Active tuning of acoustic oscillations in a thermoacoustic power generator

G. Poignand, C. Olivier, G. Penelet, P. Lotton

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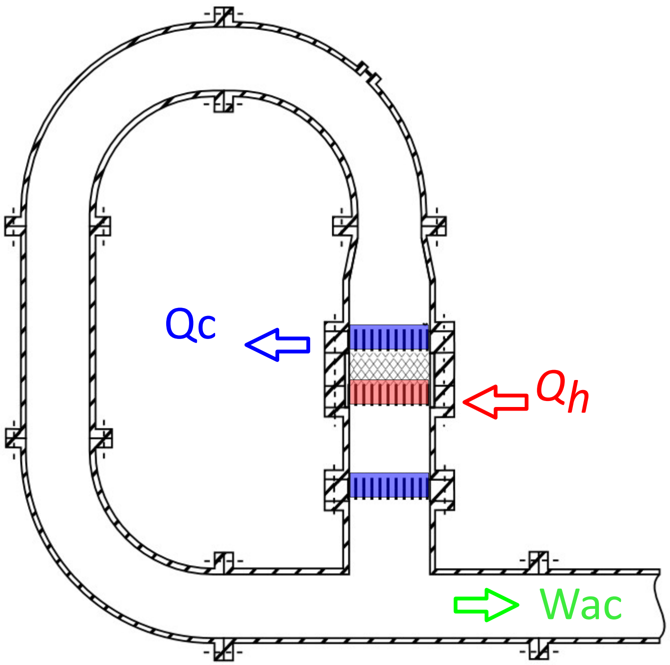
Thermoacoustic engines

- Thermoacoustic engines : autonomous oscillators, heat input Qh ⇨ acoustic power Wac
- Onset of a self sustained acoustic wave (at the frequency of the most unstable mode) controlled by linear effects
- Saturation controlled by nonlinear effects: acoustic power dissipation or temperature/acoustic field modification



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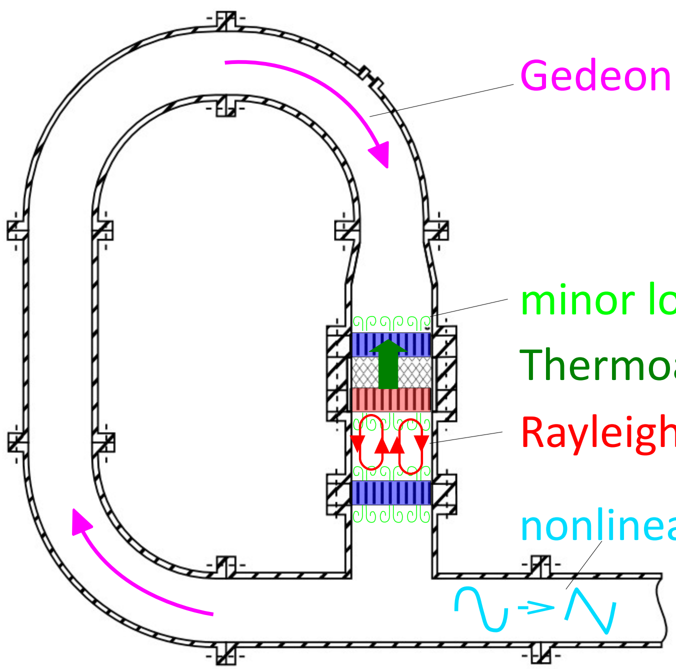
Problem : nonlinear effects = complicated processes, not fully described



Thermoacoustic engines

- Thermoacoustic engines : autonomous oscillators, heat input Qh ⇒ acoustic power Wac
- Onset of a self sustained acoustic wave (at the frequency of the most unstable mode) controlled by linear effects
- Above threshold, saturation controlled by nonlinear effects: acoustic power dissipation or temperature/acoustic field modification

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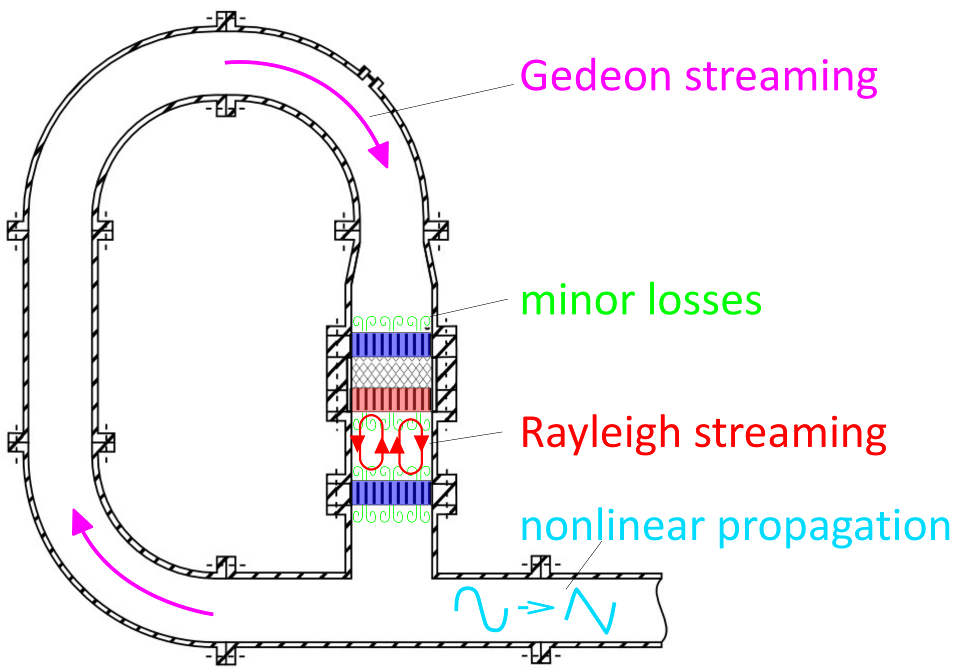
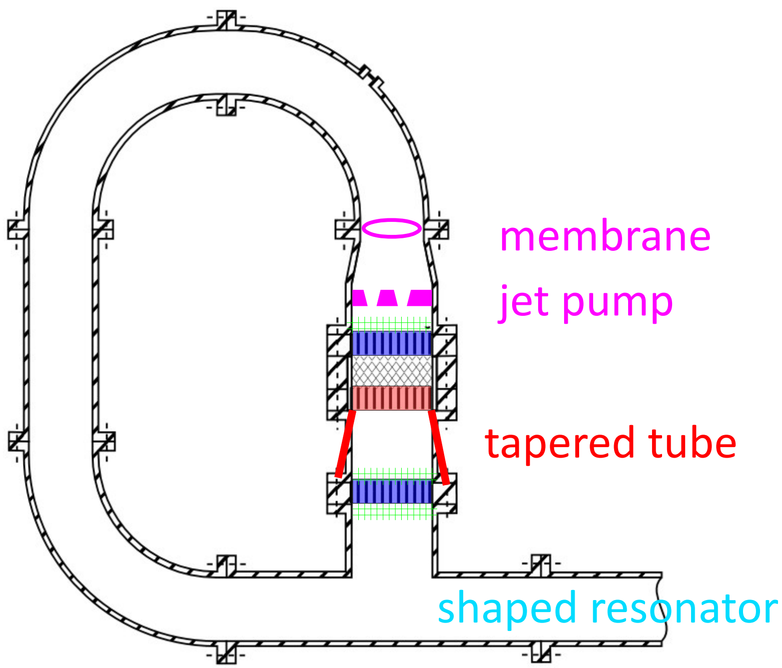
Common solution : use of passive elements (semi-empirically designed)





