SPACE TRIPS SUMMER SCHOOL

Theme 9: SPACE

Riga Latvia

June 17-20 , 2 0 1 4

Thermoacoustic Electric Generation

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LAUM

cnrs

Université du Maine

Introduction

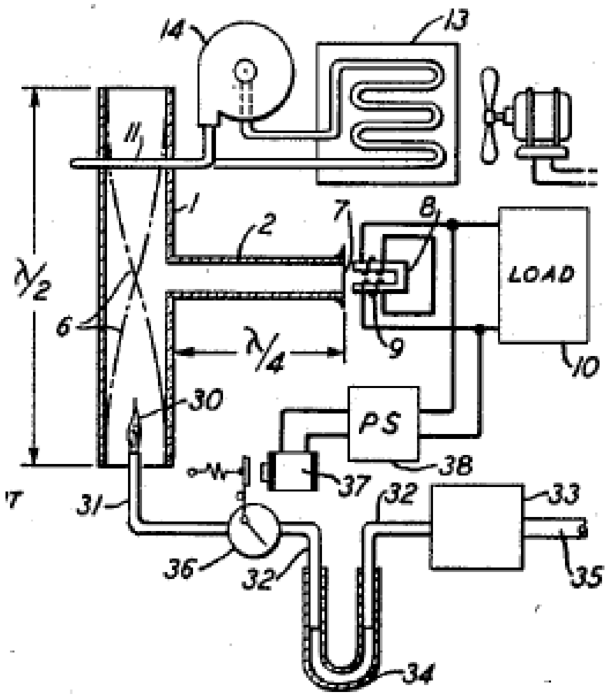
Patented Apr. 17, 1951 **UNITED STATES PATENT OFFICE**

2,549,464

ELECTRIC POWER SOURCE

Ralph V. L. Hartley, Summit, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

