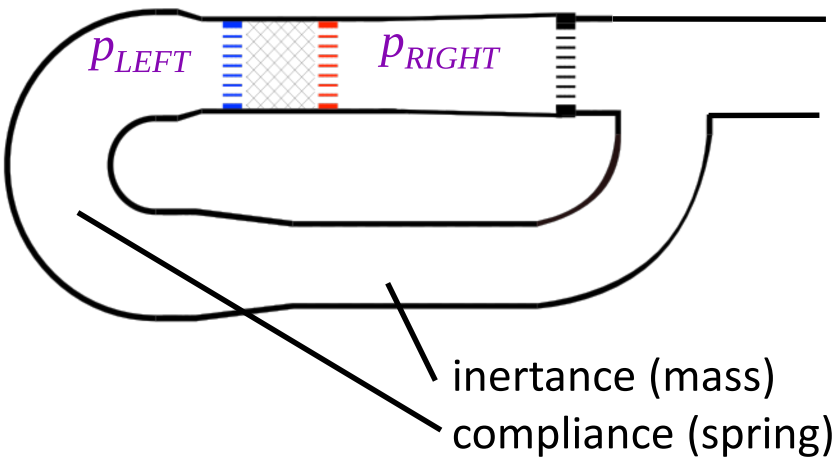


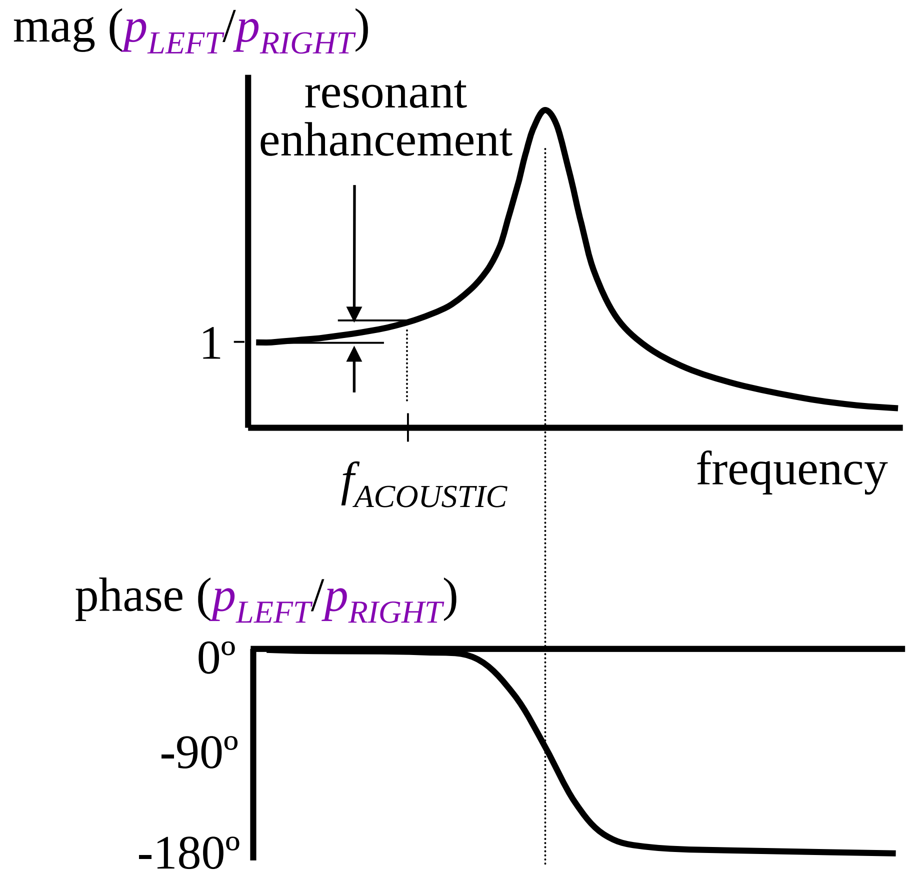


- Regenerator has pores much tighter than thermal penetration depth
- Great thermal contact to gas, so little entropy generation and higher efficiency
- Power is $p_1 \bullet U_1/2$, where p_1 is acoustic pressure, U_1 is volume velocity m^3/s
- Acoustic impedance is p_1/U_1
- Want high impedance (high p_1 low U_1) for low viscous loss in regenerator
- Standing wave in large tube provides that high impedance

Los Alamos

How it Works:





Standing wave velocity node (null) and high p_1 at regenerator

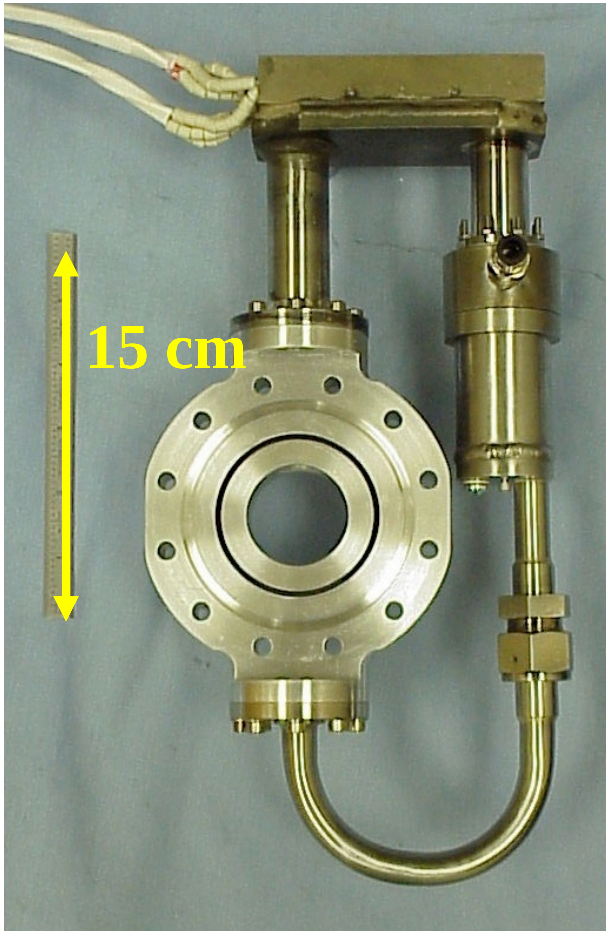
Residual high impedance traveling wave at regenerator amplifies sound

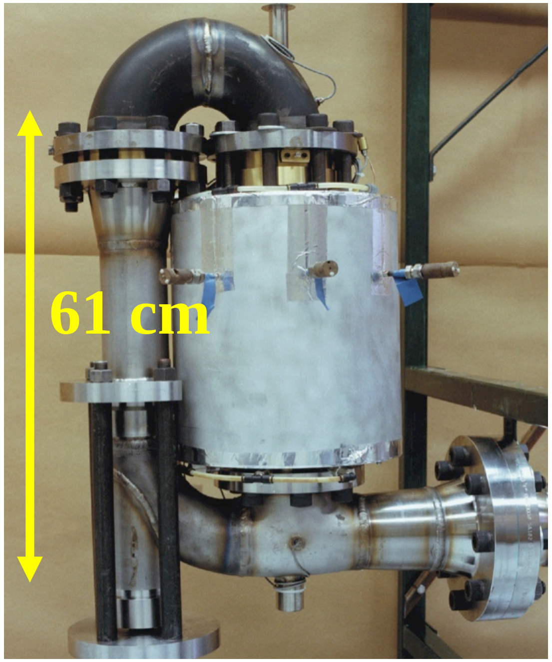
Heat converted into acoustic work

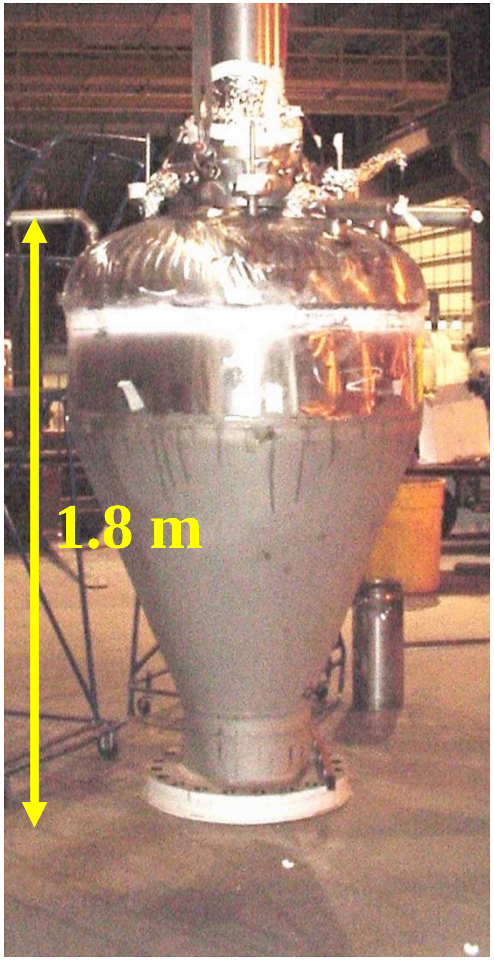
Similar to free piston Stirling engine without the pistons