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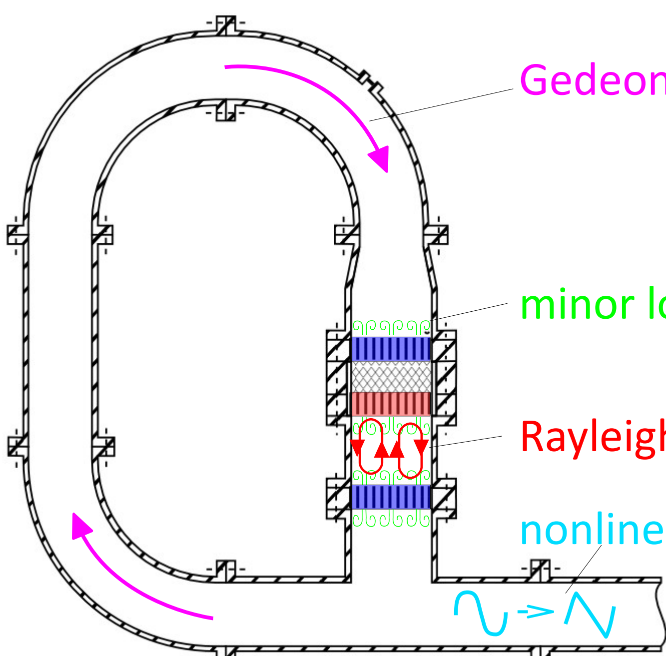
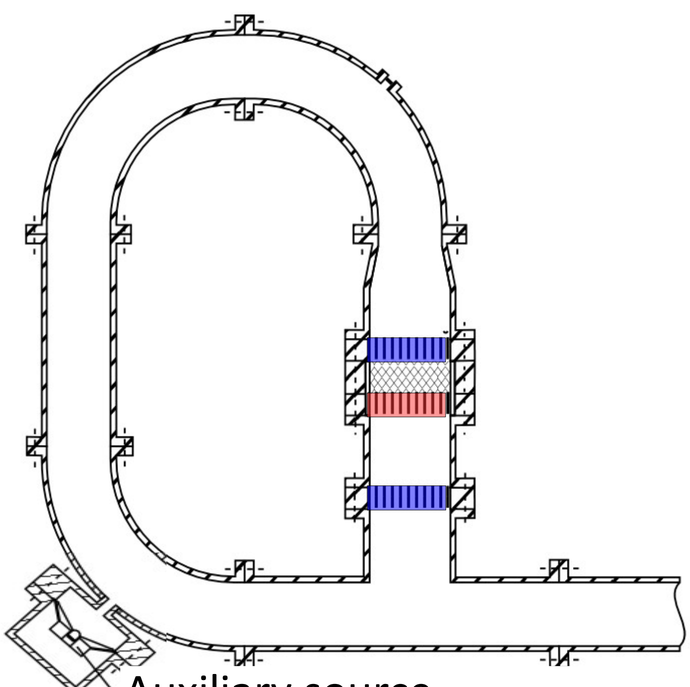
New approach : active control method to control the acoustic field
→ external forcing of the self sustained wave





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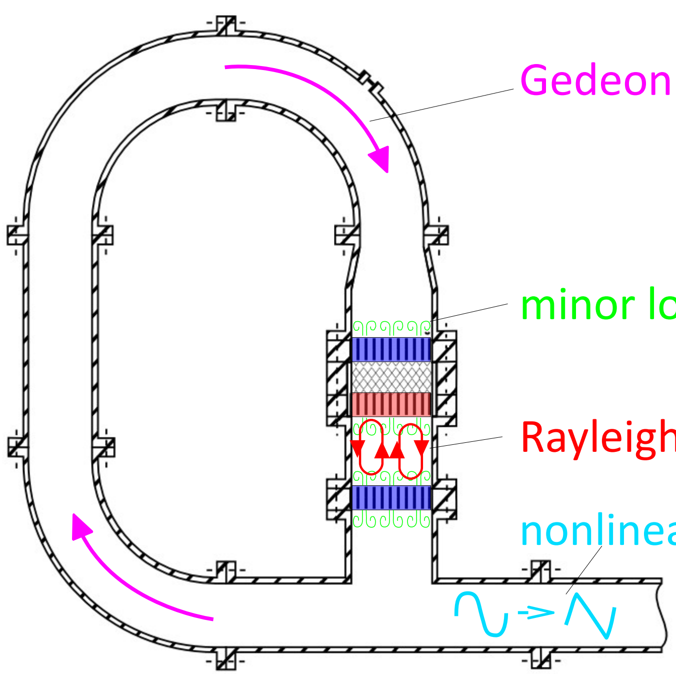
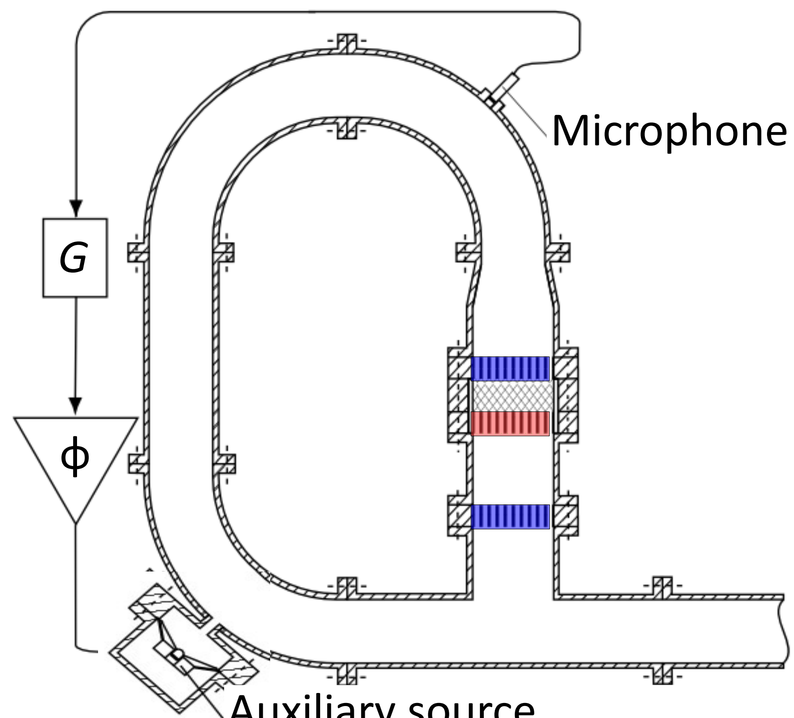


New approach : active control method
→ external forcing of the self sustained wave to control the acoustic field



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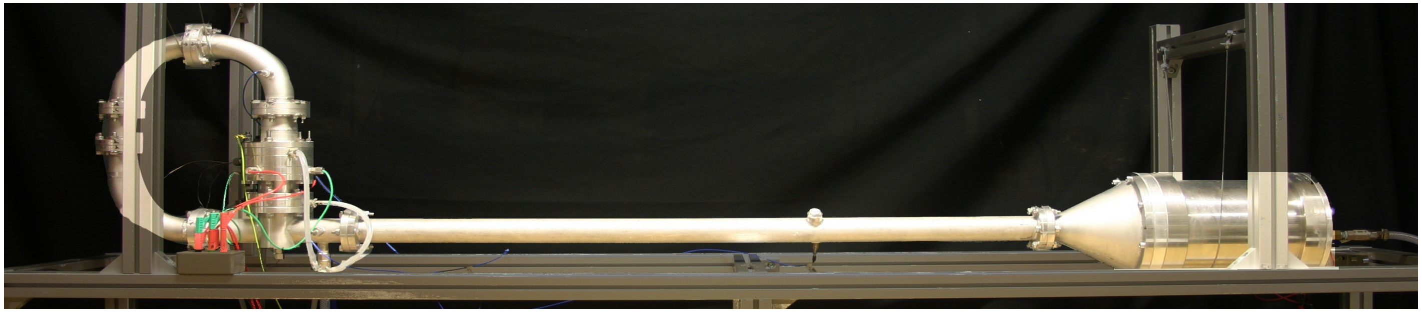
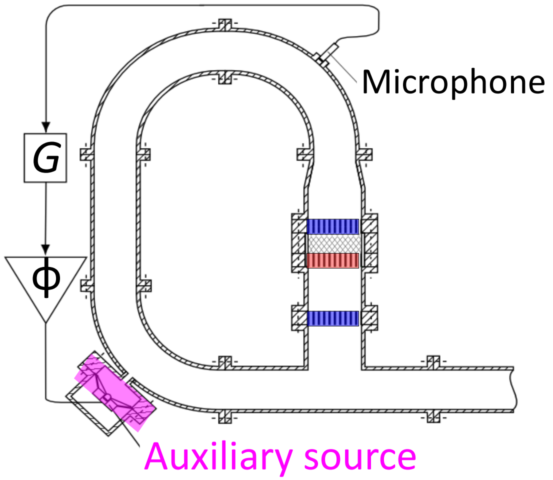