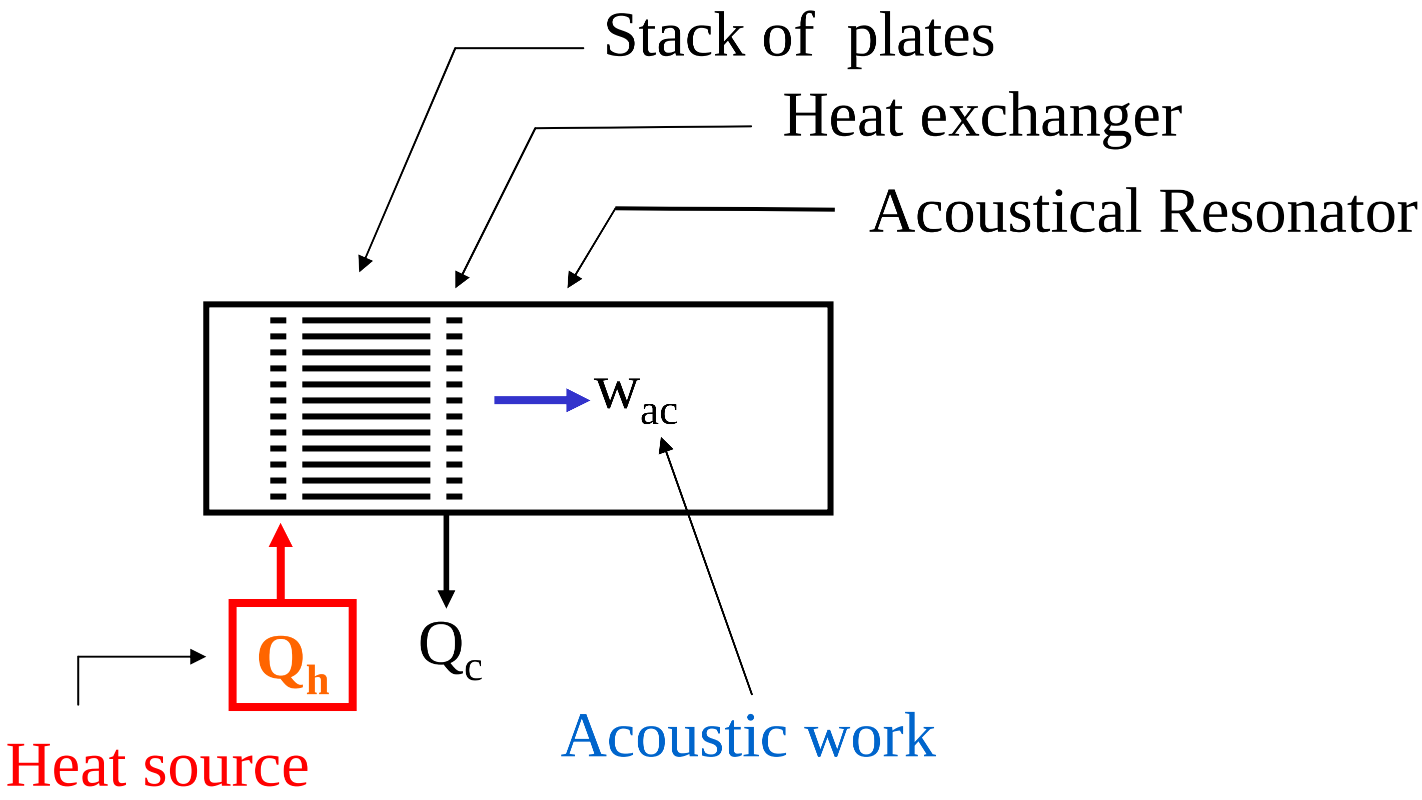
FIG. 4



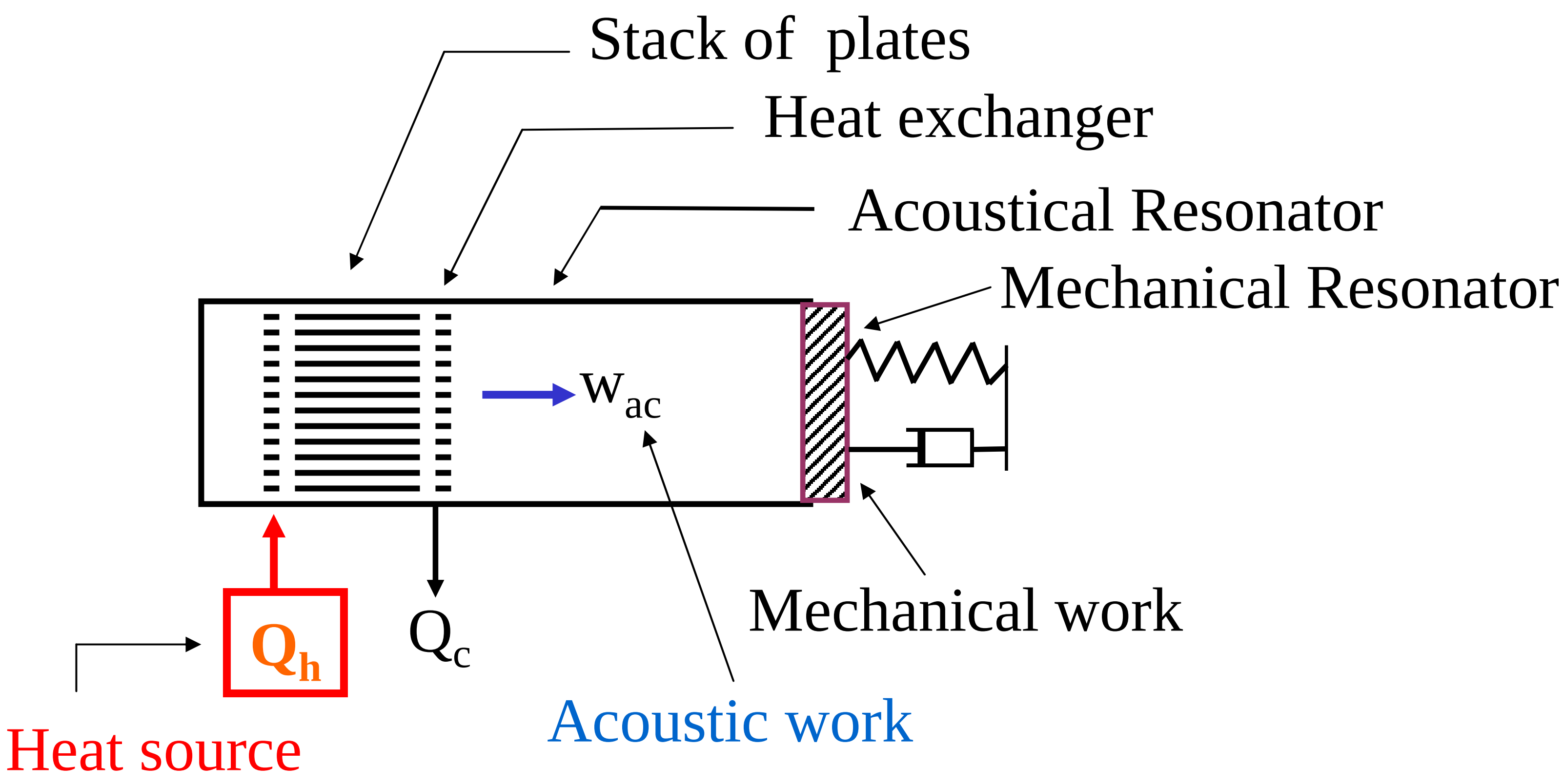
Outlines

- Introduction
- Theory
- Some realizations
- Future development

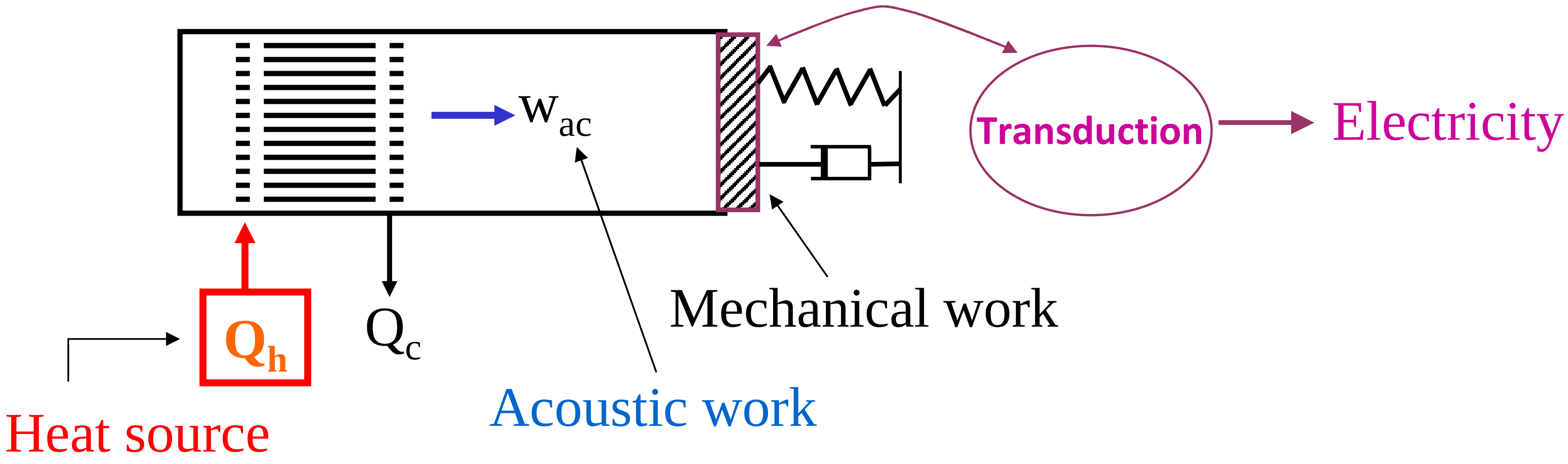
Thermoacoustic Engine



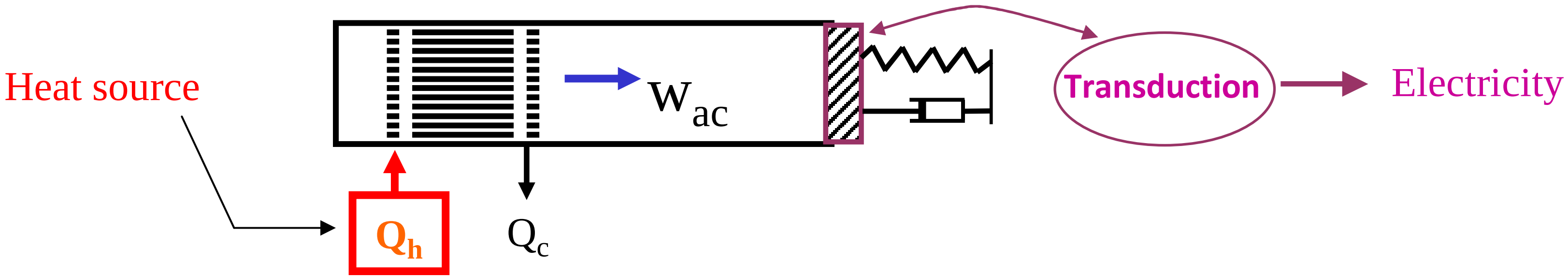
Thermo-acousto-mechanical device



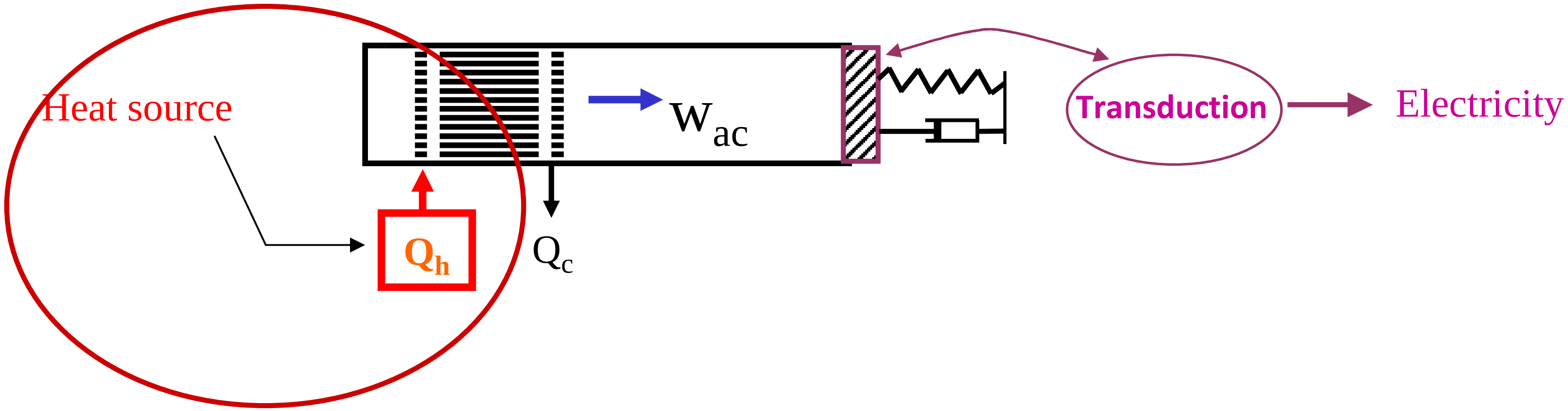
Thermo-acousto-mechanico-electrical device



Different architectures

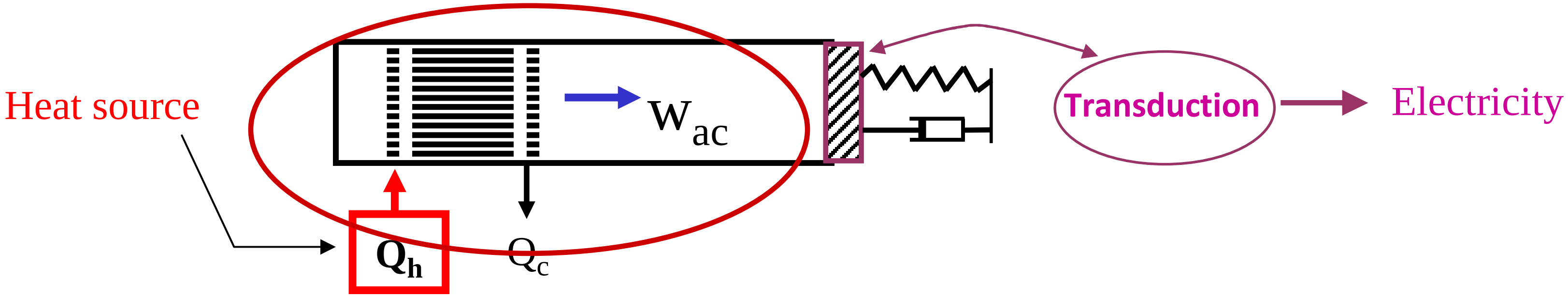


Different architectures



- Heat source
  - Solar dish
  - Waste heat
  - Biomass
  - ....

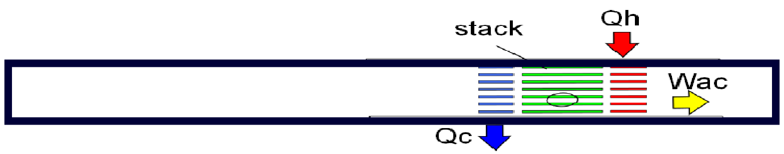
Different architectures



Resonator

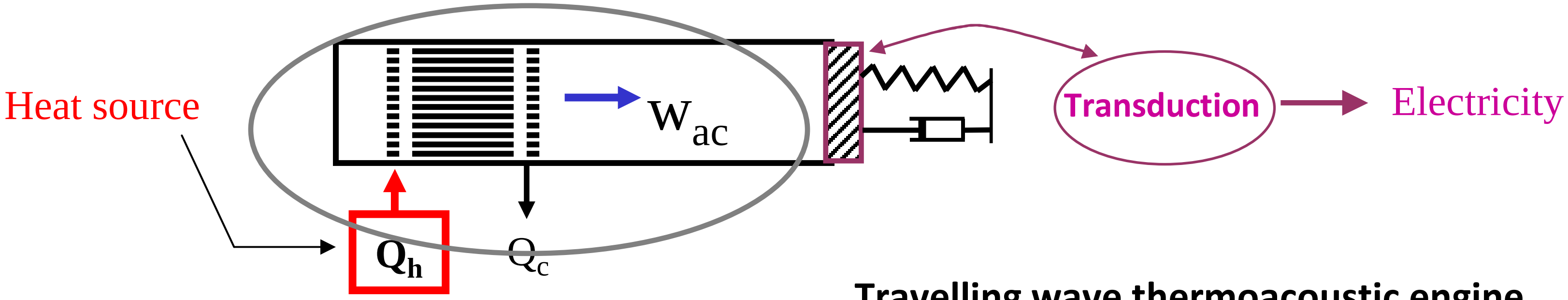
Standing wave thermoacoustic engine

- p and v are out of phase + stack



$L_{resonator} \sim \lambda/2$

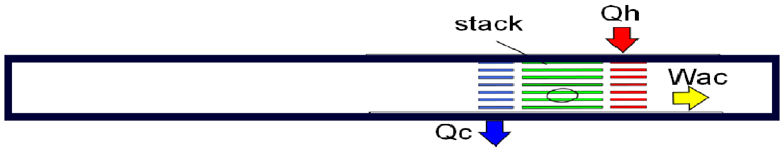
Different architectures



Resonator

Standing wave thermoacoustic engine

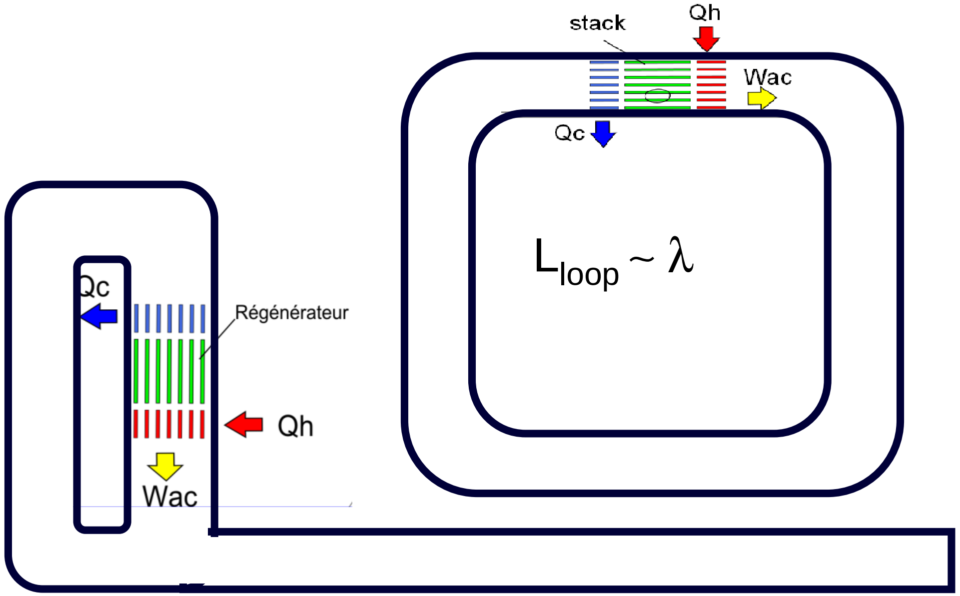
- p and v are out of phase + stack



$L_{resonator} \sim \lambda/2$

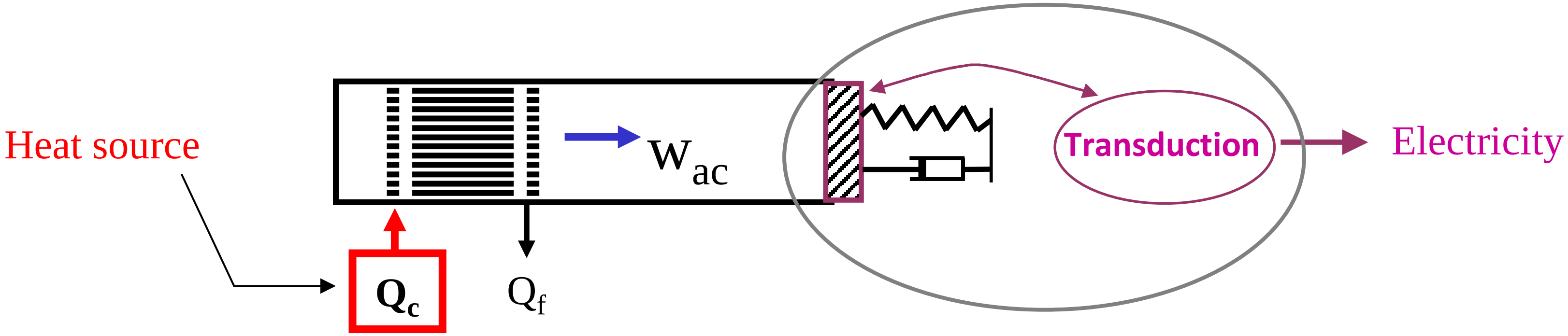
Travelling wave thermoacoustic engine

- p and v are in phase + regenerator



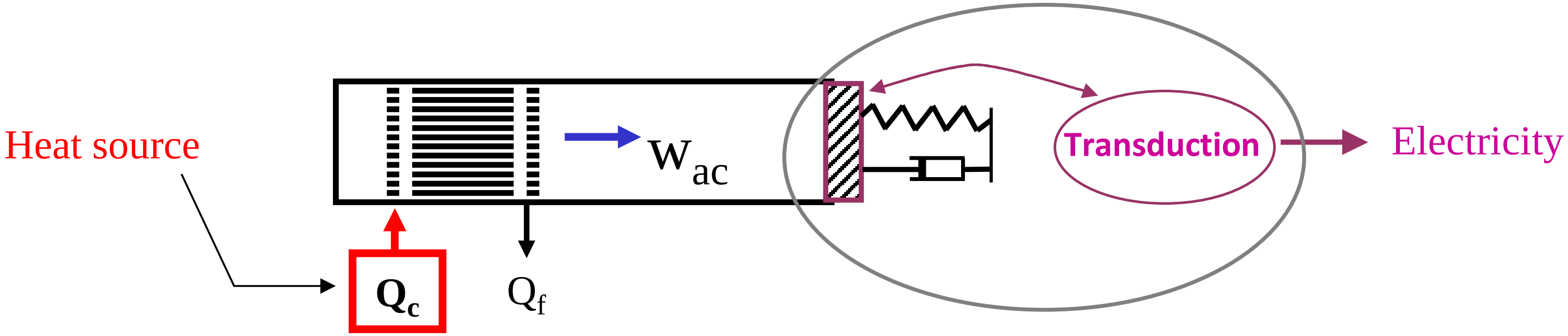
$L_{loop} \sim \lambda$ $L_{resonator} \sim \lambda/2$