No moving parts

WIDE RANGE OF POWER DEMONSTRATED BY LANL





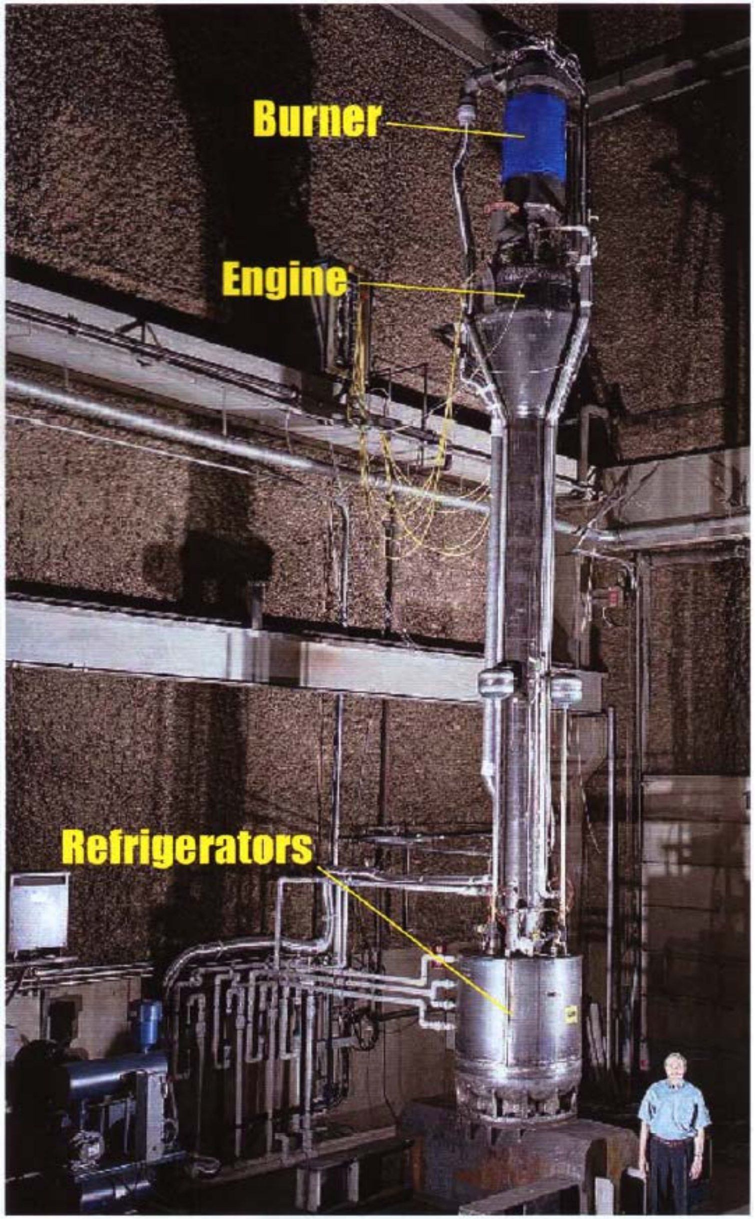


Thermoacoustic-Stirling engines:

Acoustic power:	100 W	1 kW	50 kW
TA efficiency:	23%	30%	25%

LOS ALAMOS-PRAXAIR NATURAL GAS LIQUEFIER

- Burn some gas from oil well
- Heat creates 50 kW sound at engine
- Sound liquefies remaining gas
  at acoustic refrigerators
- 500 gal/day LNG
- No moving parts so unattended
  – it's just properly shaped metal
- Truck LNG away when tanker full



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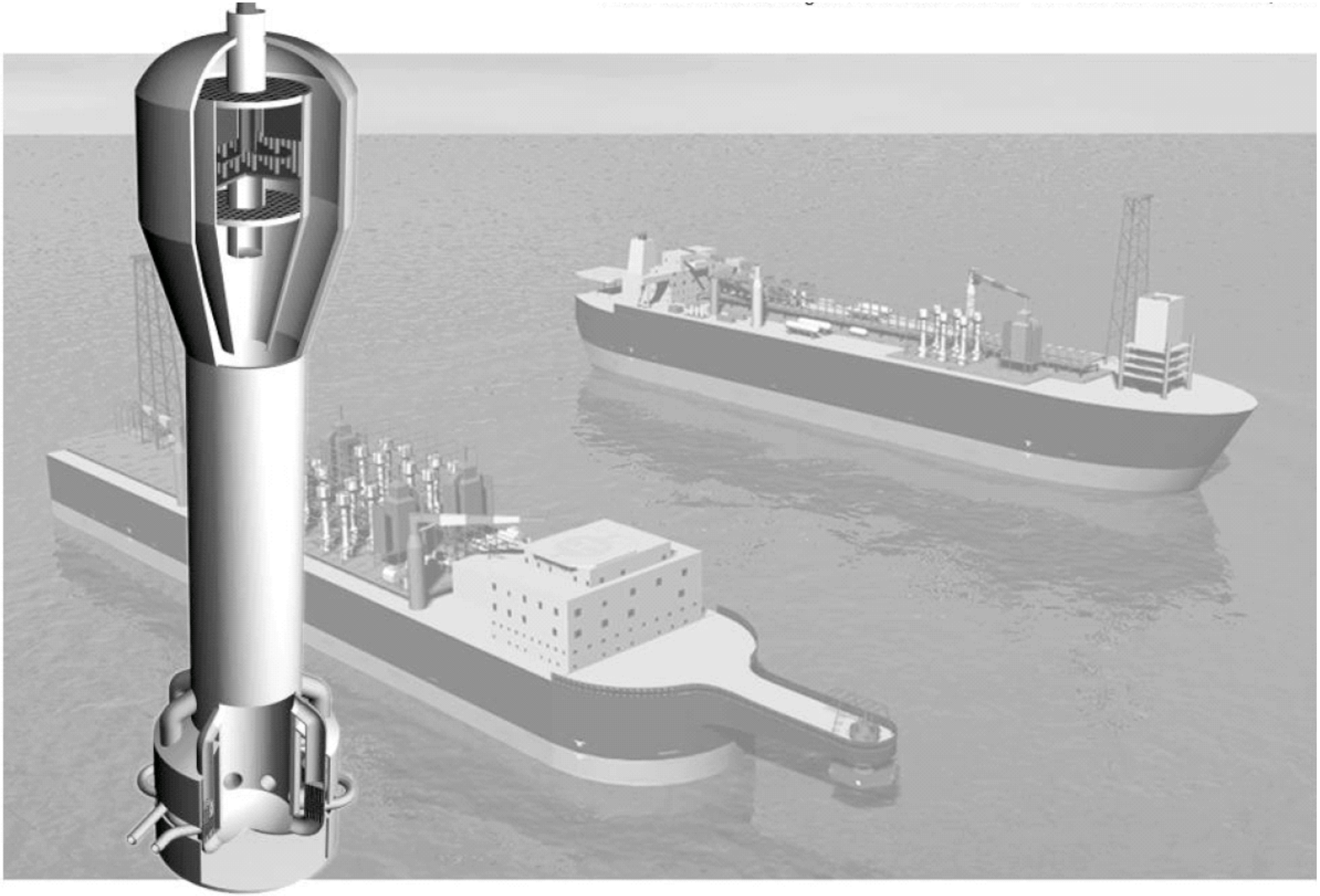
1 MW 10,000 gal/day Natural Gas Liquefier Dream

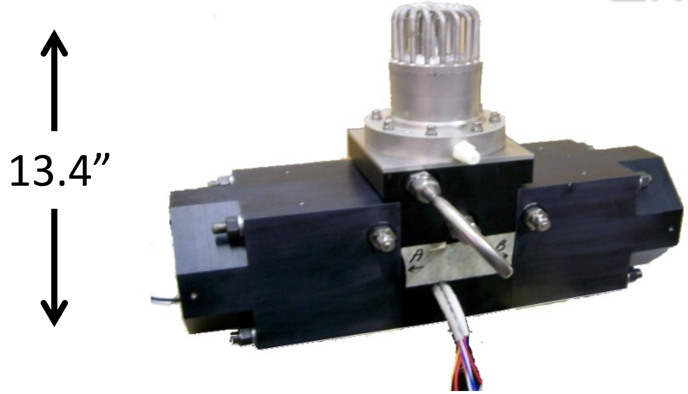


... but couldn't quite make business case for it.