2. Experimental results

2.1 External auxiliary source[1]



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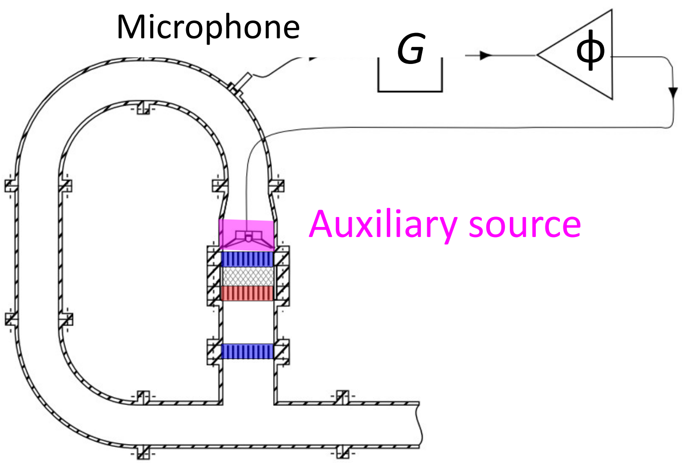
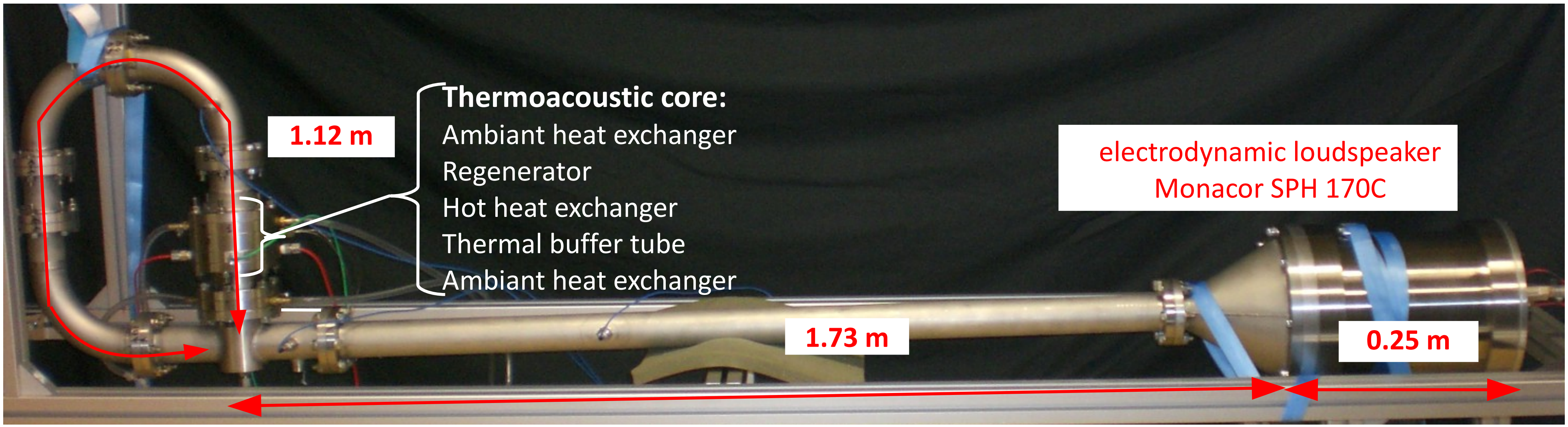


[1] C. Olivier, G. Penelet, G. Poignand and P. Lotton . « Active control of thermoacoustic amplification in a thermo-acousto-electric engine », Journal of Applied Physics, vol. 115 [17], 2014.

Thermoacoustic power generator



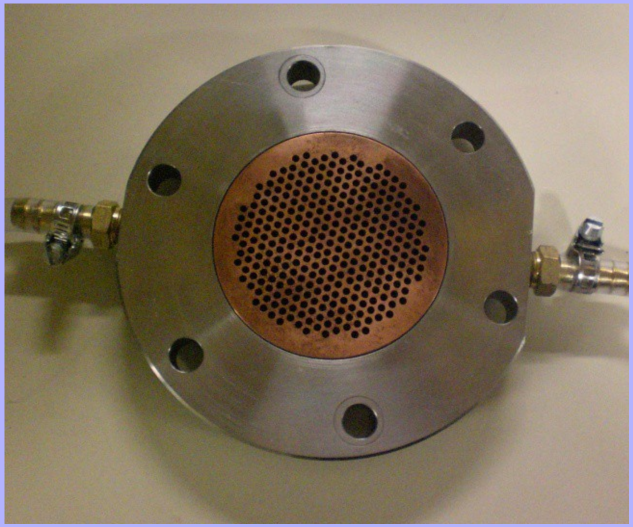
designed with Delta-Ec [W.C. Ward, G.W. Swift & J.P. Clark, J. Acoust. Soc. Am., 123(5) (2008)]

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

- Frequency: **40 Hz**
- Onset condition: $\boldsymbol{Q_h}$ **= 60 W,** $\boldsymbol{\Delta T}$ **= 401 K**
- $\boldsymbol{\eta_{max}}$ **= 1 %,** $\boldsymbol{Pel_{max}}$ **= 1W**
- Low efficiency: engine = study model (modular, limited budget, low efficiency alternator) but designed to work closed to its maximum value.

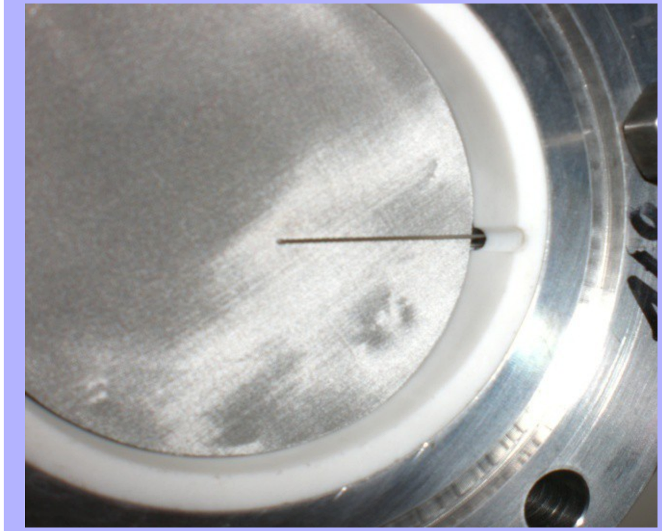
Travelling wave thermoacoustic engine part

Cold heat exchanger



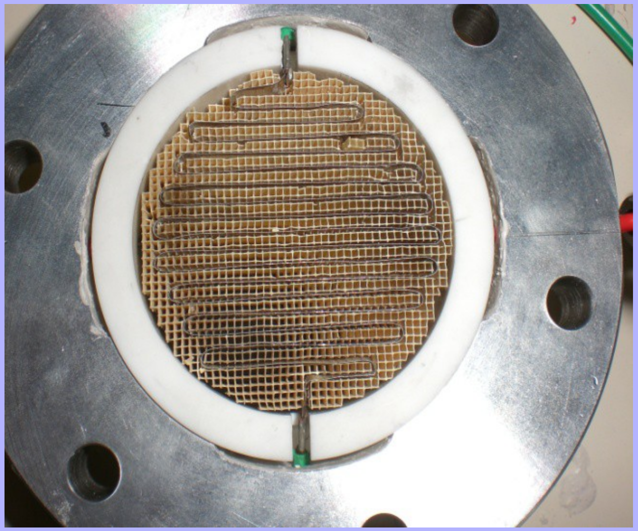
Copper block with 2 mm diameter drilled holes.
Water circulates around the block.
Porosity: 69 %
Length: 1.5 cm

Regenerator



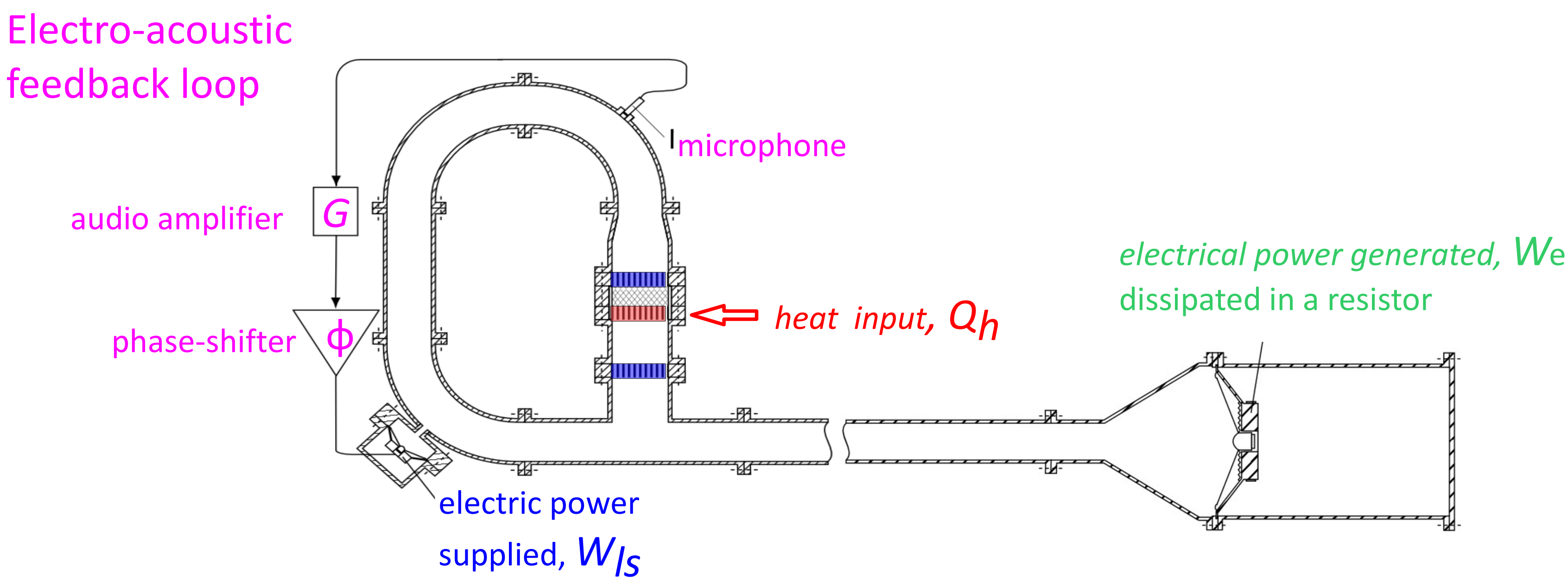
Stainless steel wire mesh
Porosity: 69 %
Hydraulic radius: 20 µm
Length: 2.3 cm