Different architectures



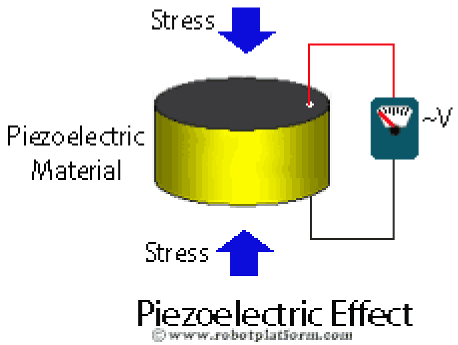
Electro-mechanical transducer

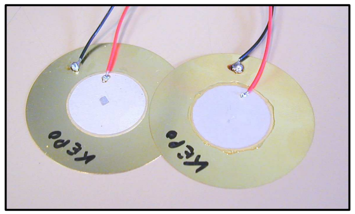
Different architectures



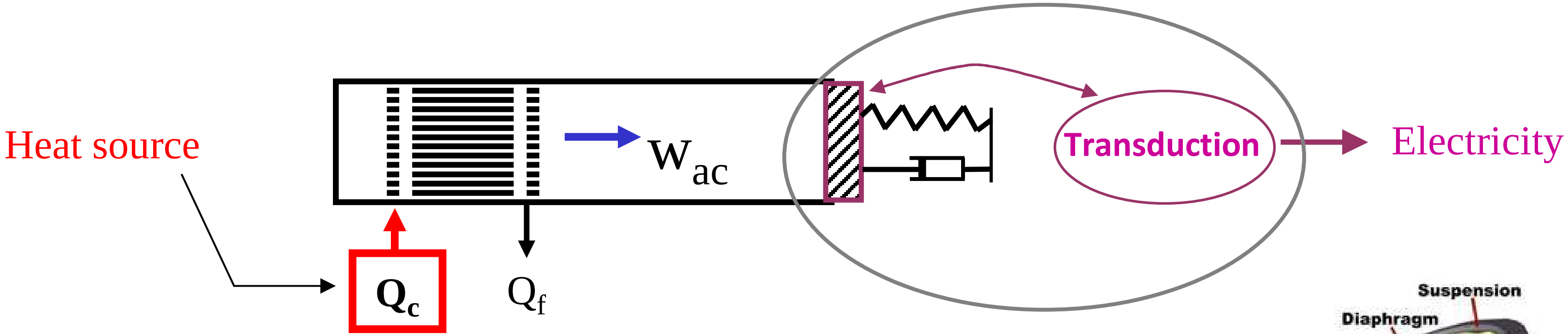
Electro-mechanical transducer

Piezoelectric sensors



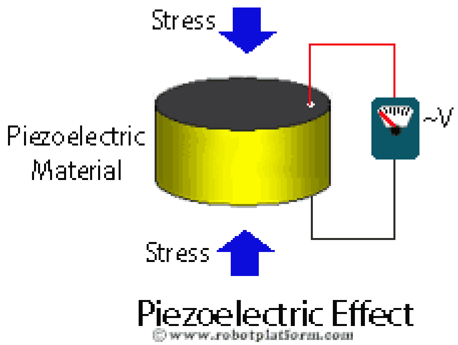


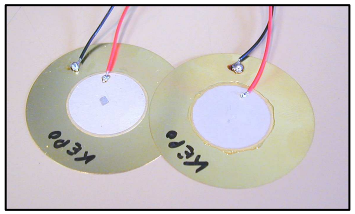
Different architectures



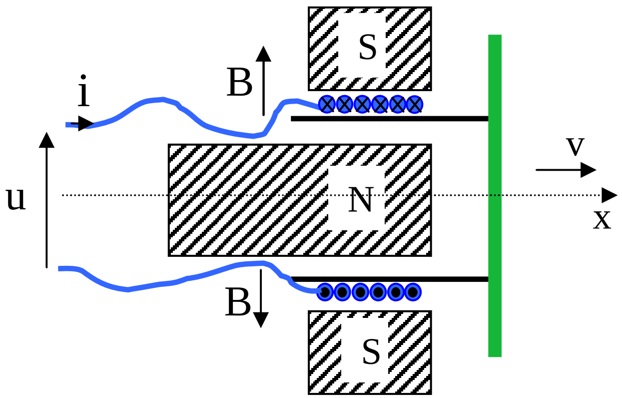
Electro-mechanical transducer

Piezoelectric sensors



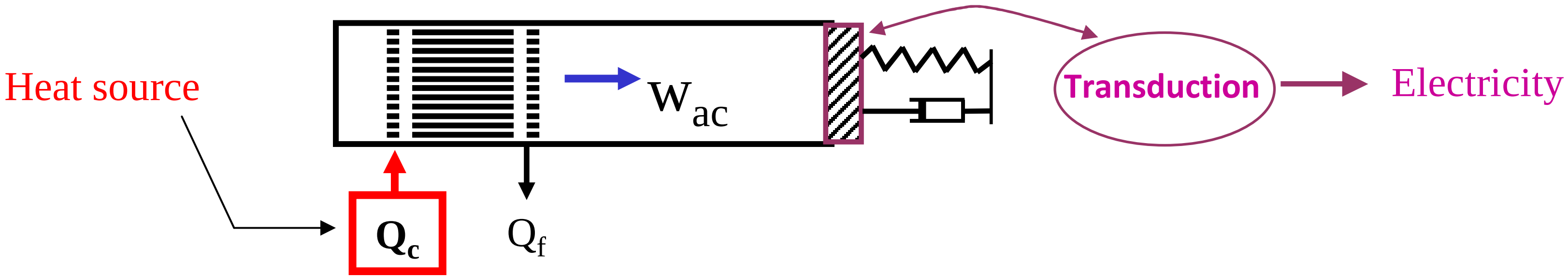


Electrodynamic sensors



Qdrive's 1S102M/A linear reciprocating motor/alternator

Different architectures



Other stuff

- Gaz
- Stack/regenerator material
- Heat exchangers
- ....

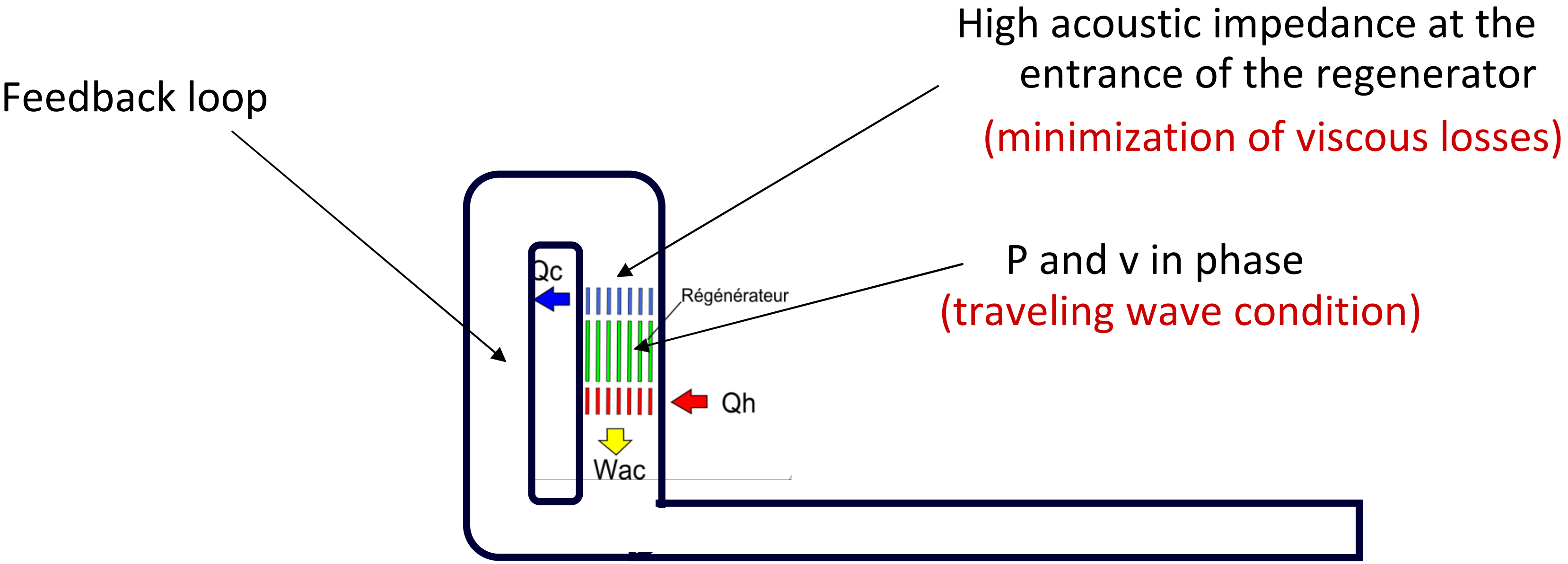
Outlines

- Introduction
- Theory
- Some realizations
- Future development

Theory : engine design

- Case of traveling-wave loop thermoacoustic device

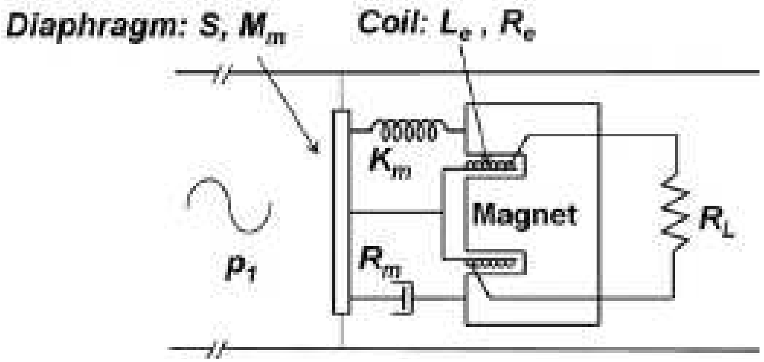
Analytical theory, but practically : Use of Delta-EC (or equivalent software)

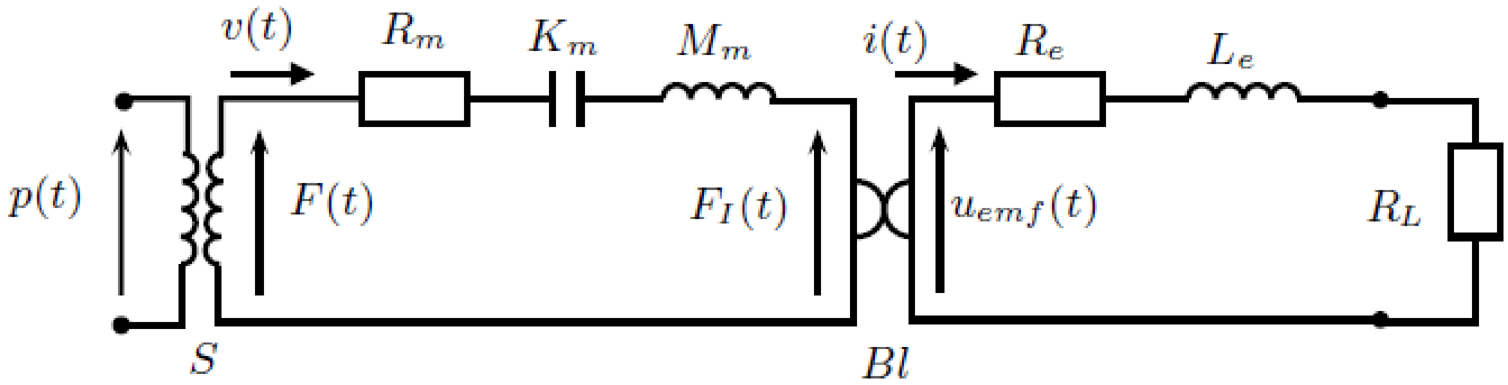


- Thermal to acoustic efficiency $$\eta_{ta} = \frac{P_a}{Q_h}$$

Theory : acousto-electric coupling

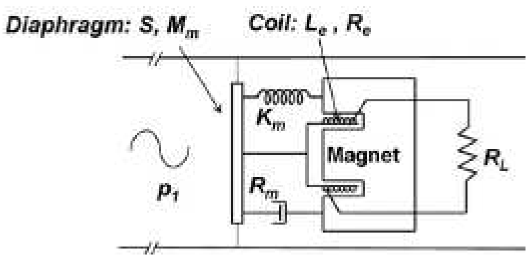
- Case of a linear alternator, seen as an electrodynamic loudspeaker