Los Alamos

Thermoacoustic-Stirling Engine-Generators

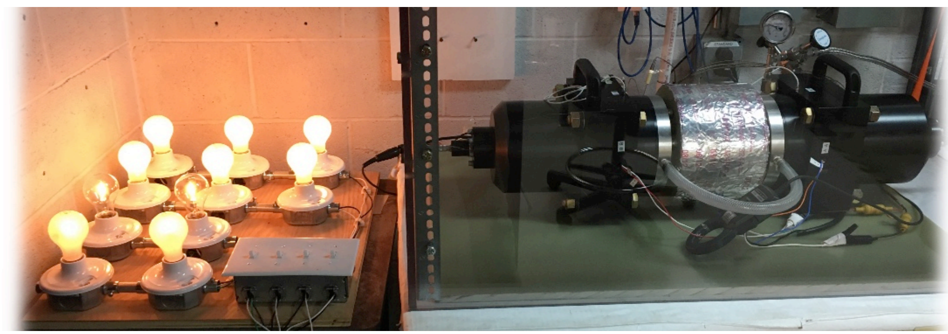
A Chart Industries Company



Much more compact version of LANL engine

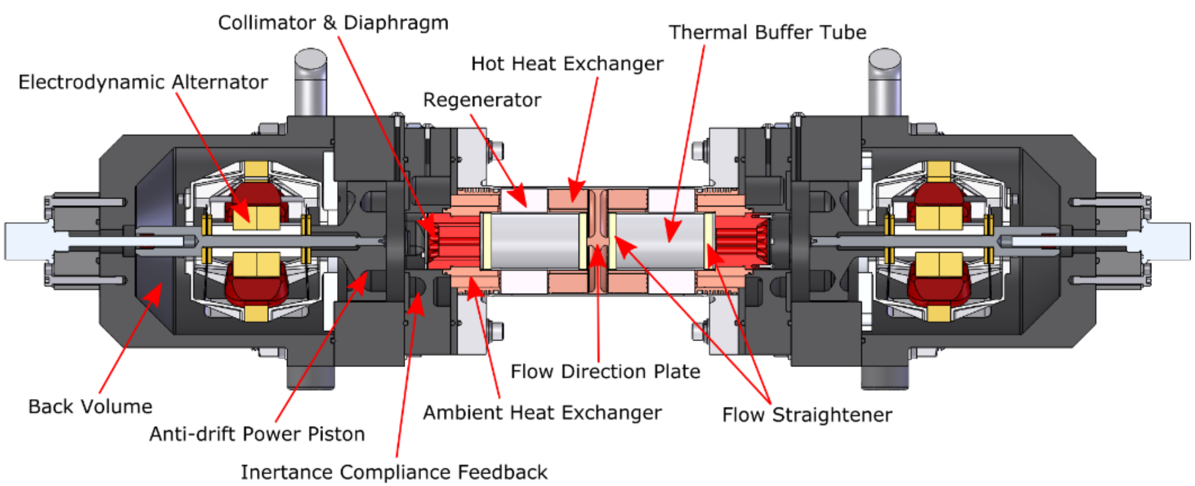
Heat to electricity

Micro combined heat and power for homes



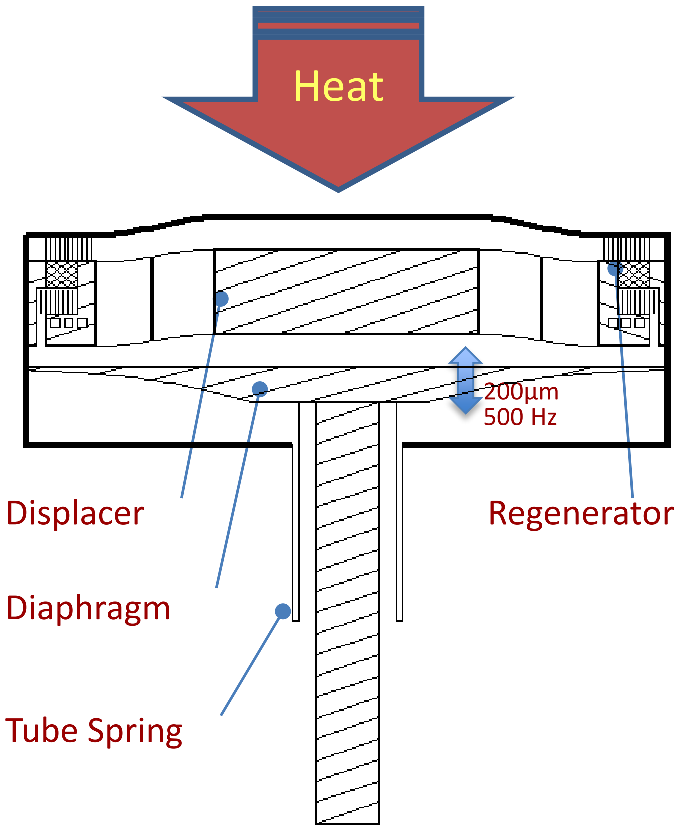
Achieved Performance Details:

- Two, functional µCHP prototypes constructed
- Achieved 100-150 W_{ELEC}
- Powered by external heat source
- $\eta_{Thermal\text{-}Electric}$ = 7-12%
- Low noise & vibration compared to free piston Stirling engine
- Prototype ≈ 80-120 lbs
- Operating temps appropriate for residential heating appliance
- Low temperature onset achieved
- Low quantity specific cost ≈ $60/W
- Second prototype still under evaluation

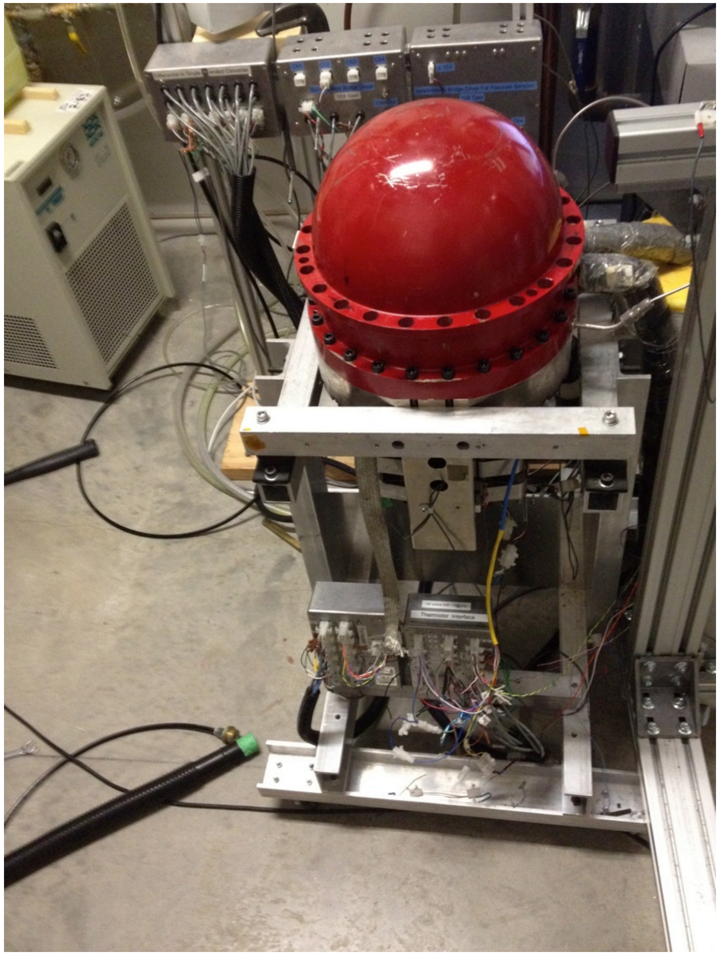


Etalim Thermal Acoustic Converter

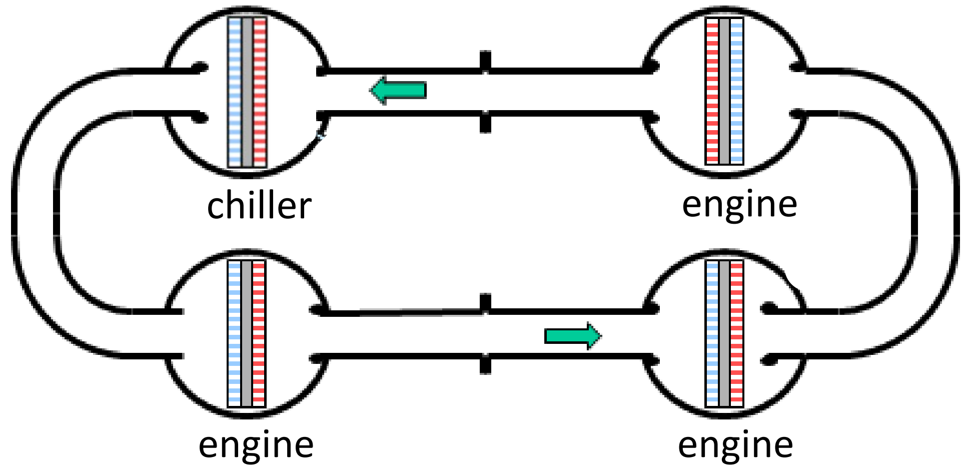
- Their previous type device, heat to electricity
- Flexing rather than sliding parts
- Newer devices are more acoustical