Hot heat exchanger



Ceramic stack with two ribbon heaters
Length: 1.5 cm
Qh max = 235 W
(Rribbon = 4.7 Ω)

Active control method



Input parameters: heat input Q_h, gain G and the phase ϕ

additional power produced

Measured parameters:

Efficiency without auxiliary source $\eta_\varnothing = \dfrac{W_{el}}{Q_h}$ and with active control: $\eta = \dfrac{W_{el}(G=0) + \Delta W_{el}}{Q_h + W_{ls}}$

Temperature difference without auxiliary source $\Delta T_\varnothing$ and with active control ΔT

Objective : play on input parameters (Qh, G, ϕ) ⇨

- $\eta < \eta_\varnothing$?
- $\Delta W_{el} > W_{ls}$?

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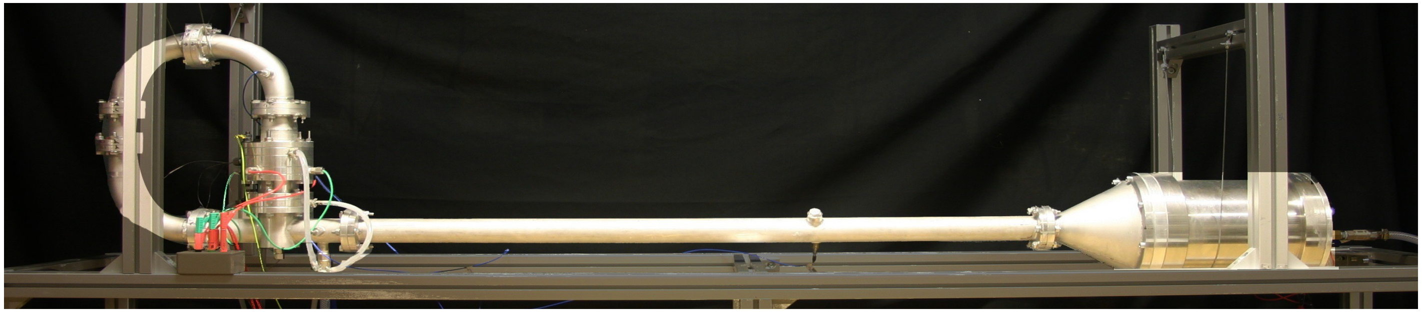

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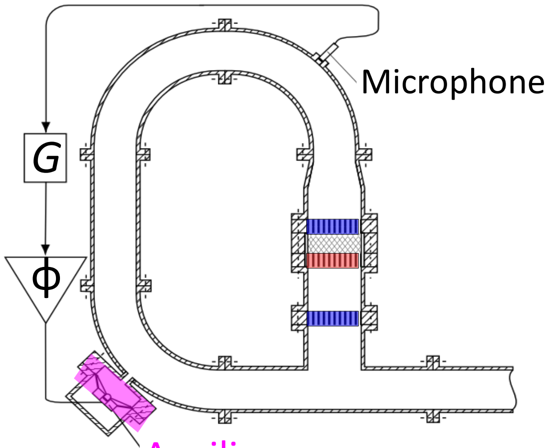

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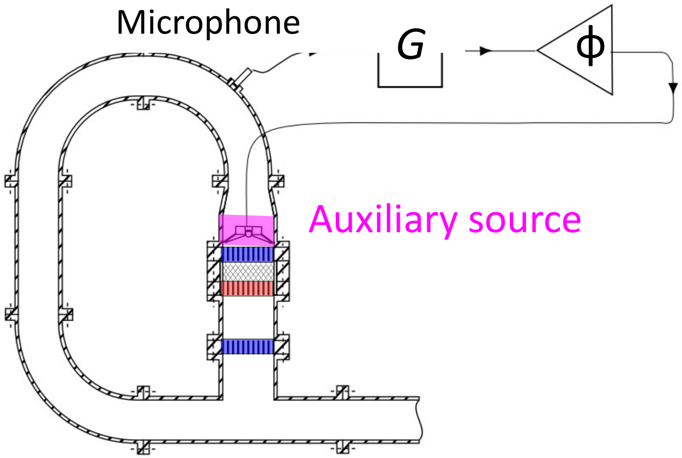
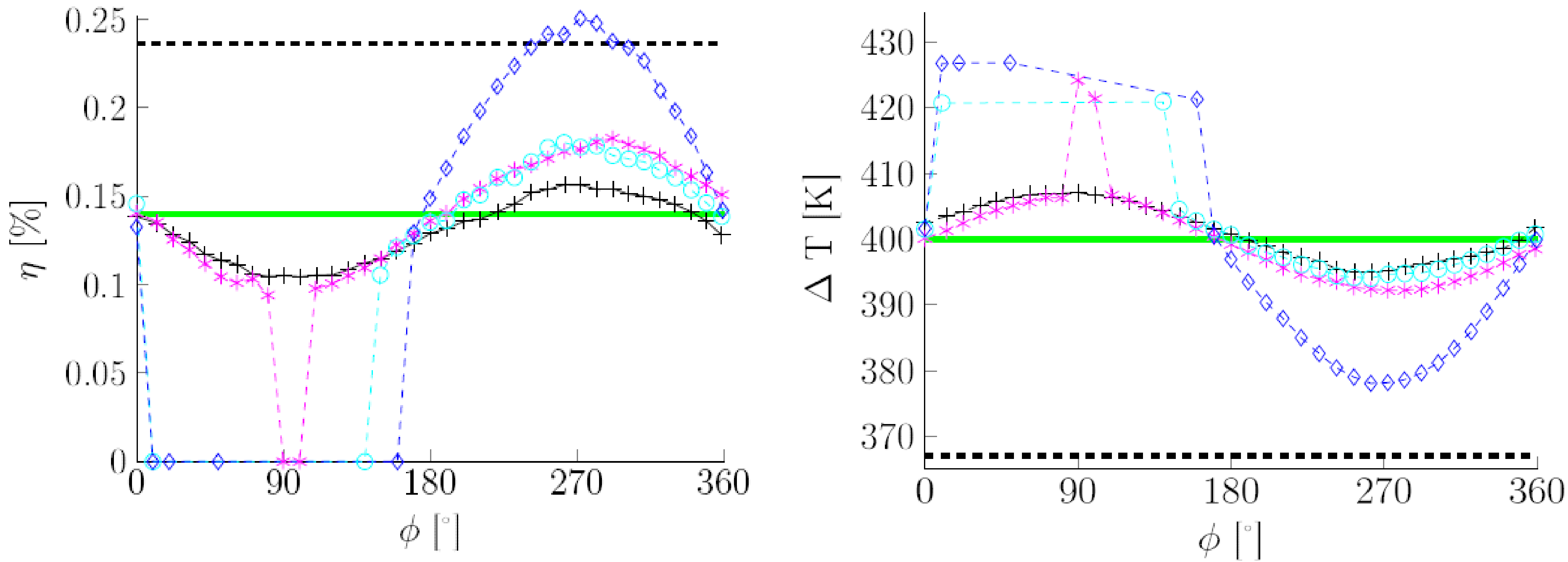


[1] C. Olivier, G. Penelet, G. Poignand and P. Lotton . « Active control of thermoacoustic amplification in a thermo-acousto-electric engine », Journal of Applied Physics, vol. 115 [17], 2014.