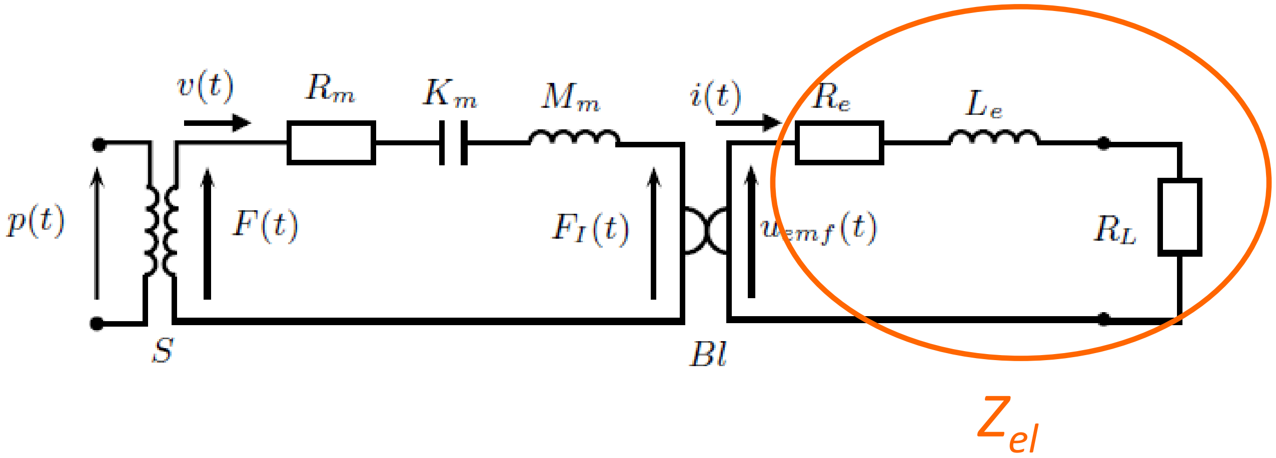




Electrical network equivalent to the alternator

Theory : acousto-electric coupling

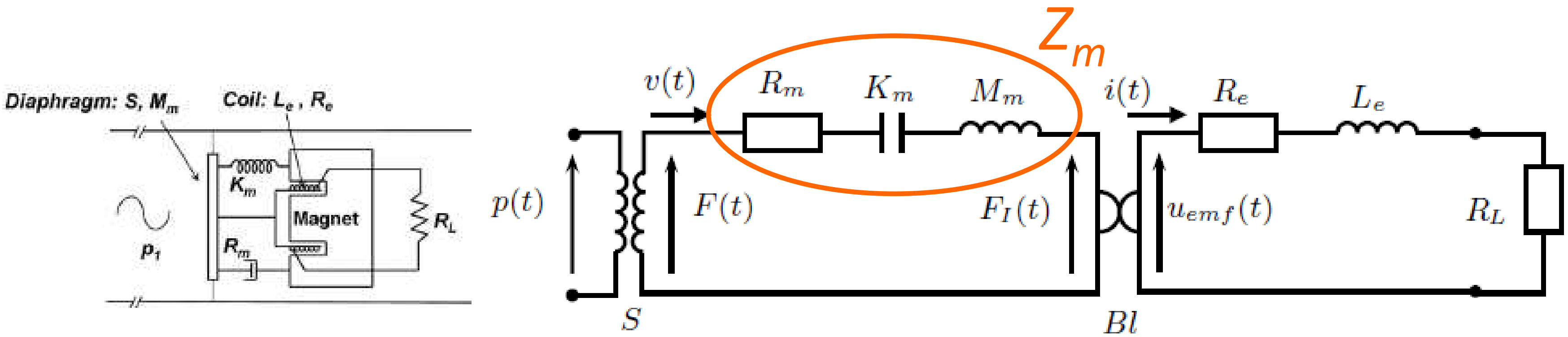




- Electrical impedance

$$Z_{el}(\omega) = R_e + j\omega L_e + R_L$$

Theory : acousto-electric coupling



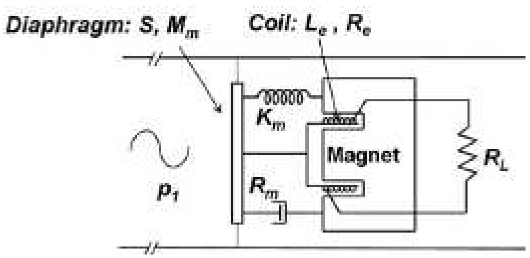
- Electrical impedance

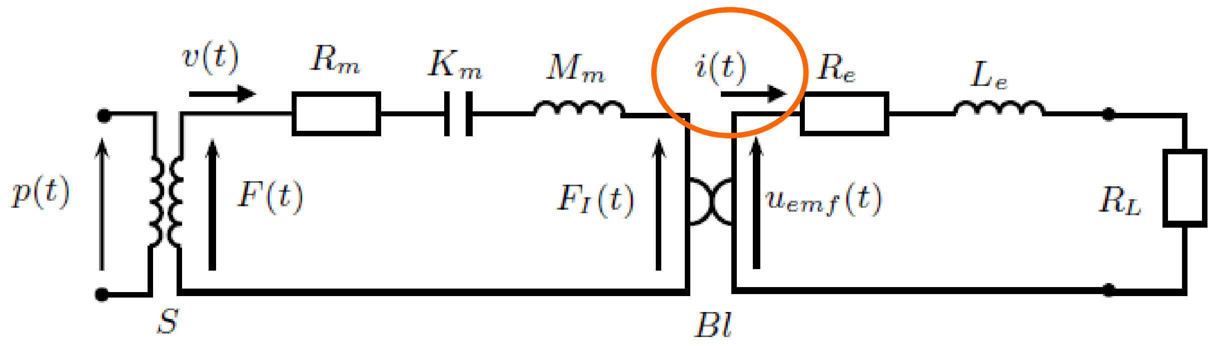
$$Z_{el}(\omega) = R_e + j\omega L_e + R_L$$

- Mechanical impedance

$$Z_m(\omega) = R_m + j\omega M_m - j\frac{K_m}{\omega}$$

Theory : acousto-electric coupling





- Electrical impedance

$$Z_{el}(\omega) = R_e + j\omega L_e + R_L$$

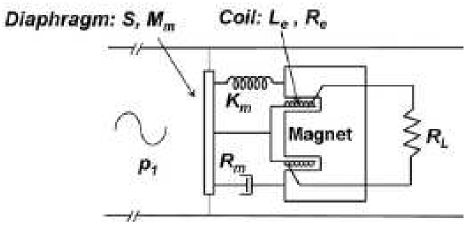
- Mechanical impedance

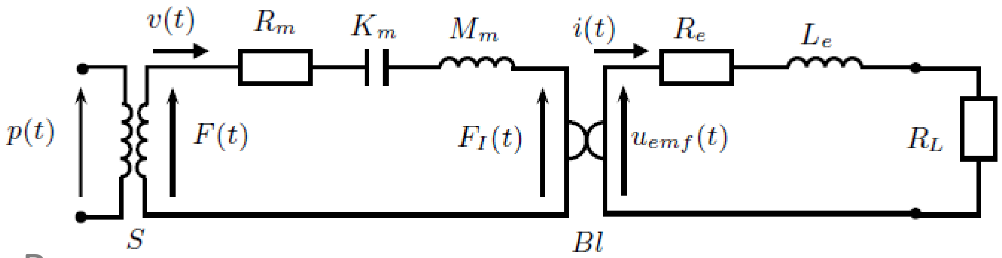
$$Z_m(\omega) = R_m + j\omega M_m - j\frac{K_m}{\omega}$$

- Electrical current flowing through the loading resistor R_L

$$I(\omega) = F(\omega)\left[\frac{Bl}{Z_e(\omega)Z_m(\omega) + Bl^2}\right] = p(\omega)\cdot S\left[\frac{Bl}{Z_e(\omega)Z_m(\omega) + Bl^2}\right]$$

Theory : acousto-electric coupling





- Electric power dissipated in resistor R_L

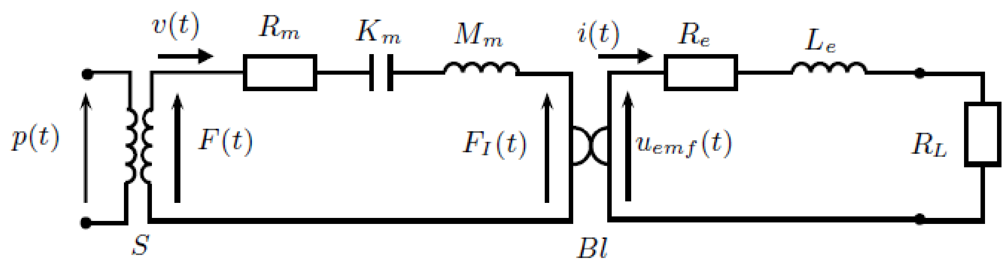
$$P_e(\omega) = \frac{1}{2}\Re\{I \cdot U^*\} = \frac{1}{2}|I(\omega)|^2 R_L = \frac{1}{2}|p(\omega)|^2 S^2 R_L \left|\frac{Bl}{Z_m(\omega)\cdot Z_{el}(\omega) + Bl^2}\right|^2$$

- Input acoustic power

$$P_a = \frac{1}{2}\Re\{p \cdot w^*\} = \frac{1}{2}\Re\left\{p \cdot \frac{p^*}{Z_a^*}\right\} = \frac{1}{2}|p|^2\Re\{\frac{1}{Z_a}\} = \frac{1}{2}|p(\omega)|^2 S^2 \cdot \Re\left\{\frac{Z_{el}(\omega)}{Z_m(\omega)\cdot Z_{el}(\omega) + Bl^2}\right\}$$

$$\eta = \frac{P_e(\omega)}{P_a(\omega)} = \frac{R_L\left|\frac{Bl}{Z_m(\omega)\cdot Z_{el}(\omega) + Bl^2}\right|^2}{\Re\left\{\frac{Z_{el}(\omega)}{Z_m(\omega)\cdot Z_{el}(\omega) + Bl^2}\right\}}$$

Theory : acousto-electric coupling



- Acoustic to electrical efficiency

$$\eta = \frac{P_e(\omega)}{P_a(\omega)} = \frac{R_L \left| \frac{Bl}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right|^2}{\Re\left\{ \frac{Z_{el}(\omega)}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right\}}$$