Basic TAC Schematic

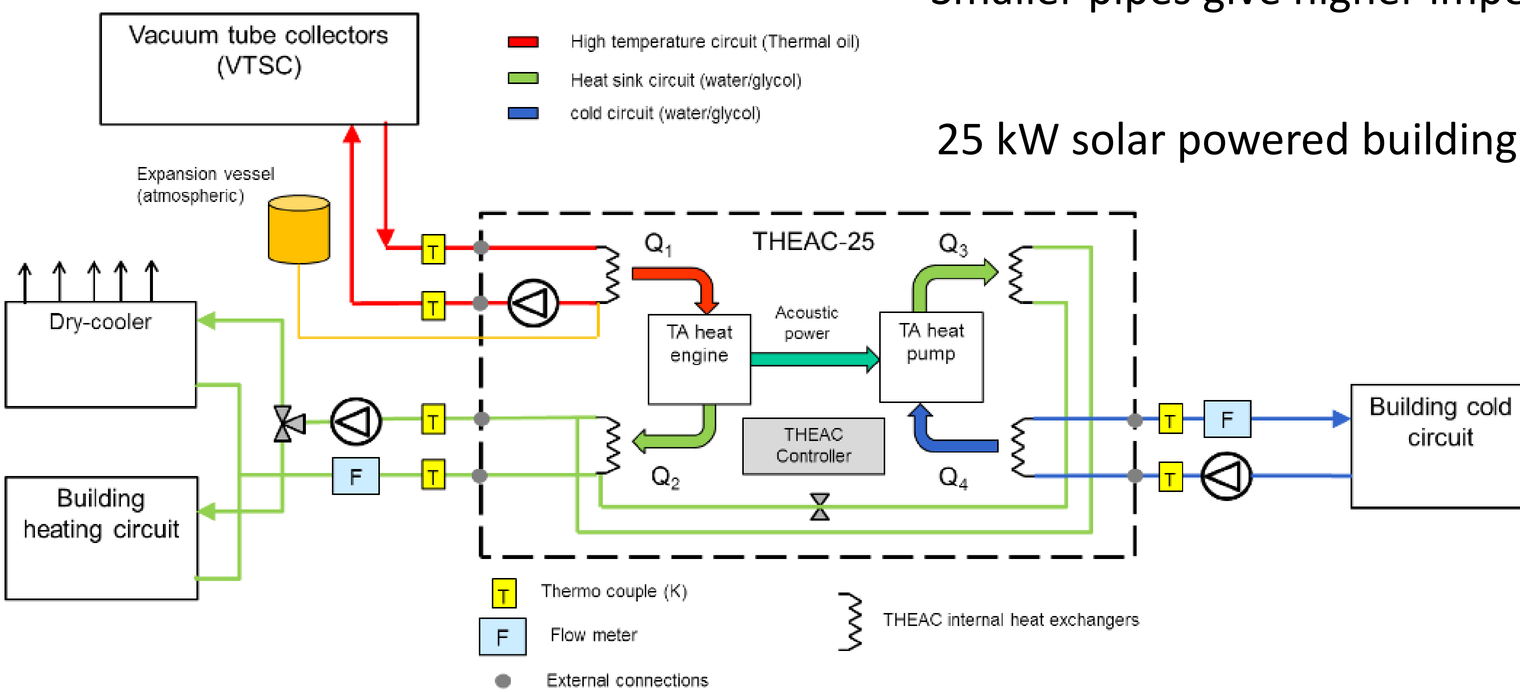


ASTER THERMOACOUSTICS LOOPED GEOMETRY



Smaller pipes give higher impedance

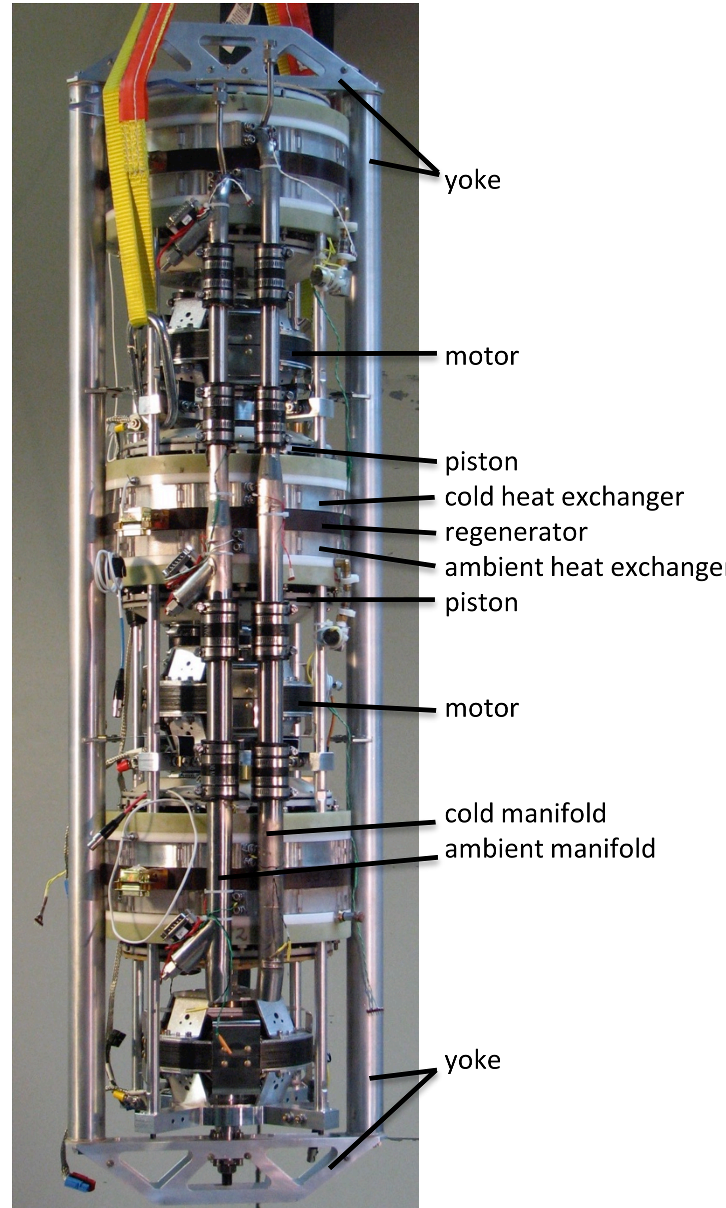
25 kW solar powered building cooling



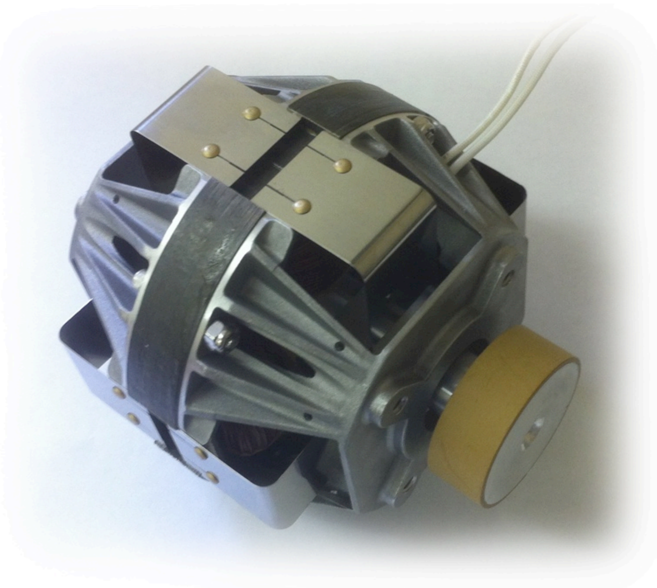
“Trillium” Inline Commercial Refrigerator

Three Chart linear motors each 120° out of phase
Three thermal stages between motors
Yoke connects bottom to top
Motor mass gives high impedance
Vibration balanced and quiet (LANL + PSU)

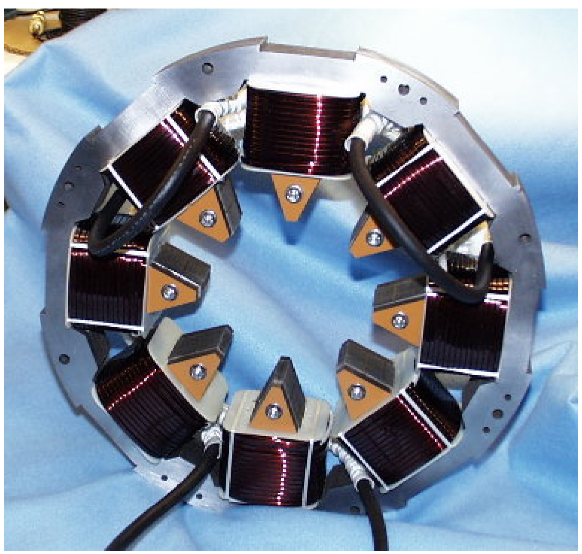
arpa·e PENNSTATE ARL → SONIC JOULE



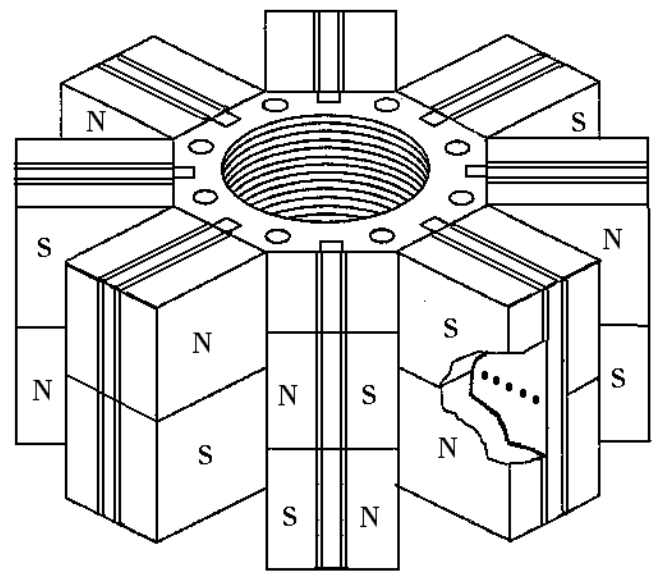
CHART/QDRIVE LINEAR MOTOR



- Commercially available very nice motor
- Available with Stirling style piston-cylinder clearance seal
- About 10 micron gap between piston and cylinder
- That clearance gap difficult to hold at large piston size