Efficiency η versus ϕ for different G

Q_h = 70 W, G = 0 (-),20 (+), 30 (*), 32 (o) or 100(◊),

without active control (--)



- with the phase ϕ : - η varies ⇨ optimal phase ϕ_{opt}

  - acoustic wave death
- when the gain G ↗ : - η ↗ and ΔT ↘

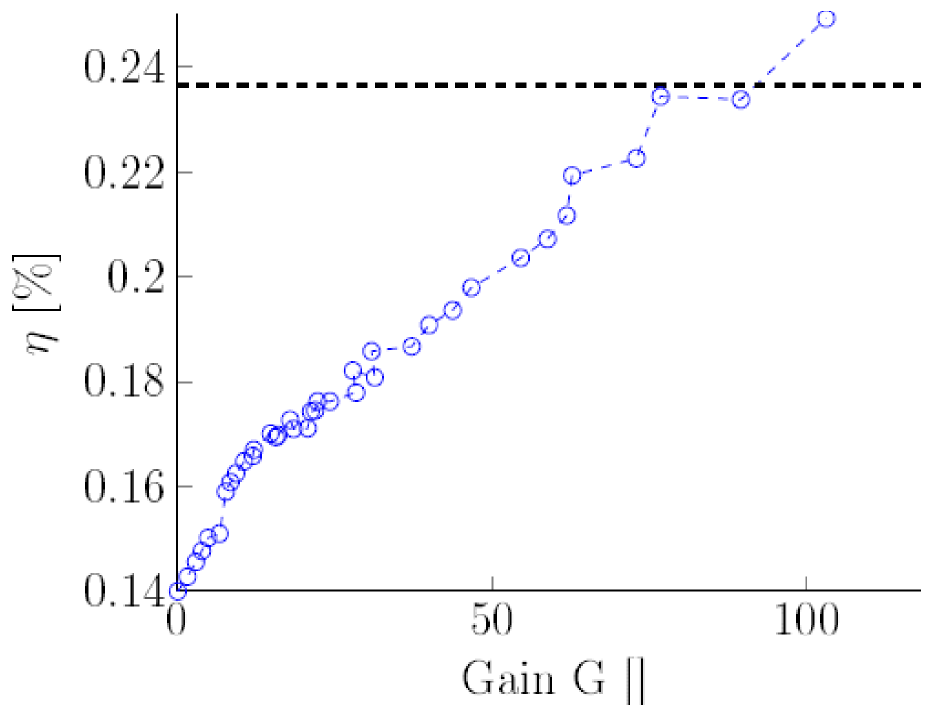
⇨ nonlinear interaction ?

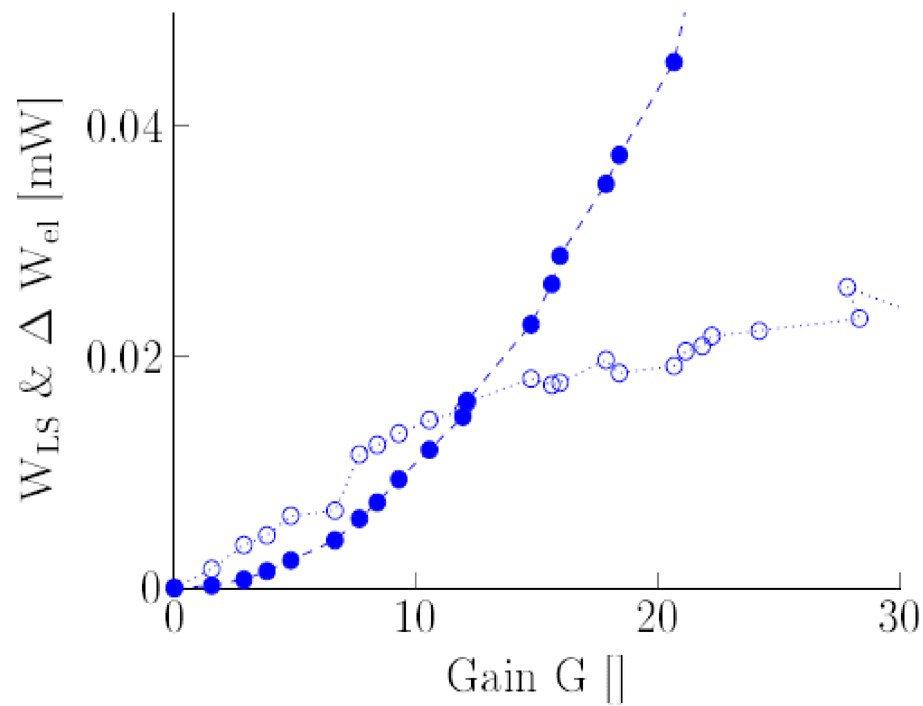
W_{ls} and W_{el} versus G for $\phi = \phi_{opt}$

Q_h = 70 W (o), without active control (--)

ΔW_{el} (o) additional power produced

W_{ls} (•) power supllied to AC source





- For low Q_h: - η increases with the gain G

  - configurations for which $\Delta W_{el} > W_{LS}$

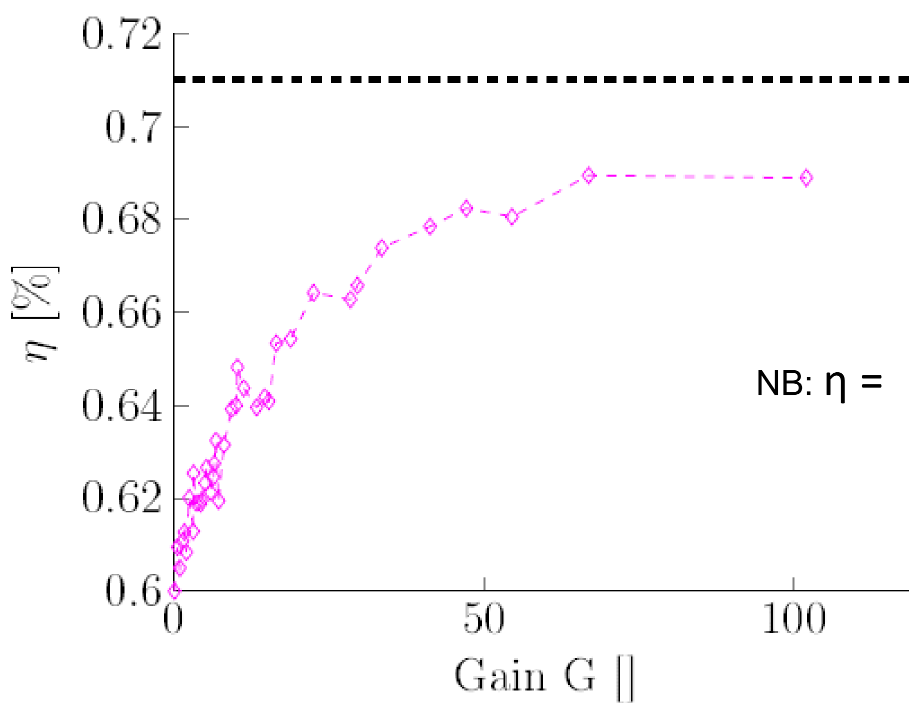
NB: $\eta = \dfrac{Wel\ (G=0) + \Delta Wel}{Q_h + W_{ls}}$

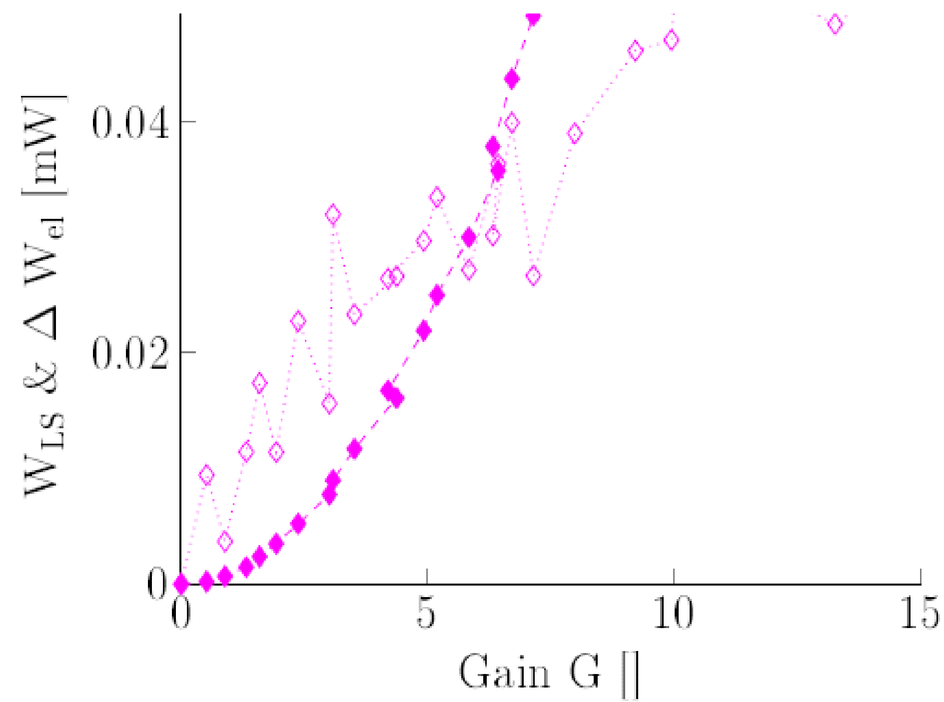
W_{ls} and W_{el} versus G for $\phi = \phi_{opt}$