- If $L_e\omega << R_e$, then $R_{el} \approx R_e + R_L$
- If $\omega = \omega_r$, then $Z_m = R_m$

$$\eta = \frac{Bl^2 R_L}{R_m \cdot (R_L + R_e)^2 + Bl^2 \cdot (R_L + R_e)}$$

Theory : thermo-electric coupling

- Thermal to electrical efficiency $\eta_{te} = \frac{P_e}{Q_h}$

Not so easy to predict from separate study of each part of the device

Strong coupling between themoacoustic resonator and alternator

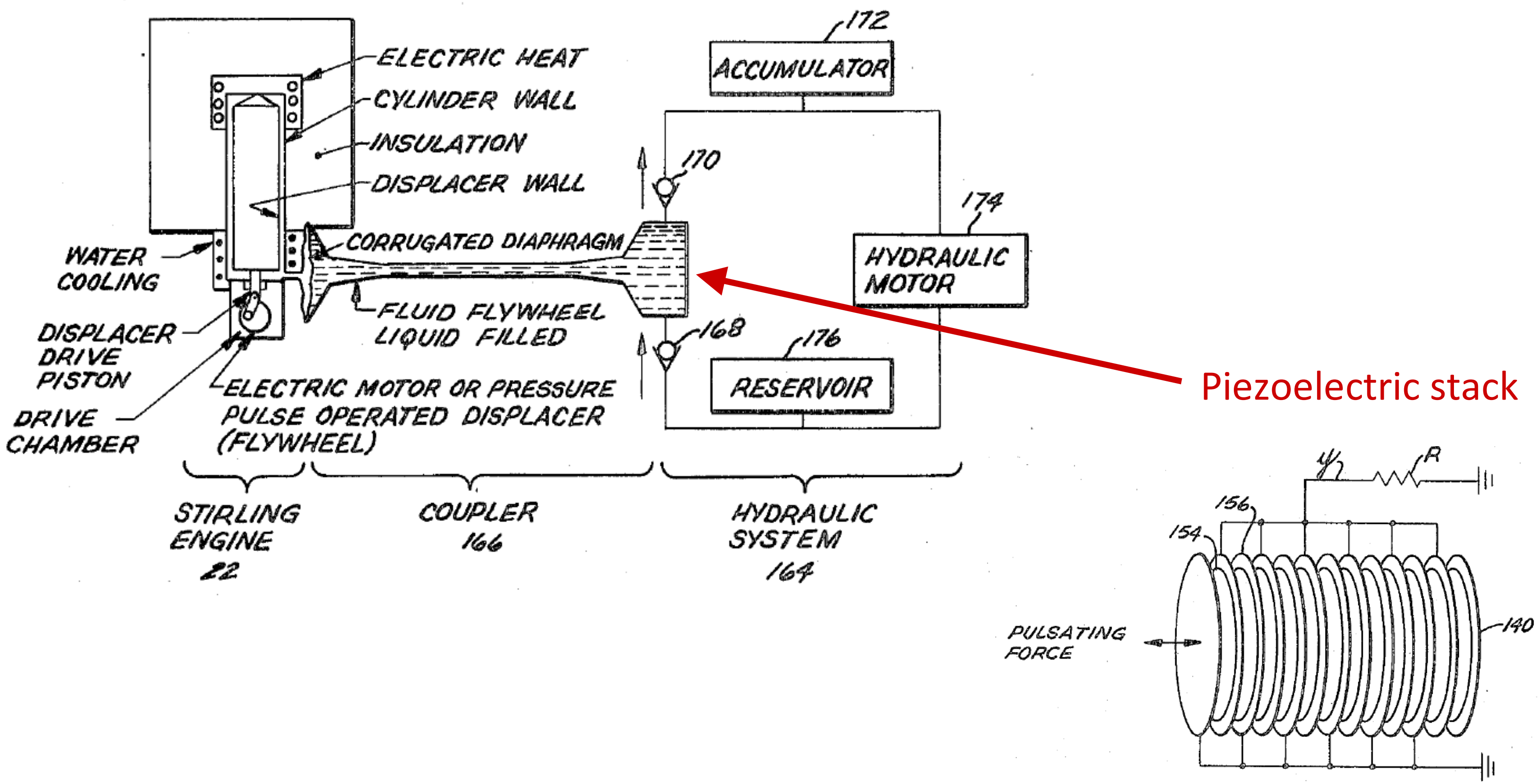
The device has to be designed as a whole

Outlines

- Introduction
- Theory
- Some realizations (non-exhaustive)
- Future development

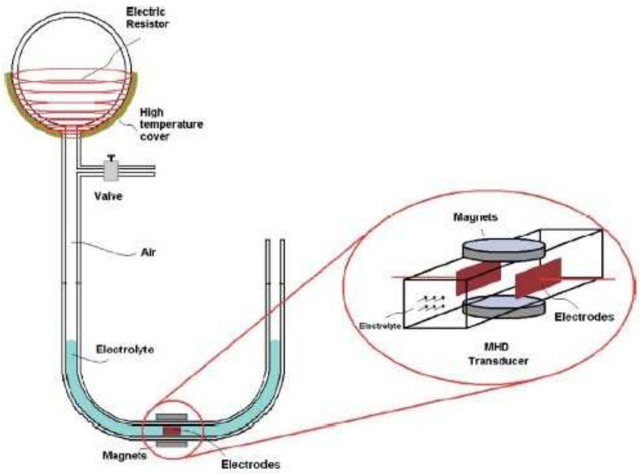
Standing waves devices

Martini et al. , Stirling engine power system, US Patent (1974)



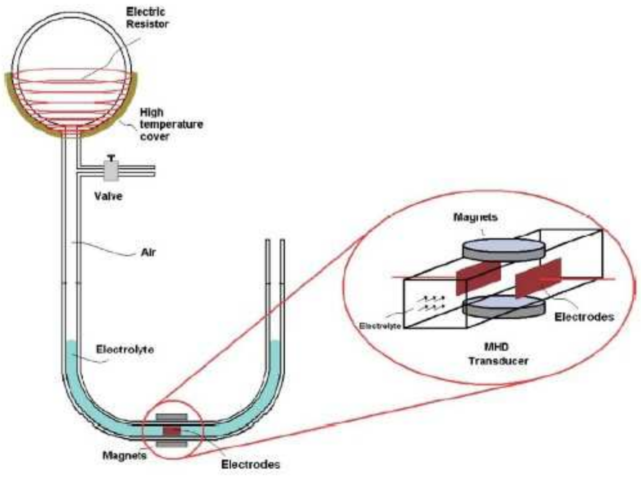
Standing waves devices

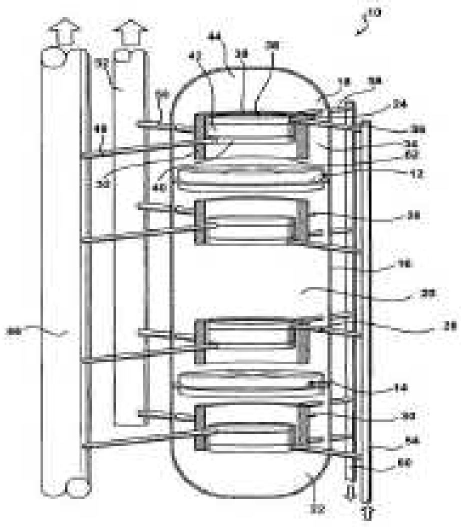
Huelsz et al., Magneto-hydro-dynamical transduction, 2006



Standing waves devices

Huelsz et al., Magneto-hydro-dynamical transduction, 2006





Keolian et al. , Thermoacoustic piezoelectric generator,

US Patent (2010)

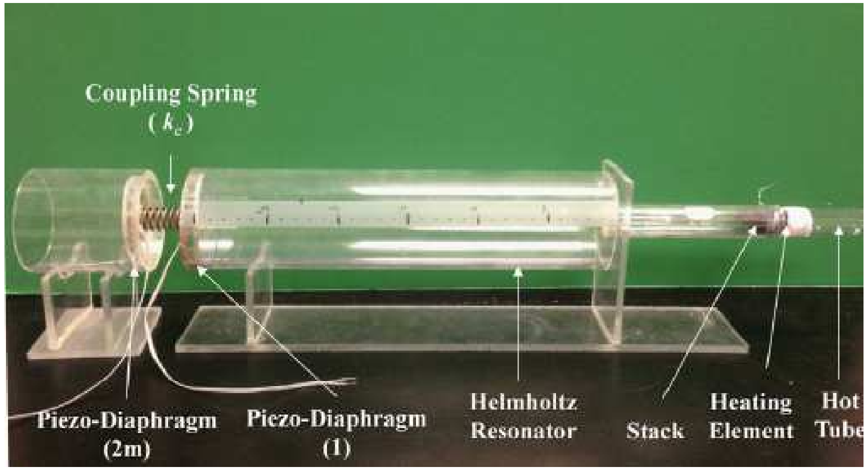
Application : Diesel truck waste heat recovery

Standing waves devices

Last development in Energy harvesting

Smoker et al., Nouh et al., 2012 - 2014

- Input heating power : $Q_h = 40$ W
- Output electric power : Pel = 0,12 mW
- Acoustic to electric efficiency : $\eta_{ae} \approx 10\%$
- Global efficiency : $\eta \approx 3.\ 10^{-4}\%$

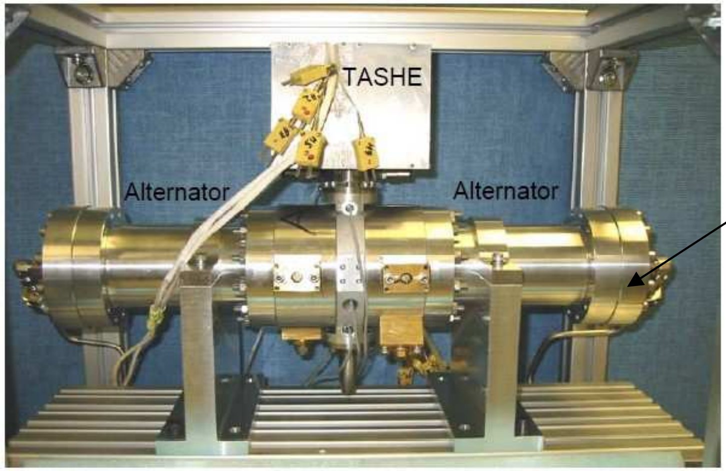


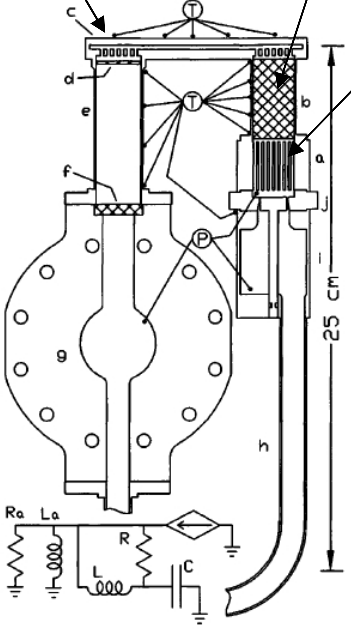
Low efficiency, but can be miniaturized and distributed

- Still in progress…

Traveling waves devices

S. Backhaus et al., Los Alamos Lab., 2004





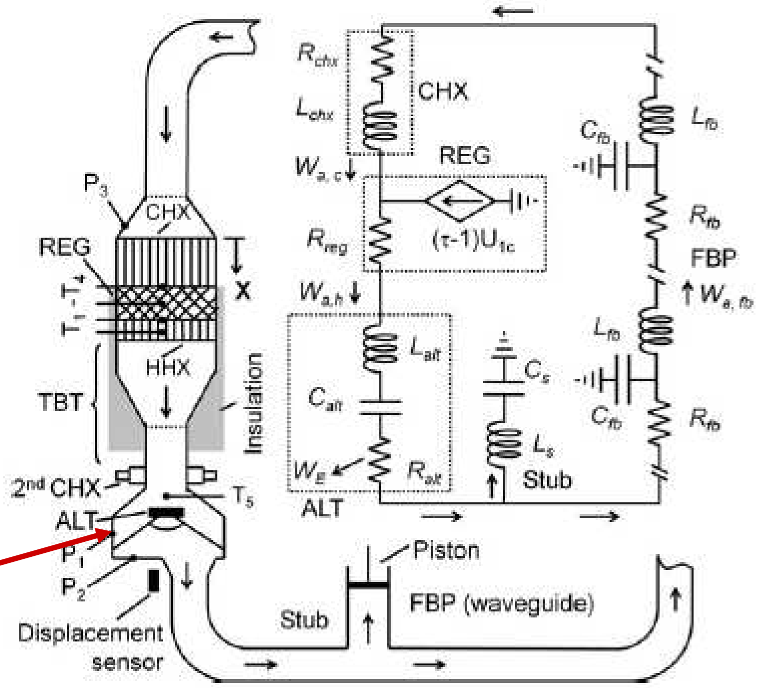
- Fluide : He, 55 Bar
- Volume :
  $V_{cavarr} = 0.6$ l,
  $V_{tot} > 2$ l
- Performance :
  $f \approx 120$ Hz
  $T_h \approx 600$ °C
  $Q_h < 400$ W
  $Q_{el_{max}} \approx 58$ W
  $\eta_{max} \approx 18$ %

Traveling waves devices

Yu et al., Score project, 2012

Low cost electricity generator for rural area driven by biomass

- Fluide : air, 1 Bar
- Volume :
  $L \approx 4.25$ m, $R=2.7$ à 6.4 cm
  $V_{tot} > 10$ l
- Performance :
  $f \approx 70$ Hz
  $T_h \approx 120$ °C
  $Q_h < 500$ W
  $Q_{el_{max}} \approx 11.6$ W
  $\eta_{max} \approx 3$ %