Stationary coil-stator structure



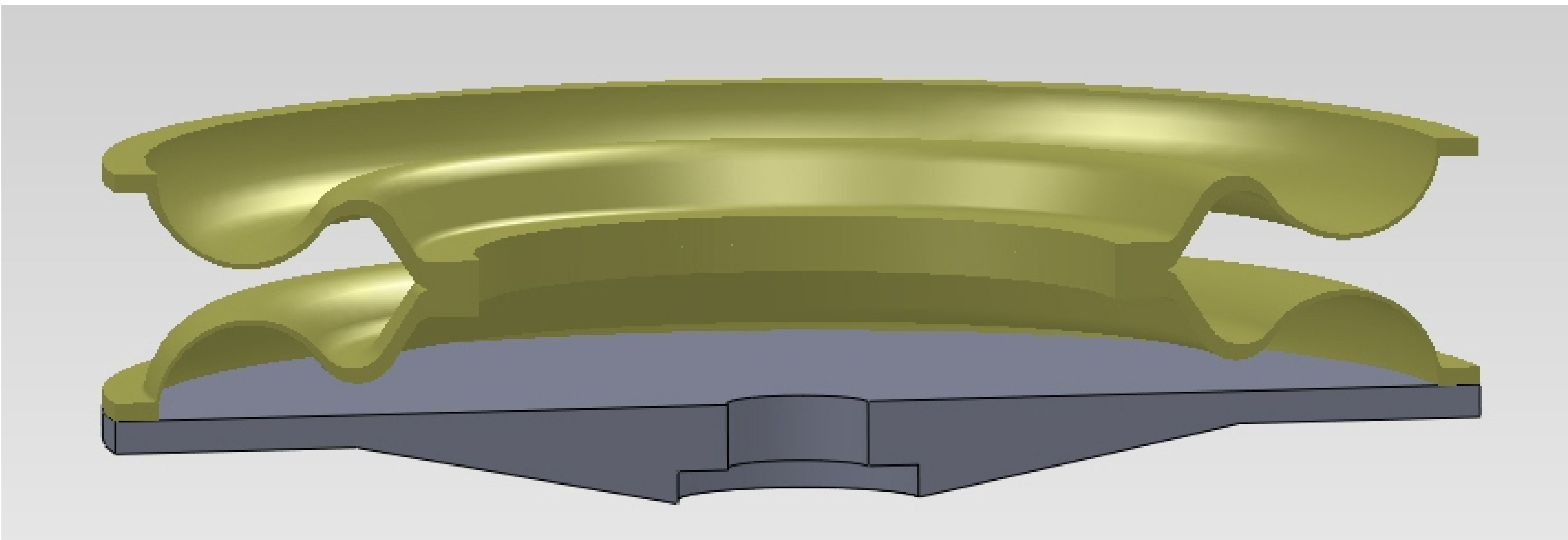
Moving magnet structure

Injection Molded Flexure Seal

Chart motor used without the Stirling style clearance seal

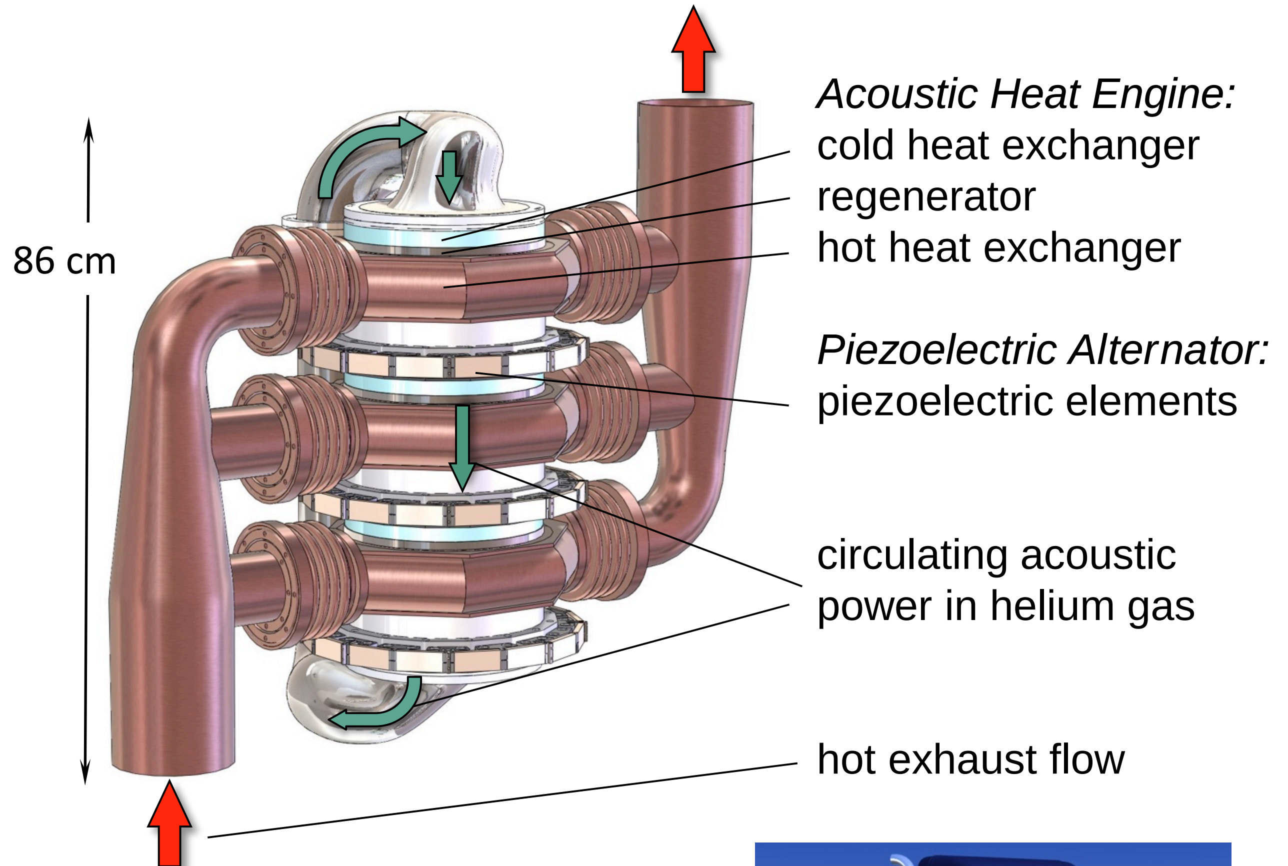
PEEK flexure allows scalability to higher power

Low loss and fatigue endurance limit



TA Piezoelectric Inline Generator

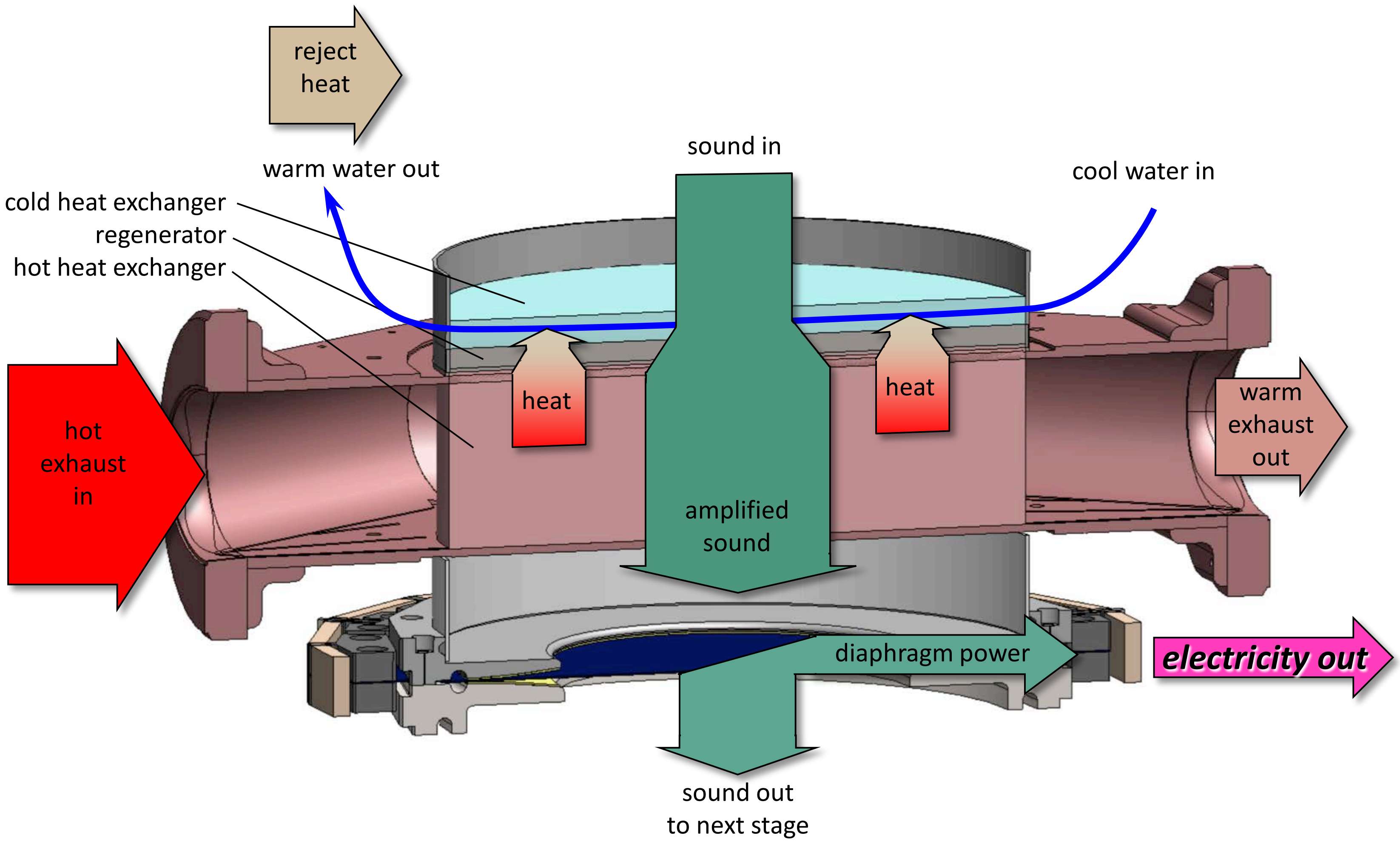
- Heat to electricity
- ~20% efficiency depending on hot temperature
- Multi-phase power from multiple stages
- Vibration balanced, quiet
- Piezoelectric alternators:
  - No pistons.
  - Compact, scalable.



DOE-Volvo Powertrain truck waste heat recovery project

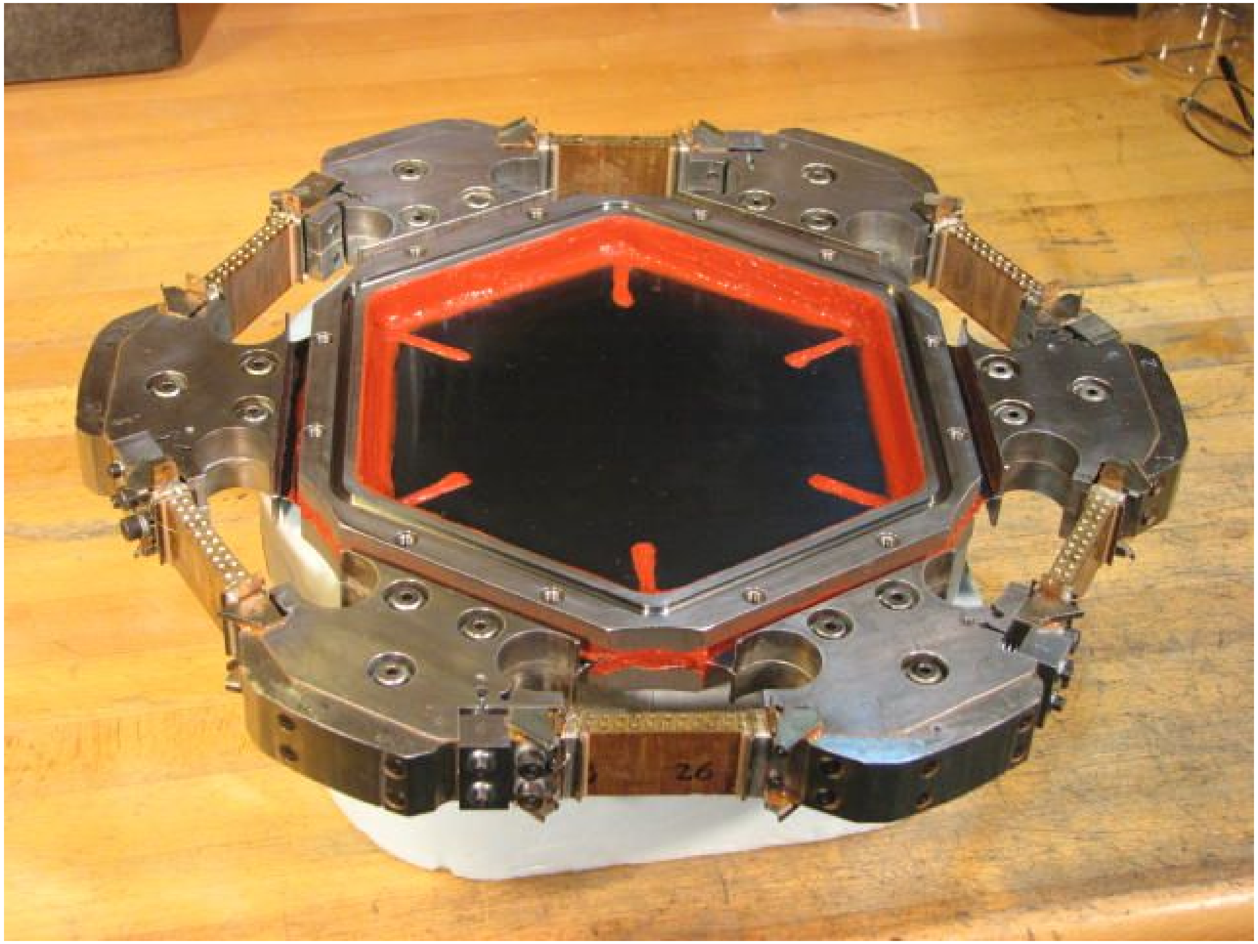
PENNSTATE ARL → SONIC JOULE

How It Works



Downward traveling wave is amplified as it transports heat upward
Flexing diaphragm collects acoustic power and stresses piezoelectric elements at perimeter
Diaphragm is acoustic mass that makes high impedance at regenerator
A way to scale up to higher powers without clearance seals