Q_h = 140 W (◇), without active control (--)

ΔW_{el} (◇) additional power produced

W_{ls} (◆) power supllied to AC source





- For higher Q_h: - efficiency improvement saturates

  - configurations for which $\Delta W_{el} > W_{LS}$

NB: $\eta = \dfrac{W_{el}\,(G=0) + \Delta W_{el}}{Q_h + W_{ls}}$

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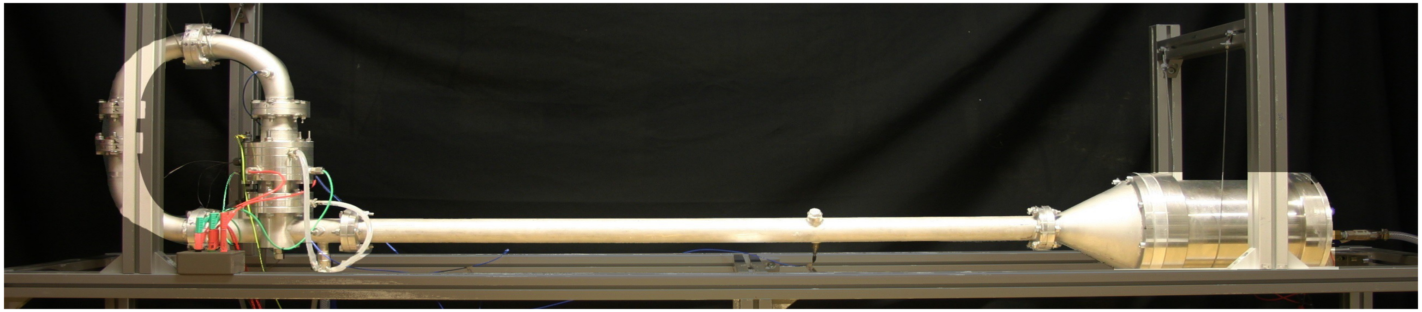

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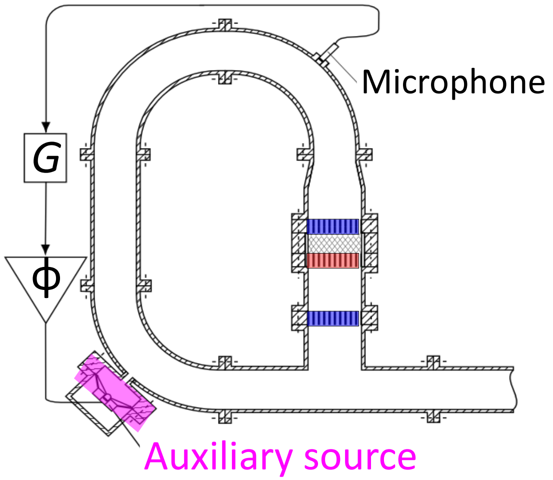

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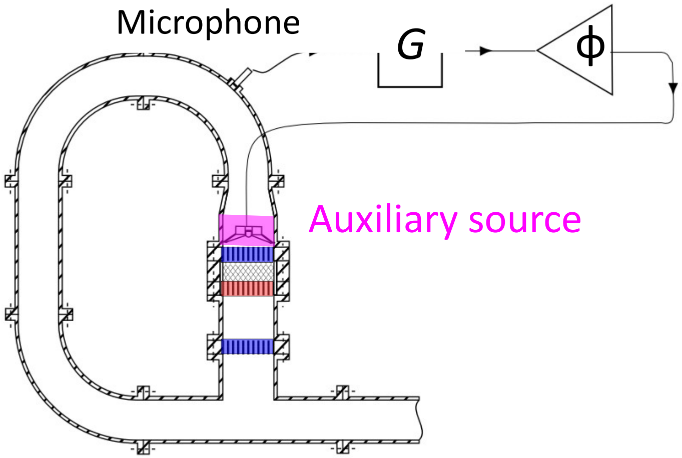

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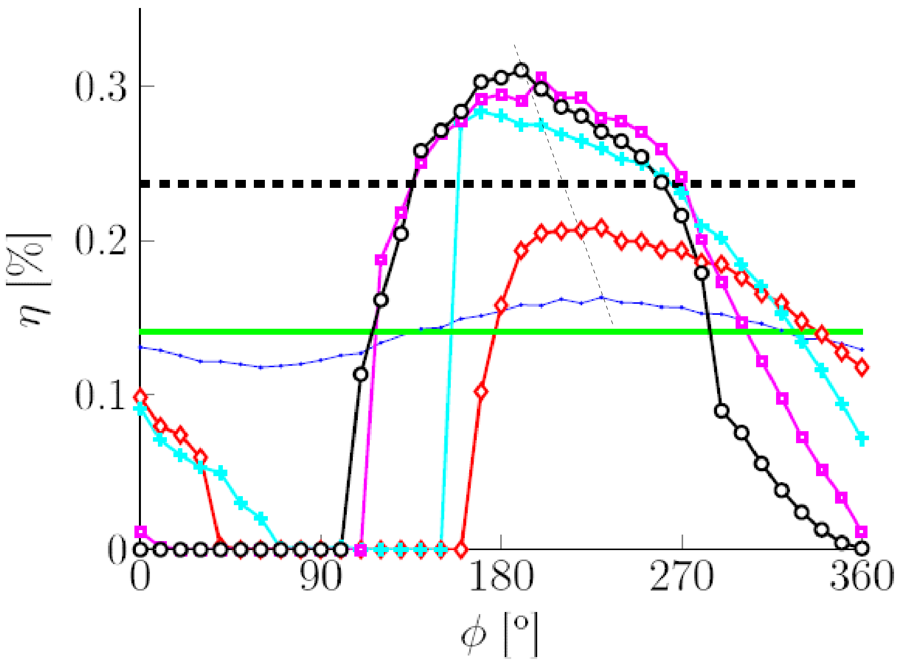
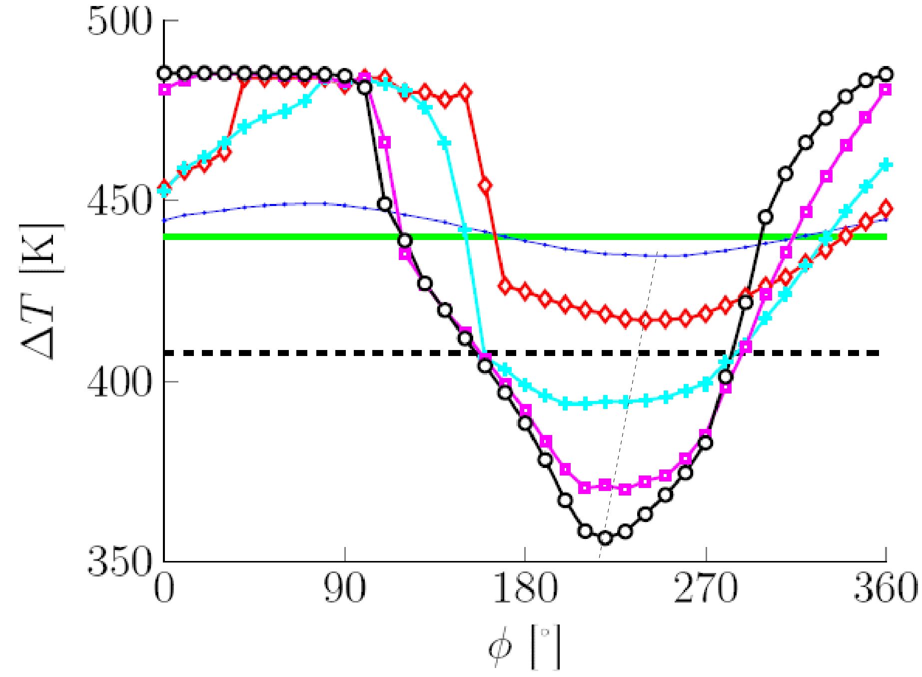
Efficiency η versus ϕ for different G

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





- Same results than for the first configuration :