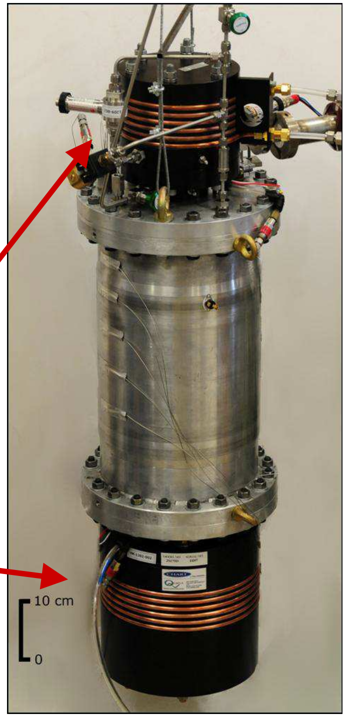
Classical loudspeaker set in the loop

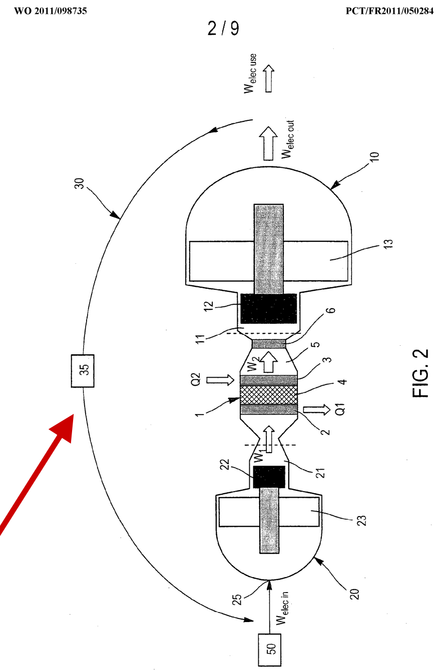
Traveling waves devices

Hekyom, 2011 : Demonstrator of thermoacoustic electricity generator

- P_{el} = 800 W
- T_h = 950 °C

2 Q-Drive transducers





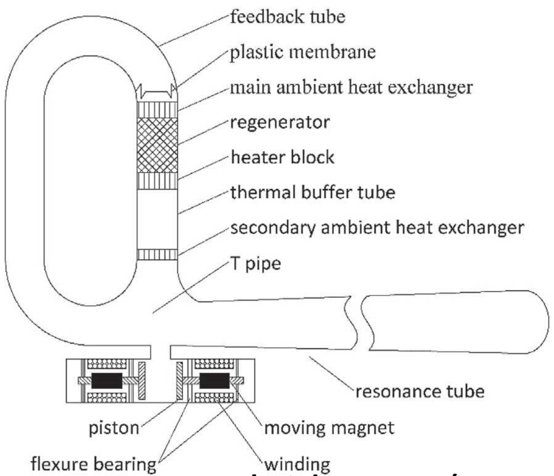
Electric feedback loop

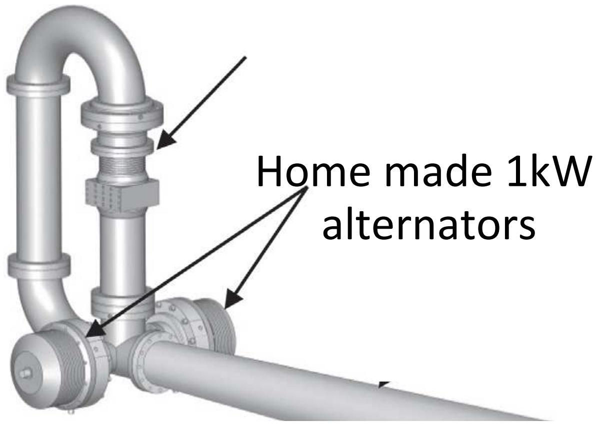
- For more information, ask M. X. FRANCOIS

Traveling waves devices

Research Program of China, 2010 – 2014, Sun et al., Wu et al.

Thermoacoustic electric generator coupled to a solar dish





- Fluide : He (95,5%) Ar (4,5%), 40 Bar
- Performance :

  f = 64 Hz

  T_h = 650 °C

  Pel max ≈ 1040 W (*)

  ηmax ≈ 19,8% (*)

** In lab conditions*

Traveling waves devices

Qnergy, TASE-3 project, 2014

Produces 1 kW of electrical power during solar operation

Qnergy's TASE-3 thermoacoustic Stirling engine during operation at the company's test facility in Ogden, Utah.

Traveling waves devices

Research Program of China, 2014, Wu et al.

3 kW double-acting thermoacoustic Stirling electric generator

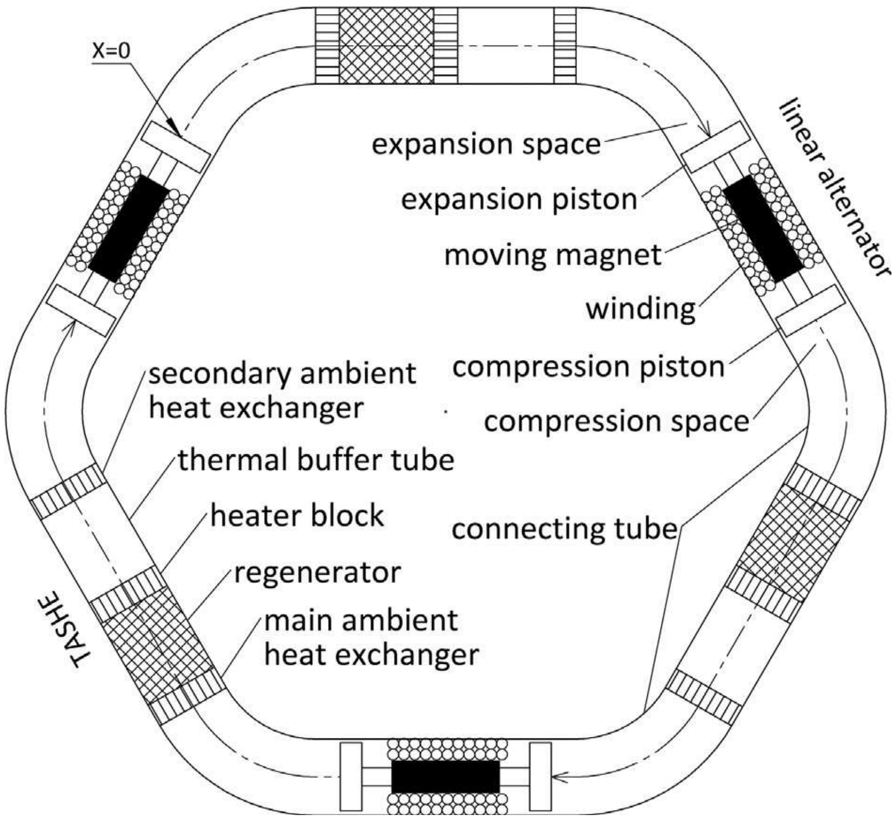
- Fluide : He 50 Bar
- Performance :

  f = 86 Hz

  T_h = 650 °C

  Pel max ≈ 1570 W

  ηmax ≈ 16,8%



Outlines

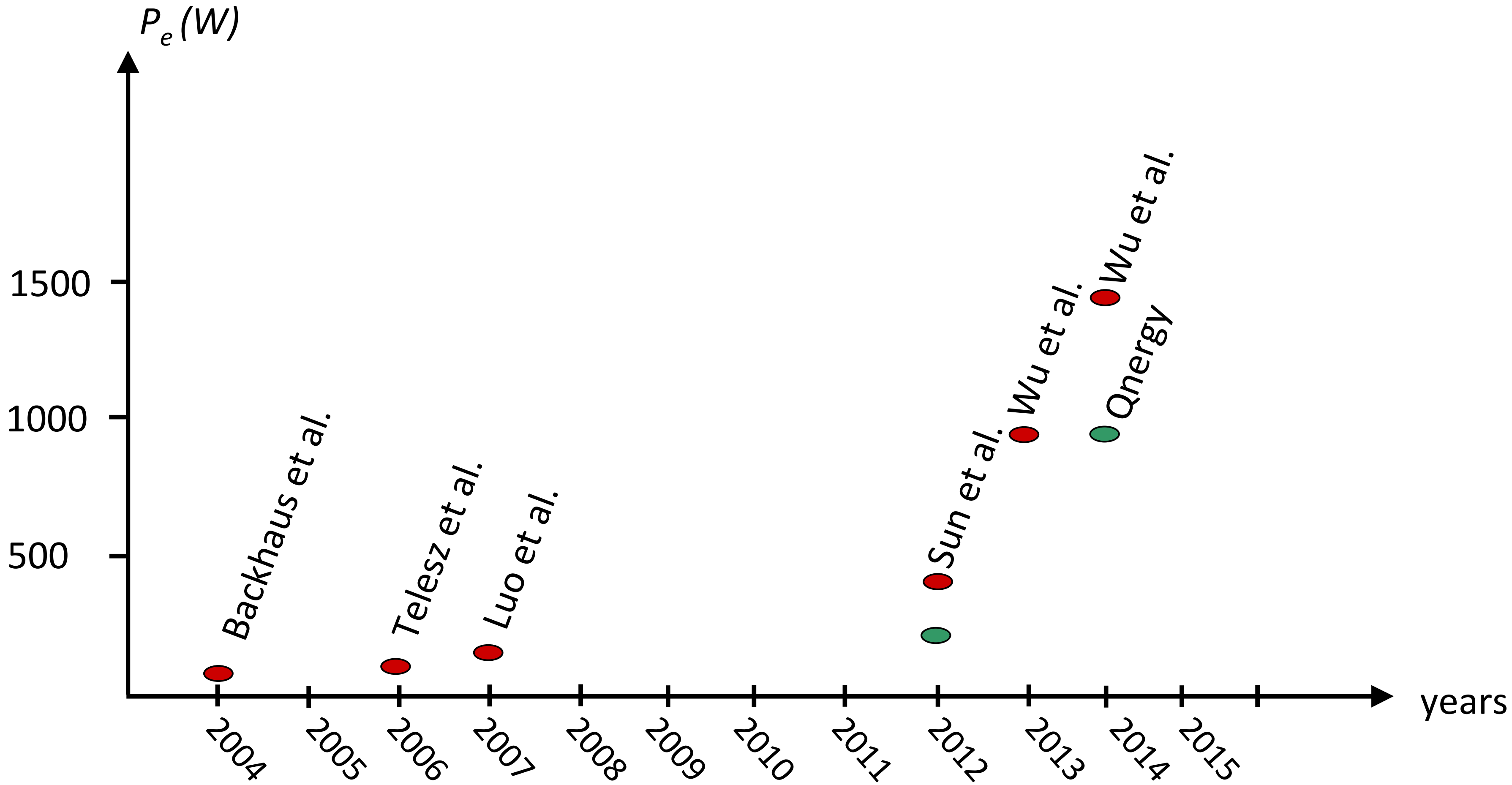
- Introduction
- Theory
- Some realizations
- Future development