Piezoelectric Alternator

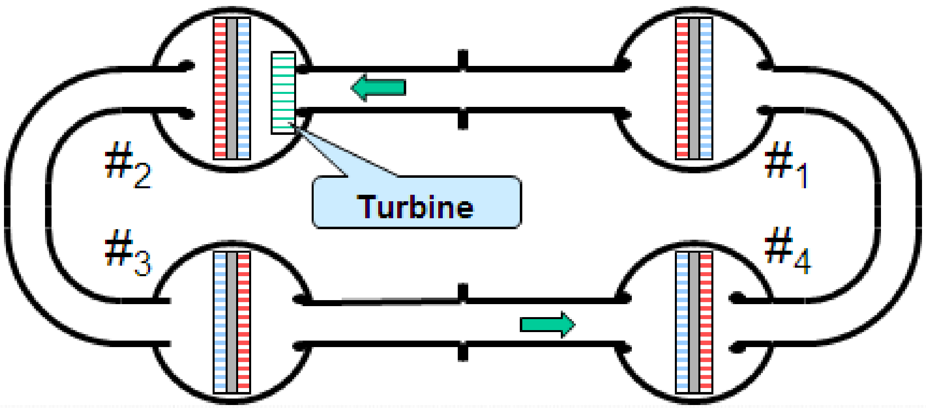


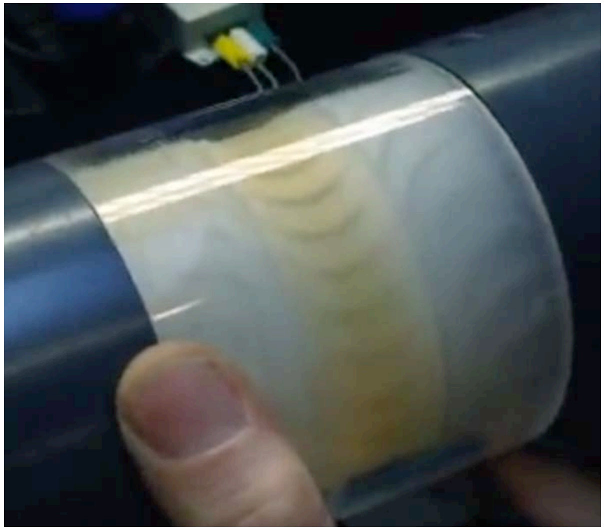
Works!

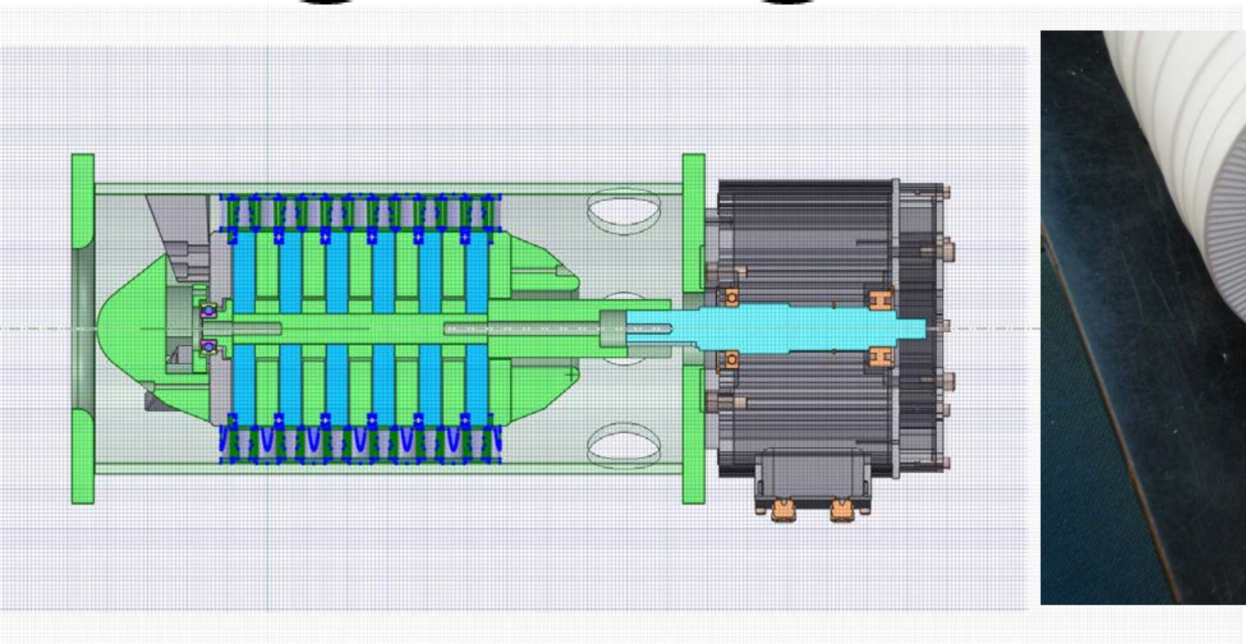
But produced only 37 W before some piezo stacks worked out of their supports and broke

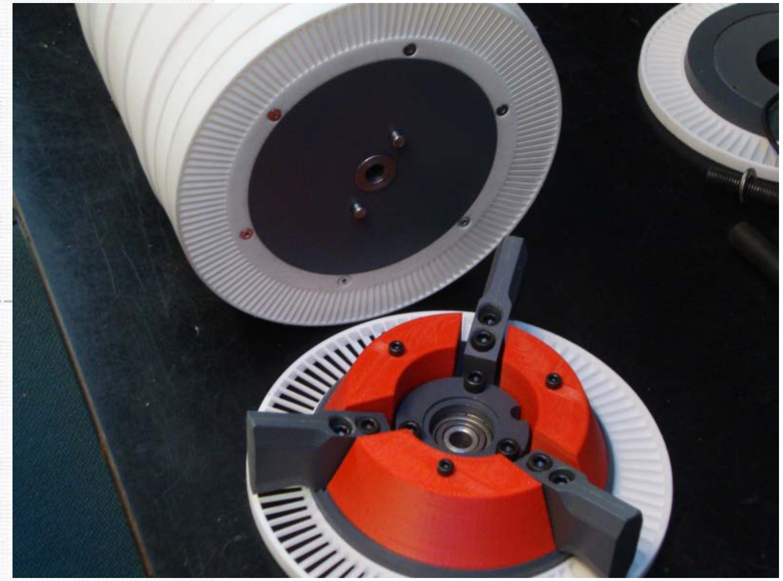
ASTER THERMOACOUSTICS BIDIRECTIONAL TURBINE

Another interesting way to scale up power
Acoustical flow in either direction
  spins turbine in same direction
Going for 10 kW



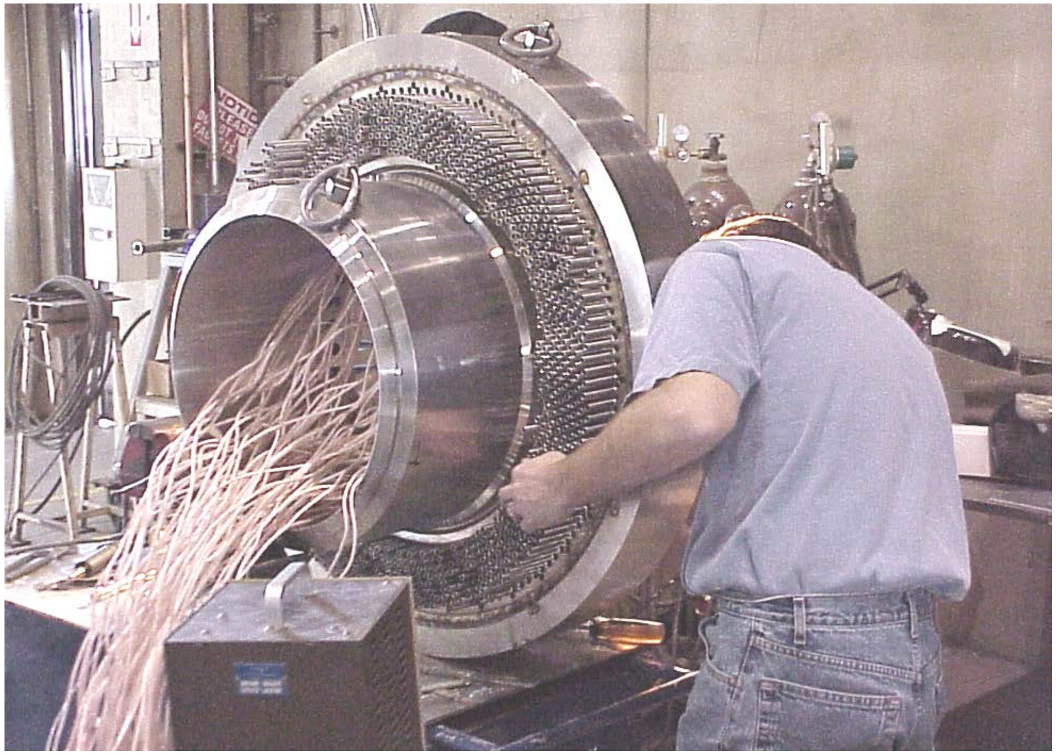






HEAT EXCHANGERS ARE A LIMIT TO POWER DENSITY

From the LANL natural gas liquefier:



Too many individually welded ¼" tubes
Different groups have favorite ways of making better heat exchangers
Better power density with smaller feature size
Heat exchangers can cost too much
Active research area

THE CHALLENGES

- Energy loss mechanisms:
  - regenerator thermal-viscous losses
  - transducer losses
  - complex set of losses at heat exchangers (perhaps the least understood)
  - some configurations sensitive to "streaming" (DC gas flow driven by sound)
  - not everything is fully understood

- The physics is mostly there, but engineering is technically difficult
  - inefficiencies creep in
  - maddeningly huge design parameter space
  - thermal expansion stresses
  - fatigue stresses (need infinite fatigue life)
  - pressure vessels are a pain
  - machines don't always work as planned

- Competing technology is pretty good
  - business case for TA can often be made, but application may be niche

The Opportunity

- Believe economic power range is around 500 W – 500 kW
  - simpler than steam or organic Rankine
  - often better efficiency and lower cost than thermoelectrics
- Because of inert gas working fluid, can design for wide range of temperatures—cryogenic to red hot
- Happy to use waste heat
- Some good advantages:
  - robust
  - simple
  - low maintenance
  - quiet
  - compact
  - good efficiency
  - lowish cost