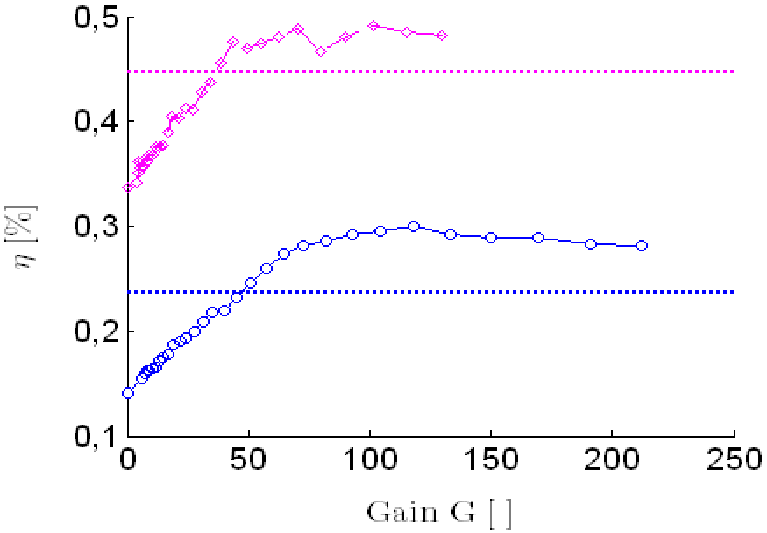
  - optimal phase ϕ_{opt} (varies with the gain)

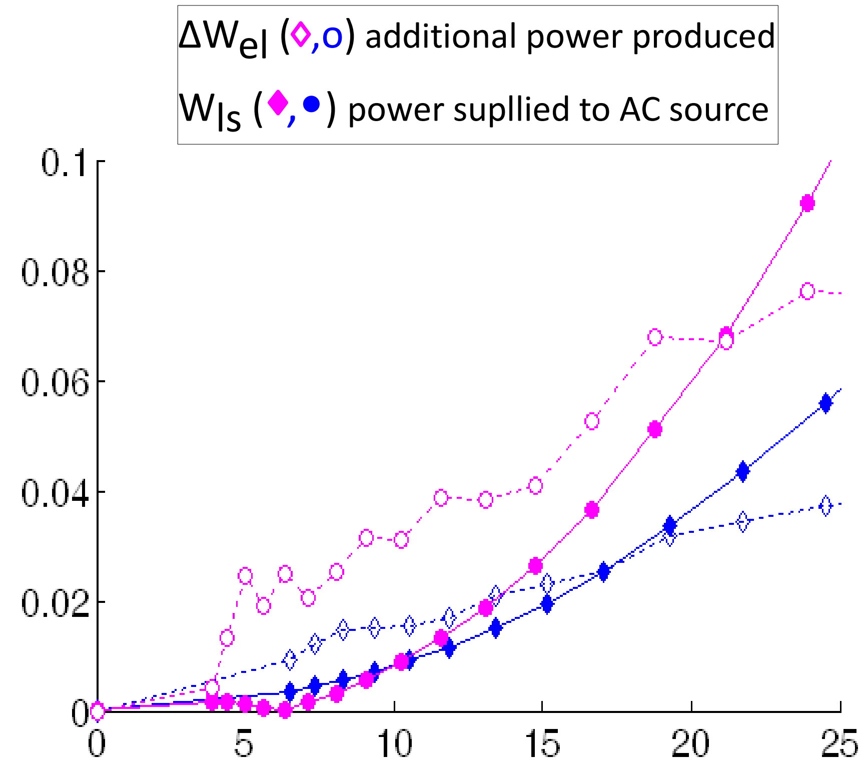
  - acoustic wave death

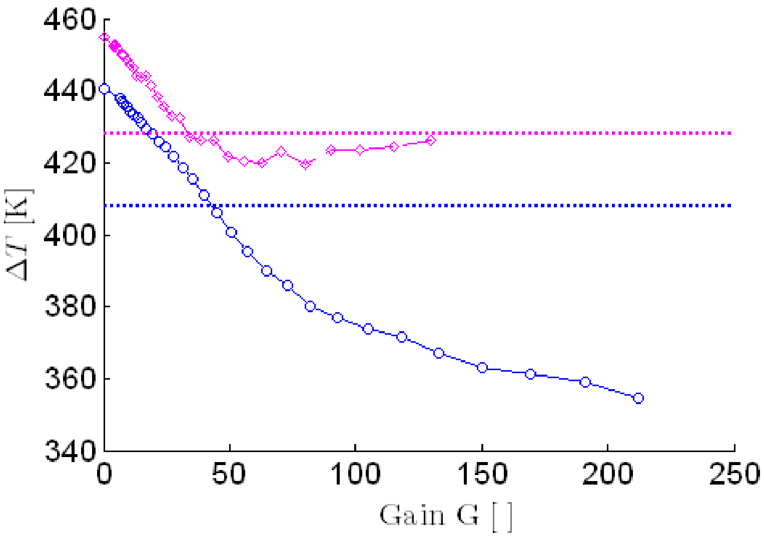
- for high G : - $\eta > \eta_{\emptyset}$, $\Delta T > \Delta T_{\emptyset}$

W_{ls} and W_{el} versus G for $\phi = \phi_{opt}$

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







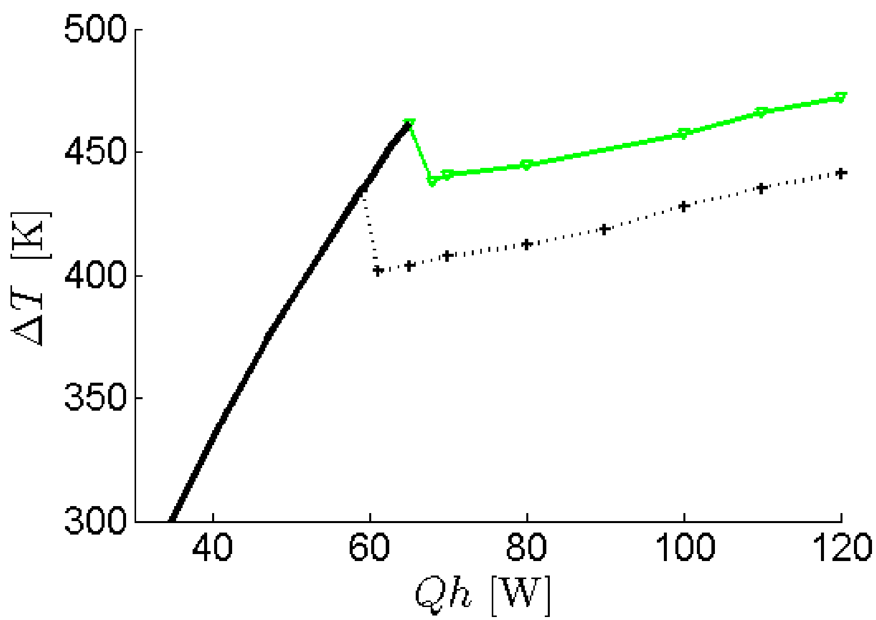
- efficiency improvement saturates
- configurations for which $\Delta W_{el} > W_{LS}$

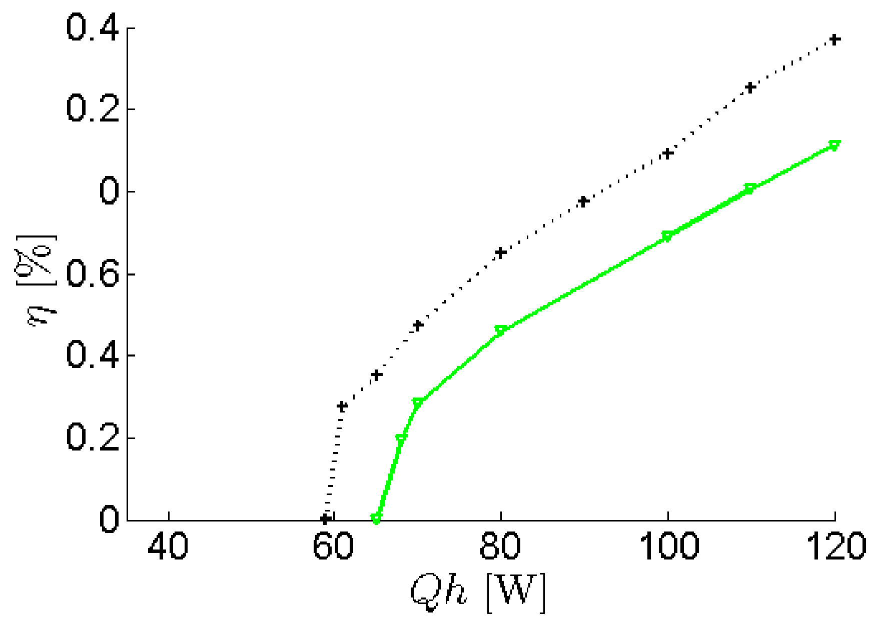
NB: $\eta = \dfrac{W_{el}\,(G=0) + \Delta W_{el}}{Q_h + W_{ls}}$

Hysteresis behaviour

Method : 1. Search onset condition, Qh ↗
2. Above onset : Efficiency measurement when Qh ↗ and then Qh ↘
3. Search offset condition
Steady-state measurements

$\phi = \phi_{opt}$, $G = 0$ (-)
without active control (..)