Future development

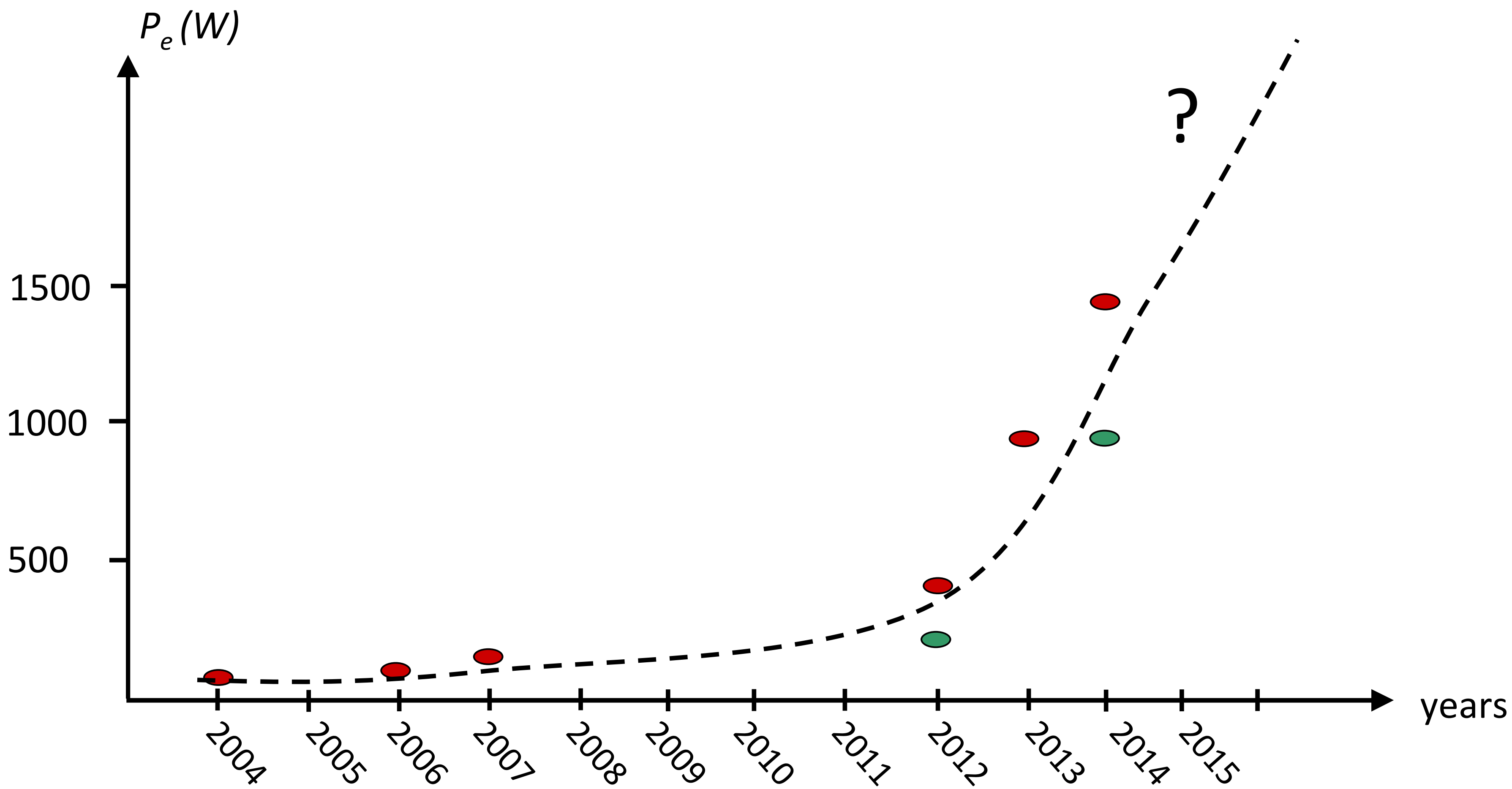
Key points

- Heat exchangers
- Alternators
- Thermoacoustic process

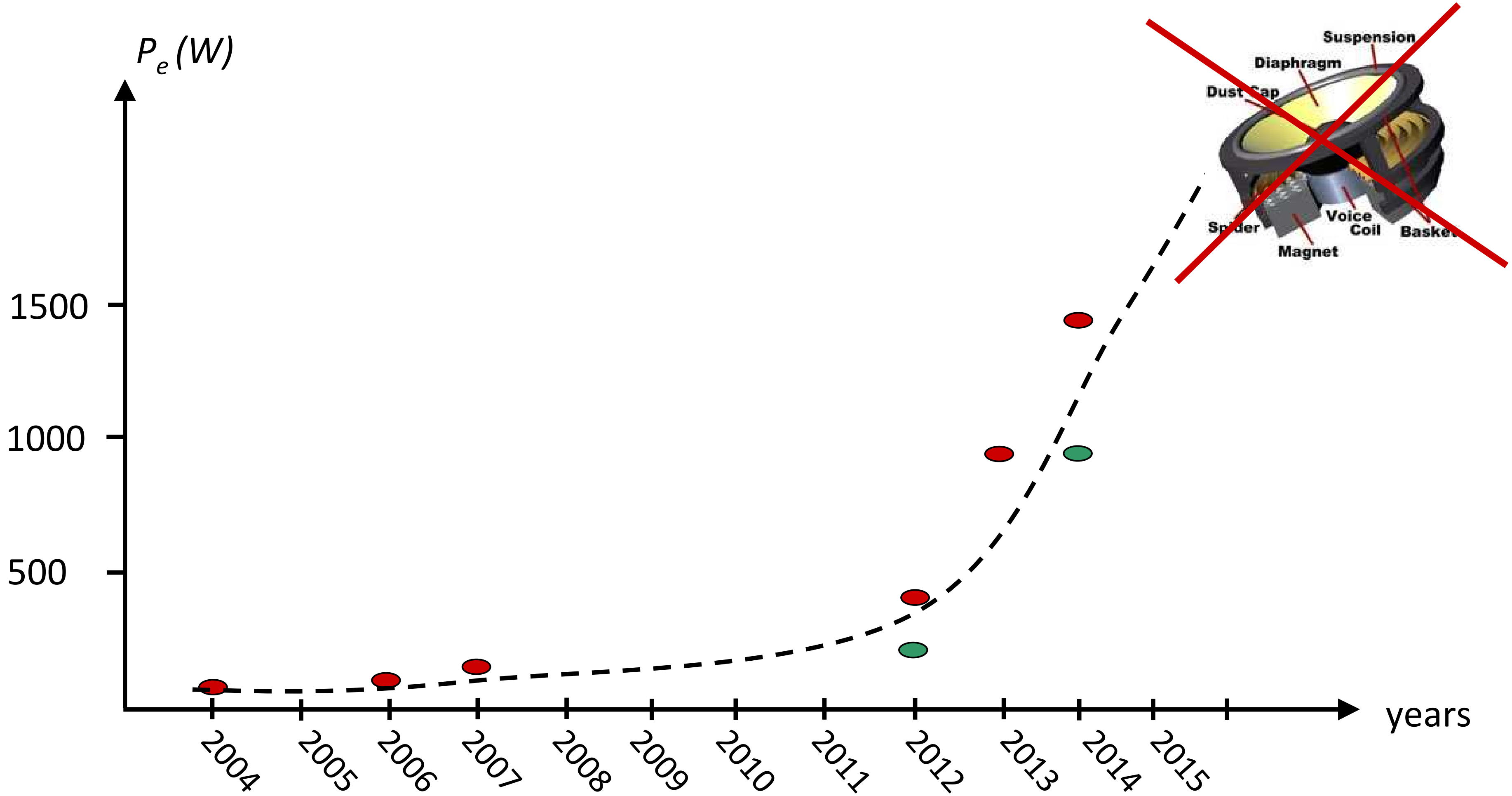
Future development



Future development

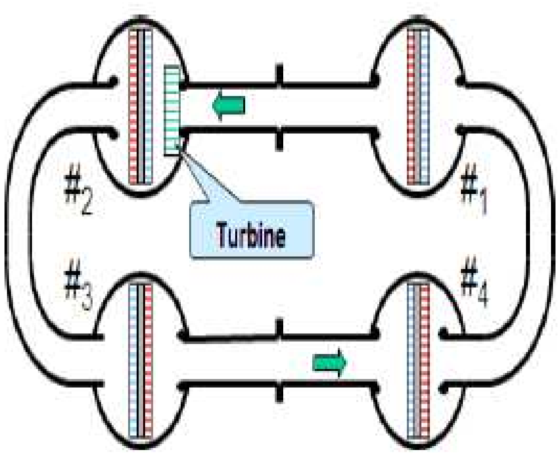


Future development



Other alternators?

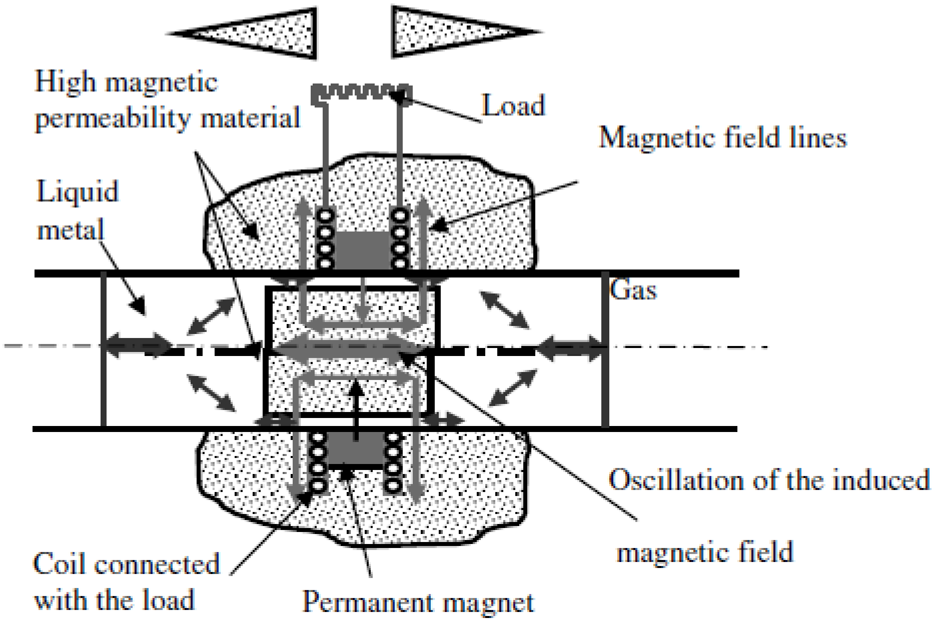
Thermo Acoustic Power Program, ASTER, K. de Block, 2013



- For more information, ask K. de Block

Other alternators?

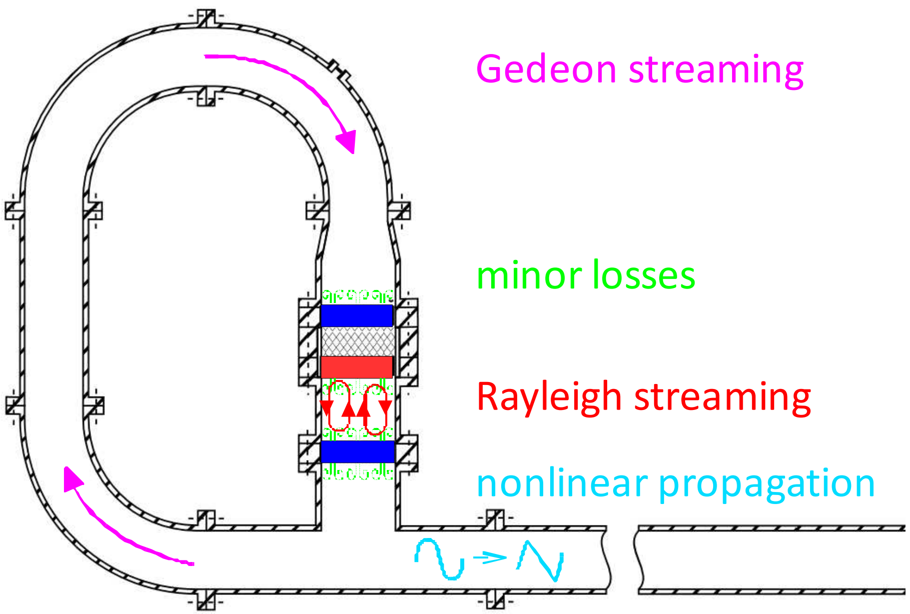
MHD Electric Generator, A. Alemany et al., 2010



- For more information, see presentation of A. Alemany

Thermoacoustic process optimization

- Control of non linear effects
  - For example : Acoustic streaming

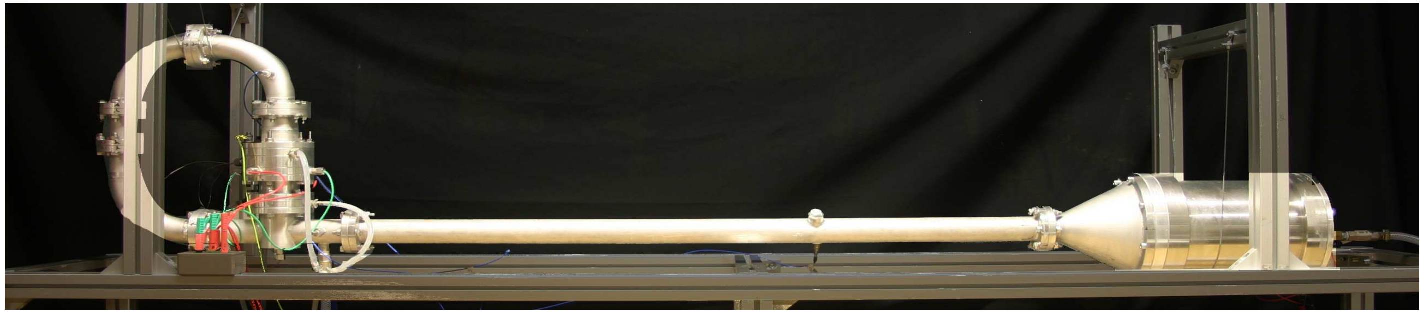


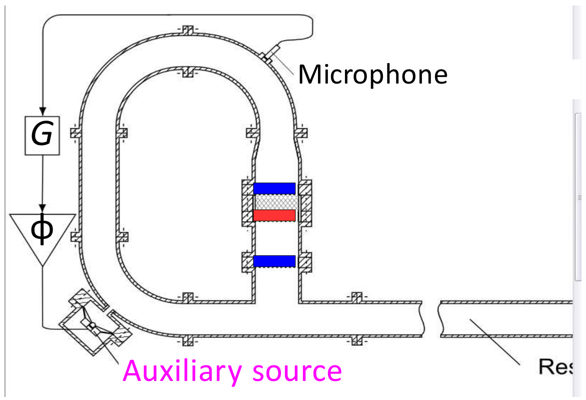
- For more information, see presentation of H. Bailliet