- Rough rule of thumb: around 35% – 45% of Carnot efficiency should be possible, depending on competing tradeoffs chosen (size, weight, cost, ...)
  - DeltaEC program from LANL is pretty good at predicting performance

KEY PROBLEMS TO BE SOLVED

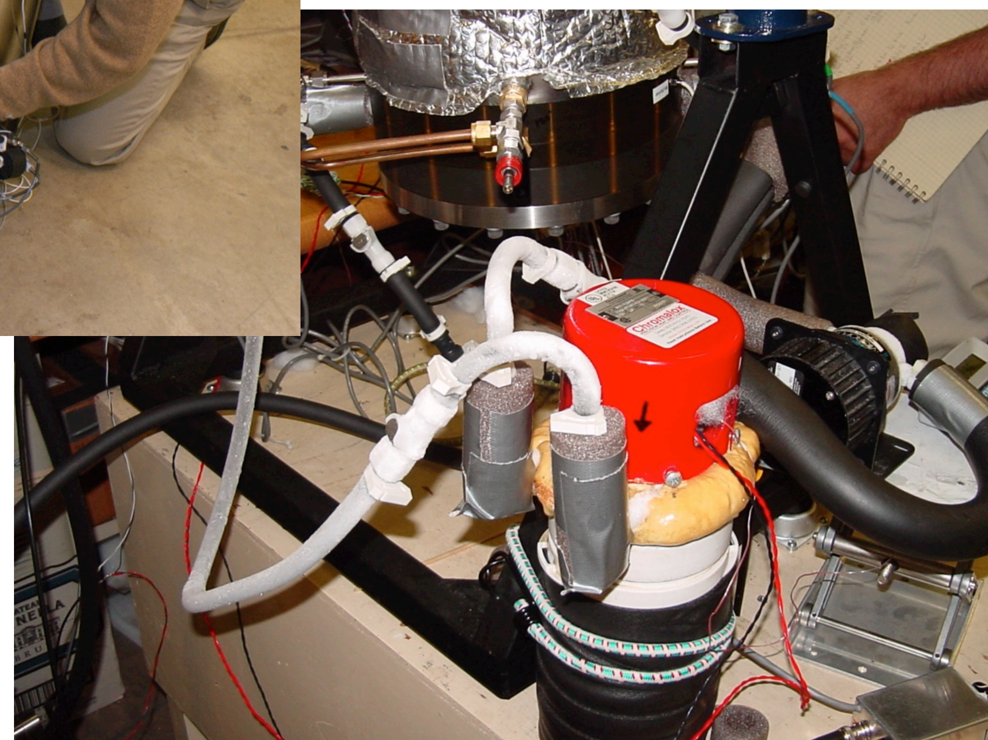
- Better performing but cheaper heat exchangers
- Better, cheaper transducers (motors, alternators, alternatives)
- Find and demonstrate clever applications
- Lower costs, simpler fabrication techniques, commercialization

Extra Slides

Penn State – Ben&Jerry's "Bellows-Bounce" Freezer

Performance

- 120 W cooling capacity
- -20 °C load temp
- 19% of Carnot

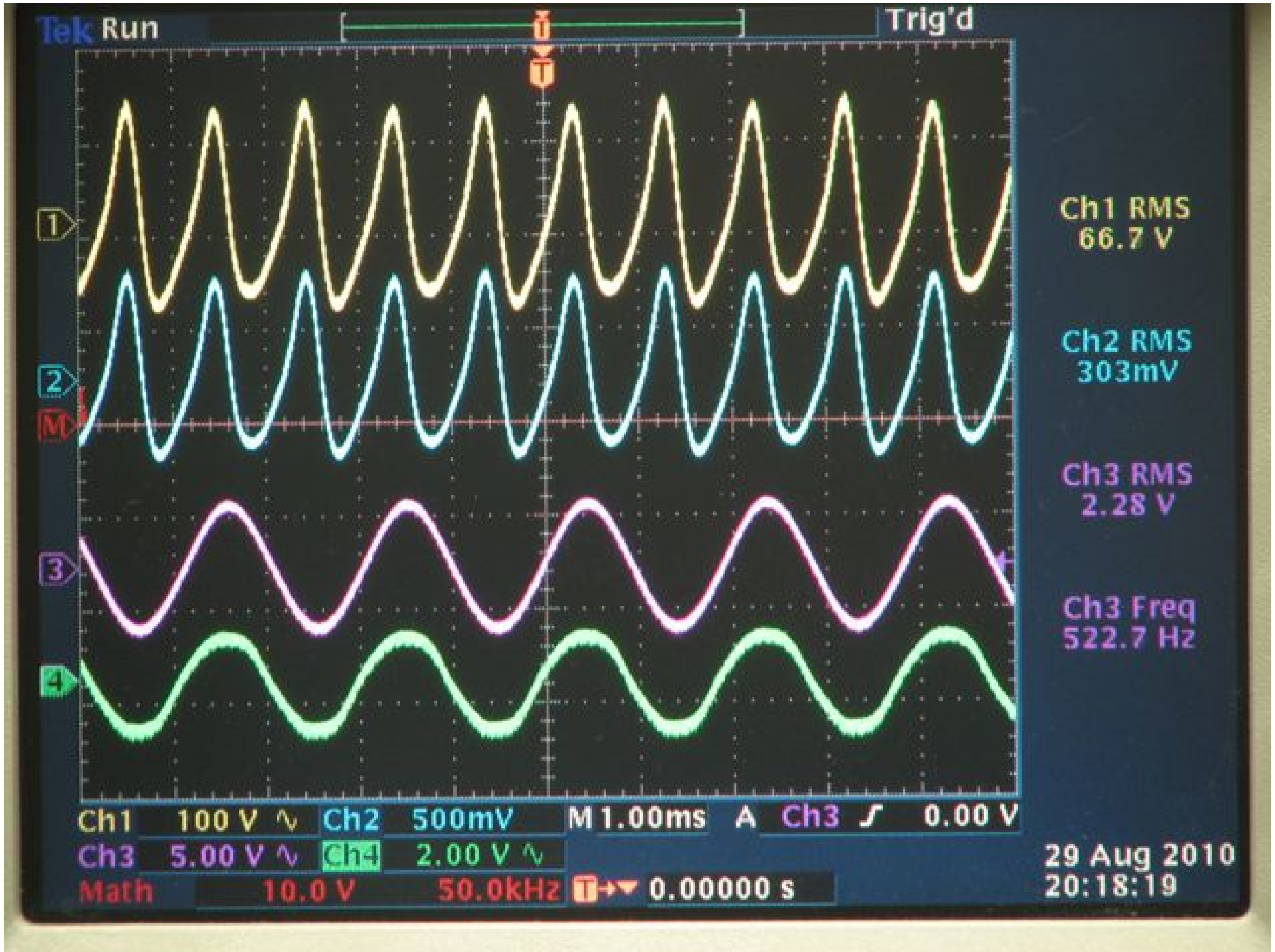


All Natural BEN&JERRY'S VERMONT'S FINEST

Unilever

PIEZOELECTRIC ALTERNATOR WAVEFORMS

Good waveforms showing expected frequency doubling, while giving 21 W:



Piezo Voltage

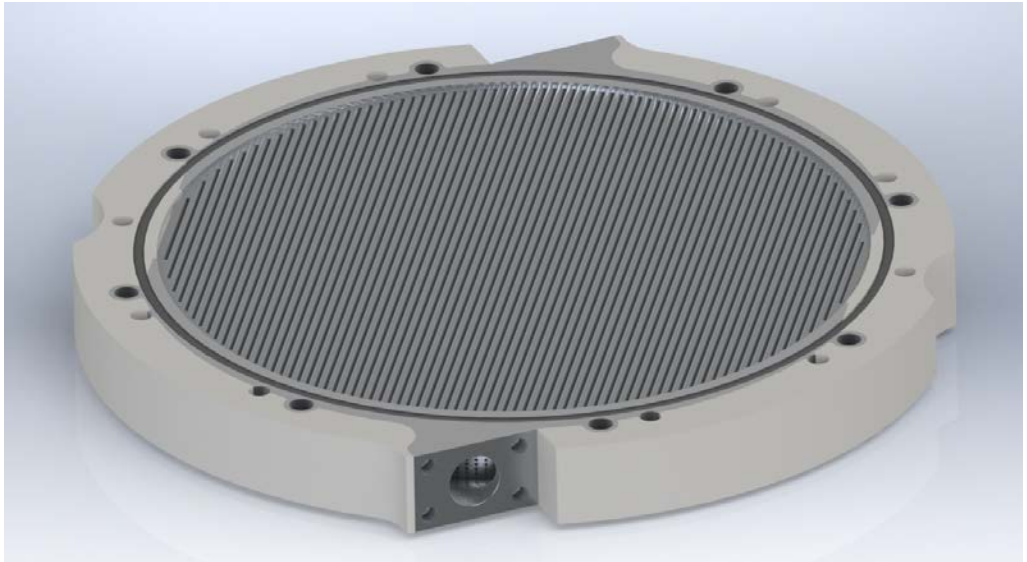
Piezo Current

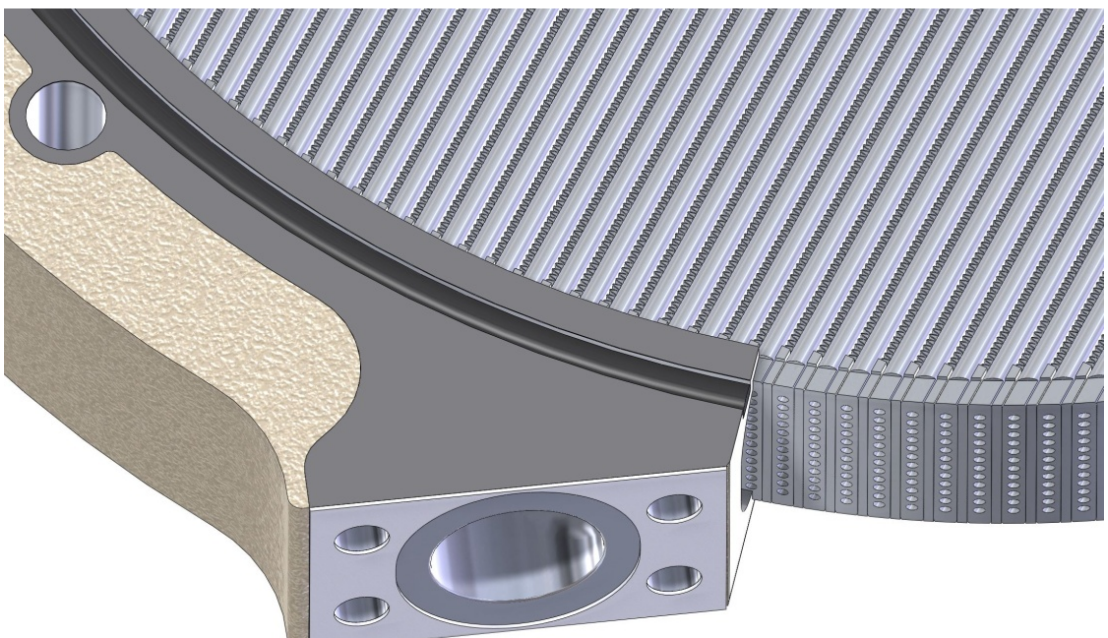
Pressure above diaphragm

Pressure below diaphragm

Bad waveforms also happen.

Trillium Brazed Aluminum Heat Exchanger

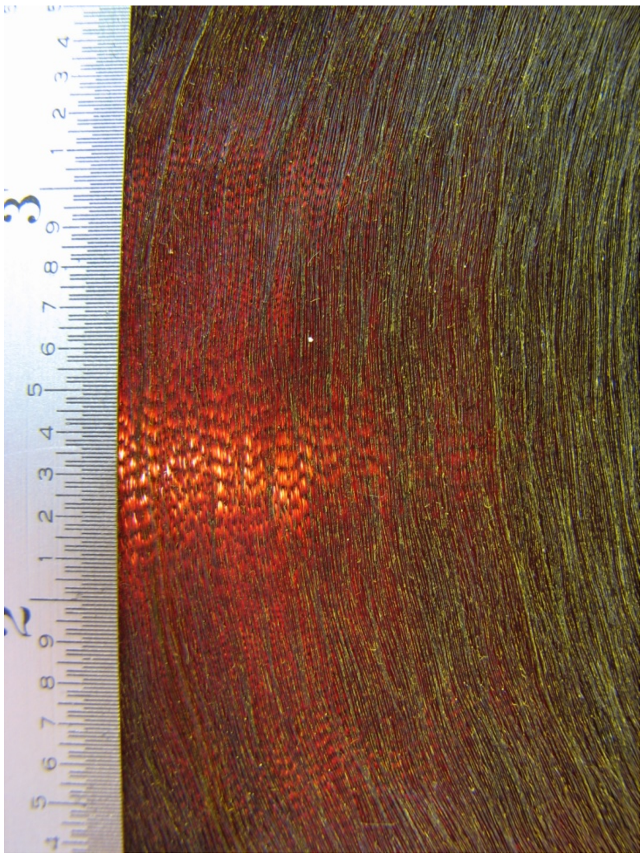


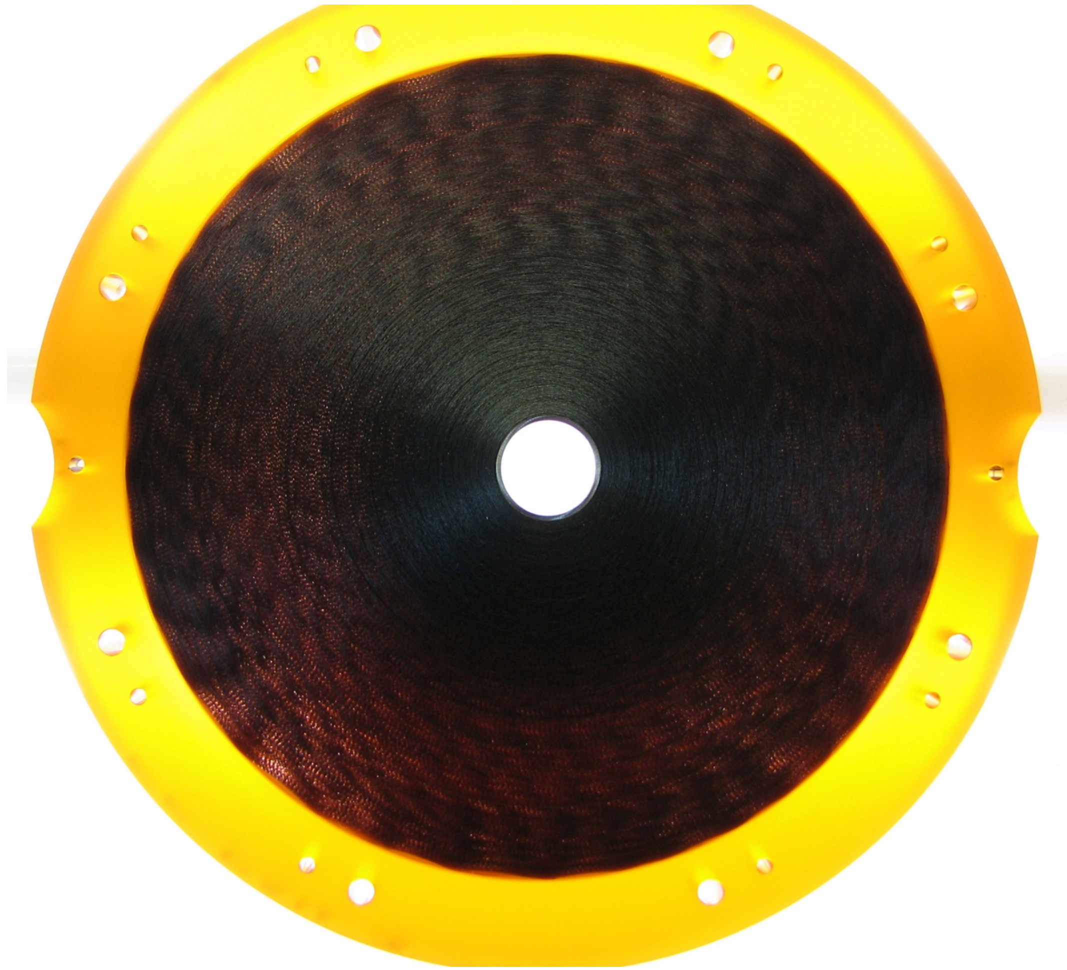


- Brazed aluminum microchannel tubes with 800 µm amplitude corrugated fins
- 84 µm hydraulic radius r_h on helium side. $r_h/\delta_\kappa = 0.35$
- Regenerator-like pores for low S_{GEN} and effectiveness ≈ 1

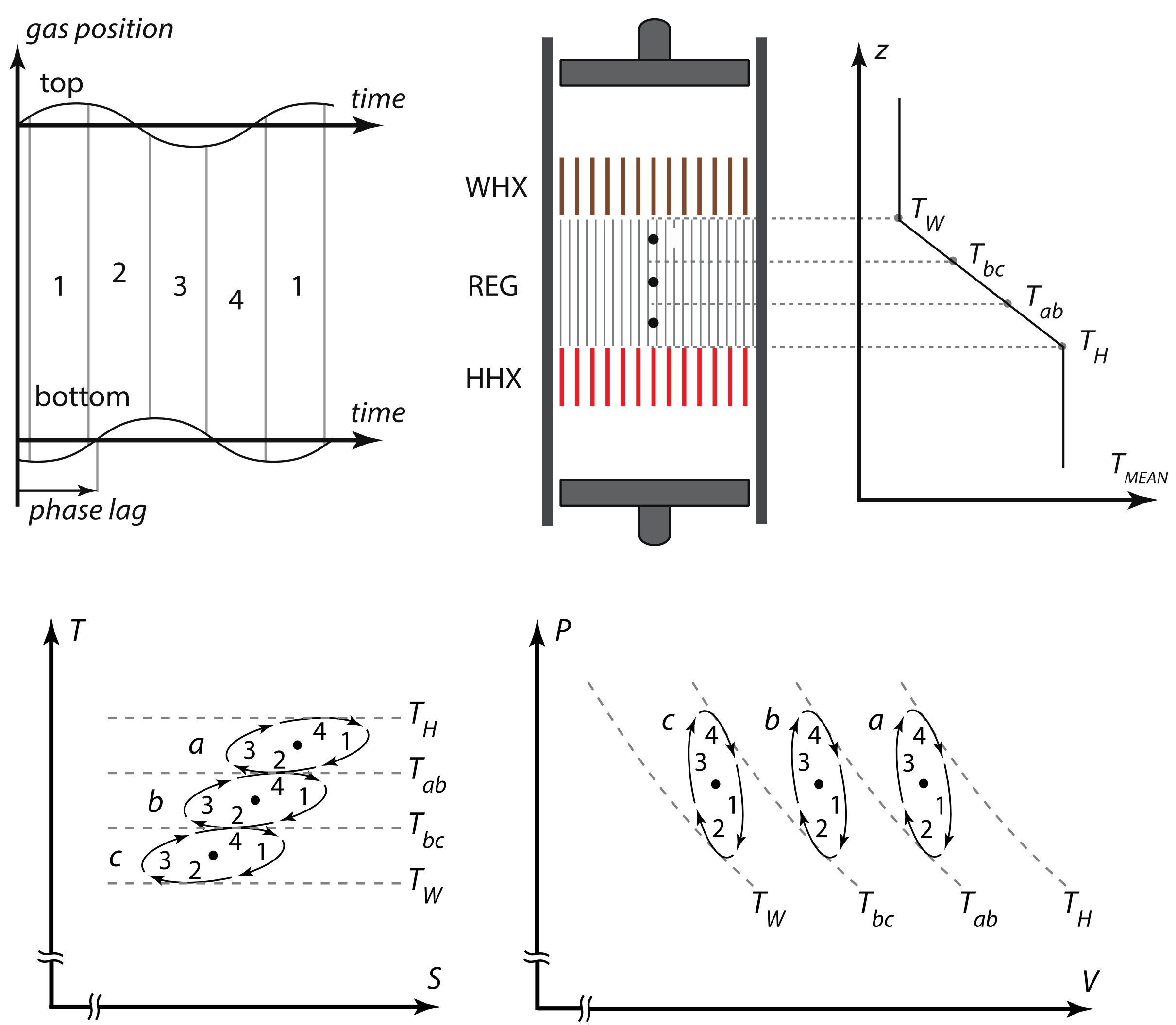
TRILLIUM WOUND KAPTON REGENERATOR

Manufactured by Cool Energy, Inc.





Thermoacoustic Stirling Engine Cycle



Thermoacoustic Stirling Refrigeration Cycle