Thermoacoustic process optimization

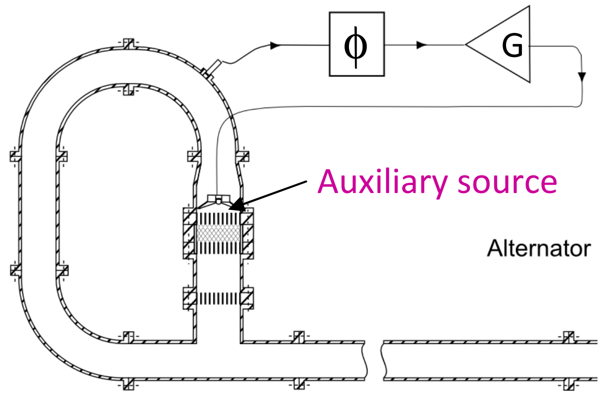
- Active tuning of acoustic oscillations in a thermo-acoustic power generator

Work in progress at « Laboratoire d'Acoustique de l'Université du Maine » (LAUM)





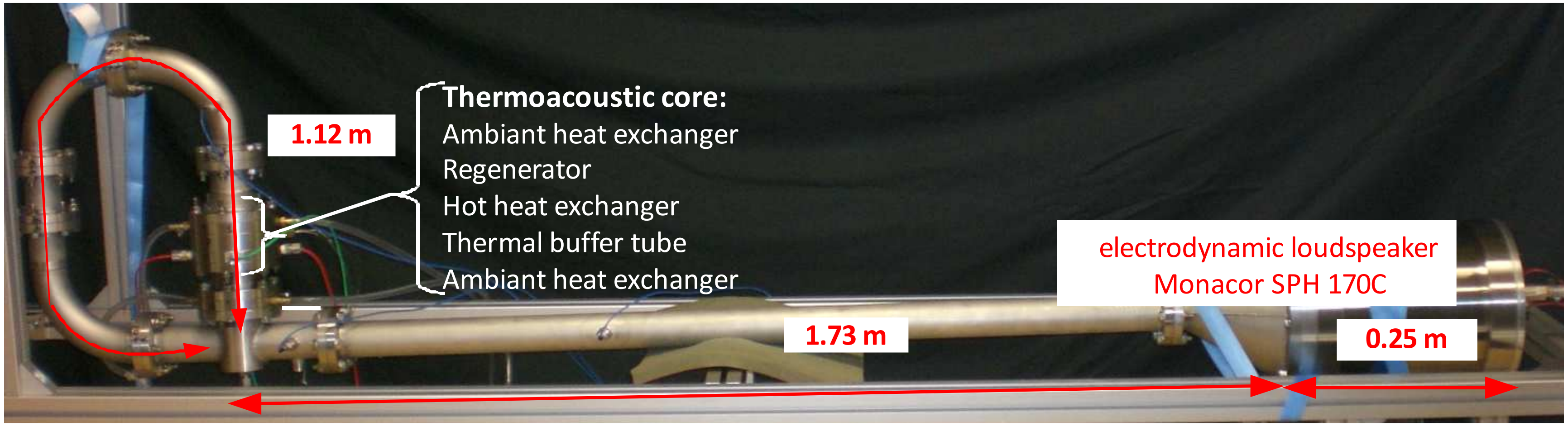
Experimental setup



[1] C. Olivier, G. Penelet, G. Poignand and P. Lotton . « Active control of thermoacoustic amplification in a thermo-acousto-electric engine », Journal of Applied Physics, vol. 115 [17], 2014.

Thermoacoustic process optimization

- Active tuning of acoustic oscillations in a thermo-acoustic power generator



- Fluid : **air**
- Static pressure : **5 Bars**
- Ambient temperature : **295 K**

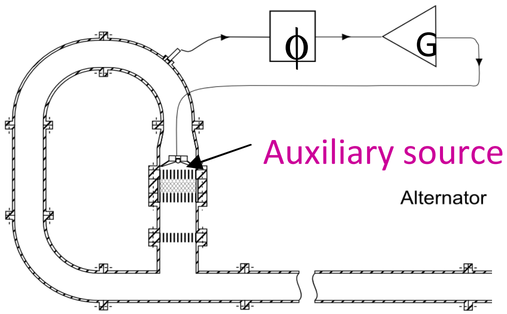
- Frequency: **40 Hz**
- Onset condition: Q_h = **60 W, ΔT = 401 K**
- Above onset: Q_h **= 70 W, DR = 1 %, $\eta_{\varnothing}$ = *0.24 %*, $\Delta T_{\varnothing}$ = 407.7 K**

  Q_h **= 140 W, DR = 3.2%, $\eta_{\varnothing}$ = *0.71 %*, $\Delta T_{\varnothing}$ = 452 K**
- Low efficiency: engine = study model (modular, limited budget, low efficiency alternator) but designed to work closed to its maximum value.

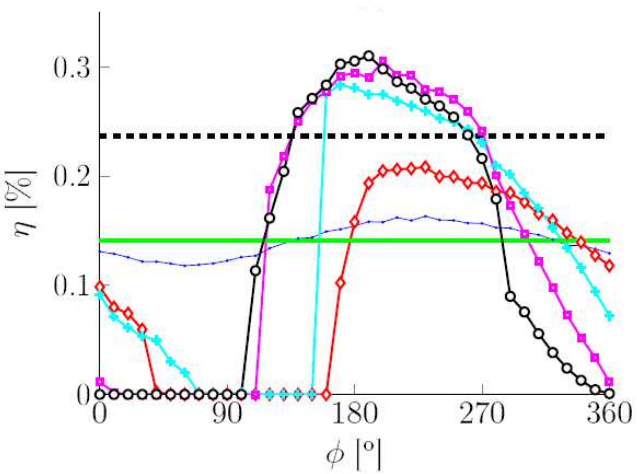
Thermoacoustic process optimization

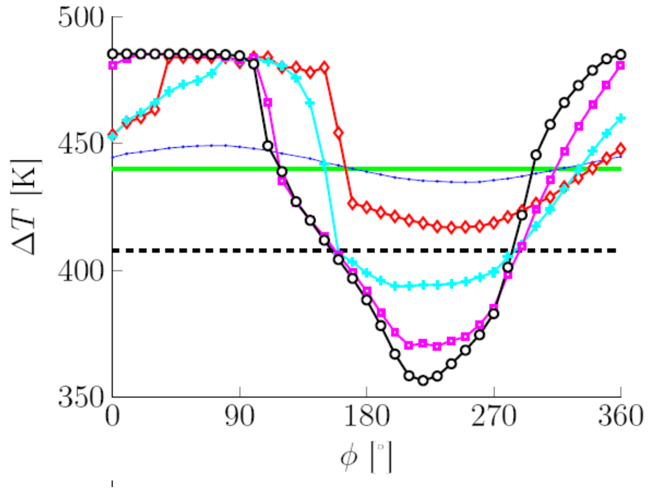
- Experimental results : case with internal auxiliary source

$$\eta = \frac{W_{el}(G=0)+\Delta W_{el}}{Q_h + W_{ls}}$$



- Efficiency η versus ϕ for different G

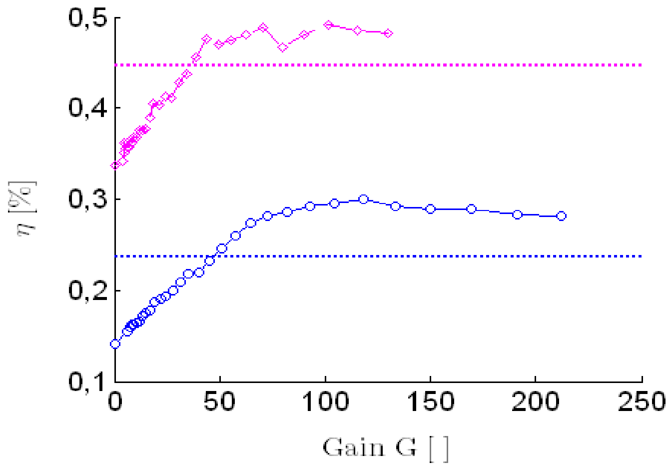




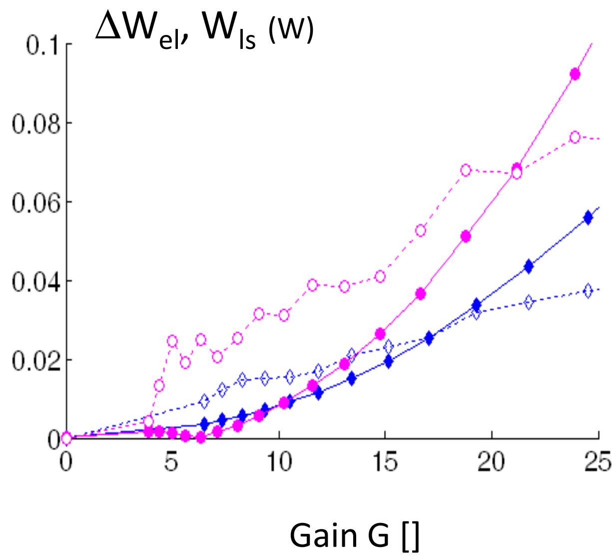
Q_h = 70 W, G = 0 (-), 10 (-), 40 (◊), 70 (+) , 135 (□) or 190(o), without active control (--)

Thermoacoustic process optimization

- Efficiency η versus G for ϕ = ϕ optimal



Q_h = 70 W (o), 100W (o), without active control (..)



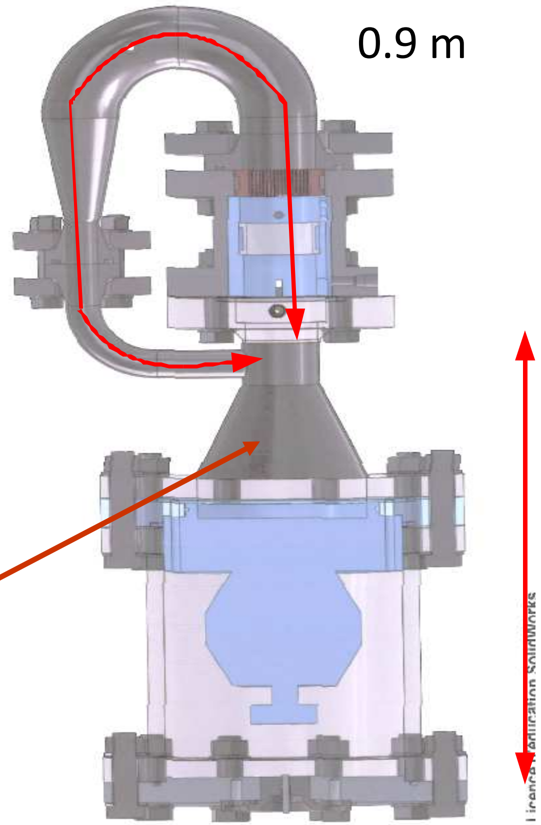
- ΔWel (o) : additional power produced
- Wls (•) : power supplied to the auxiliart source

Thermoacoustic process optimization

- Active control applied on a high power thermoacoustic compact engine (currently being built at LAUM)

- Fluid : **helium**
- Static pressure : **22 Bars**

- Heat input : **1000 W**
- Efficiency (theoretical): **20 %**
- Electric power: **200 W**



Work in progress …

Thank you for your attention . . .

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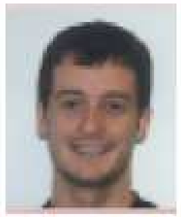

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