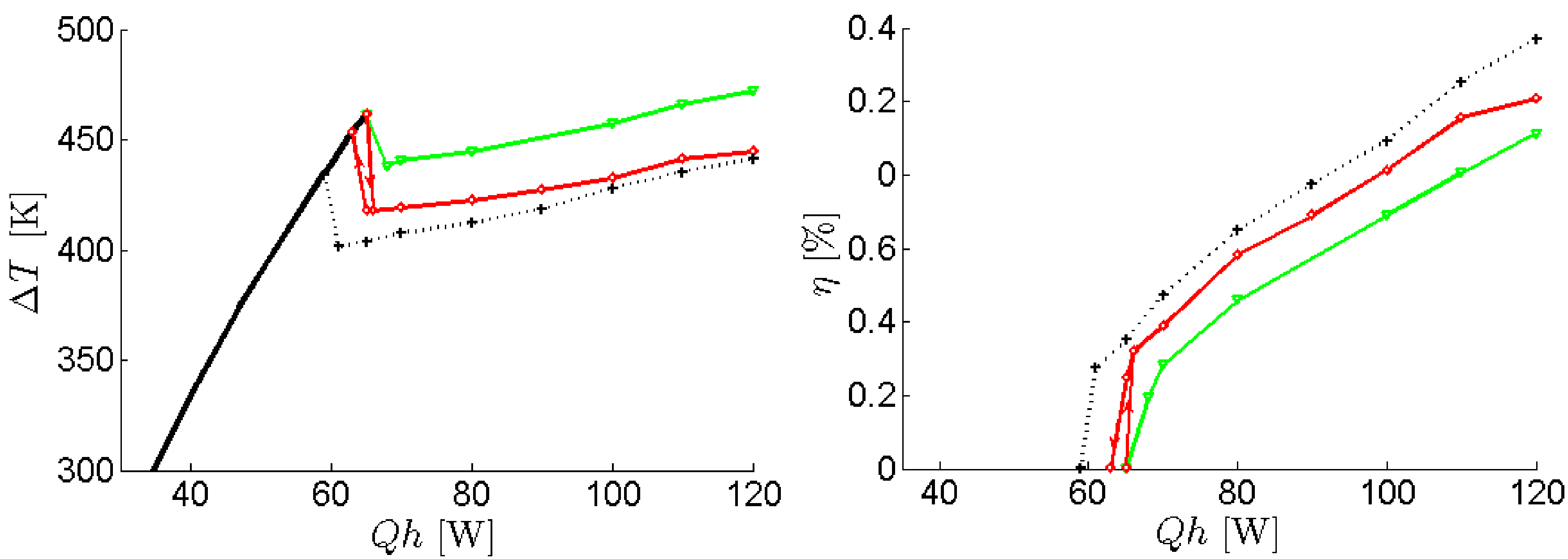


- For $G = 0$, $\Delta T_{onset} > \Delta T_{\varnothing\ onset}$ and $\eta < \eta_{\varnothing}$

Hysteresis behaviour

$\phi = \phi_{opt}$, G = 0 (-), 40 (◊)

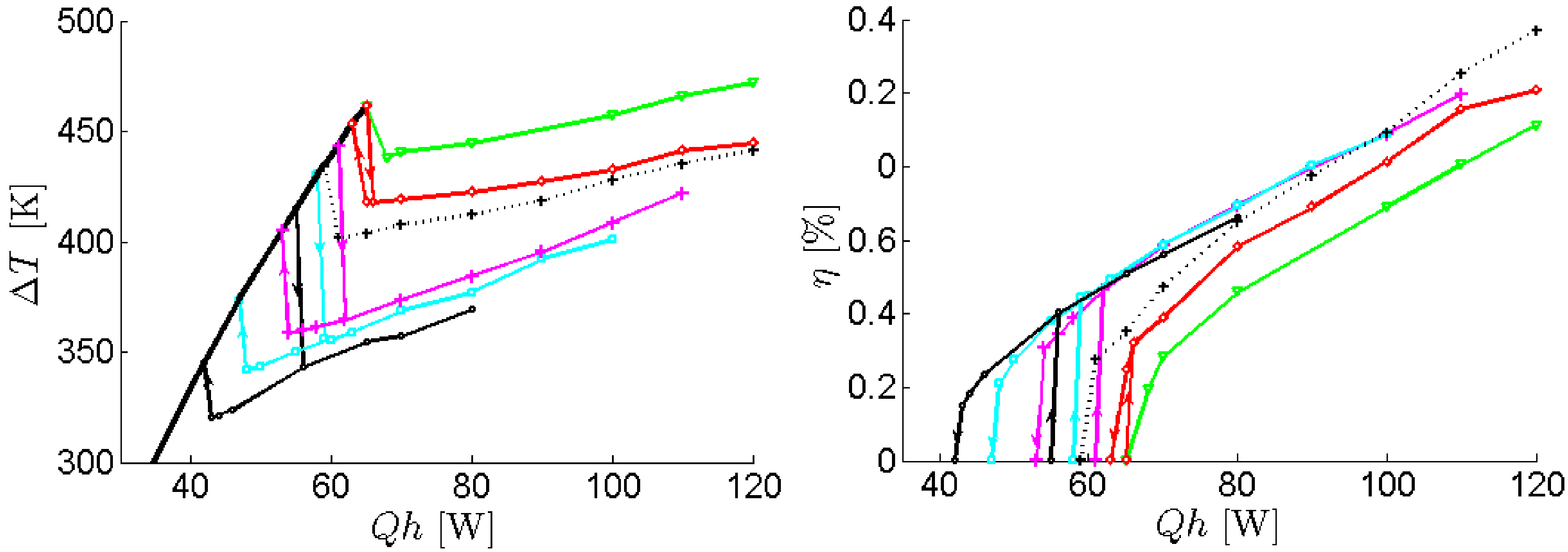
without active control (..)



- For $G = 0$, $\Delta T_{onset} > \Delta T_{\emptyset\ onset}$ and $\eta < \eta_{\emptyset}$
- For $G \neq 0$, hysteresis behaviour: $\Delta T_{offset} < \Delta T_{onset}$, system works for $Qh < Qh_{onset}$

Hysteresis behaviour

$\phi = \phi_{opt}$, G = 0 (-), 40 (◊), 70 (+) , 135 (□) or 190(**o**),
without active control (..)



- For G = 0, $\Delta T_{\text{onset}} > \Delta T_{\emptyset\ onset}$ and $\eta < \eta_{\emptyset}$
- For $G \neq 0$, hysteresis behaviour: $\Delta T_{offset} < \Delta T_{onset}$, system works for $Qh < Qh_{onset}$
- With the gain G, ΔT_{offset} ↘, $\Delta T_{\text{onset}} < \Delta T_{\emptyset\ onset}$, $\eta > \eta_{\emptyset}$

Conclusions

Active control works :

- *Efficiency improvement:* efficiency η higher than the one without active control $\eta_{\text{ø}}$
- *Lower onset temperature:* onset temperature ΔT_{onset} lower than the one without active control $\Delta T_{\text{ø}\, onset}$
- hysteresis behaviour: offset temperature ΔT_{offset} lower than onset temperature ΔT_{onset}

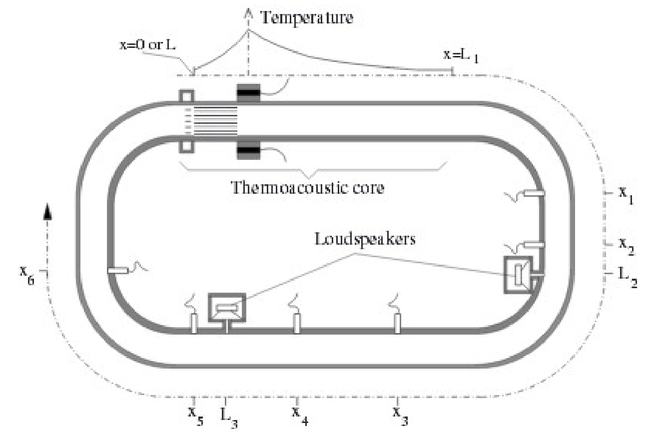
But why ?

- simplified model to get better comprehension

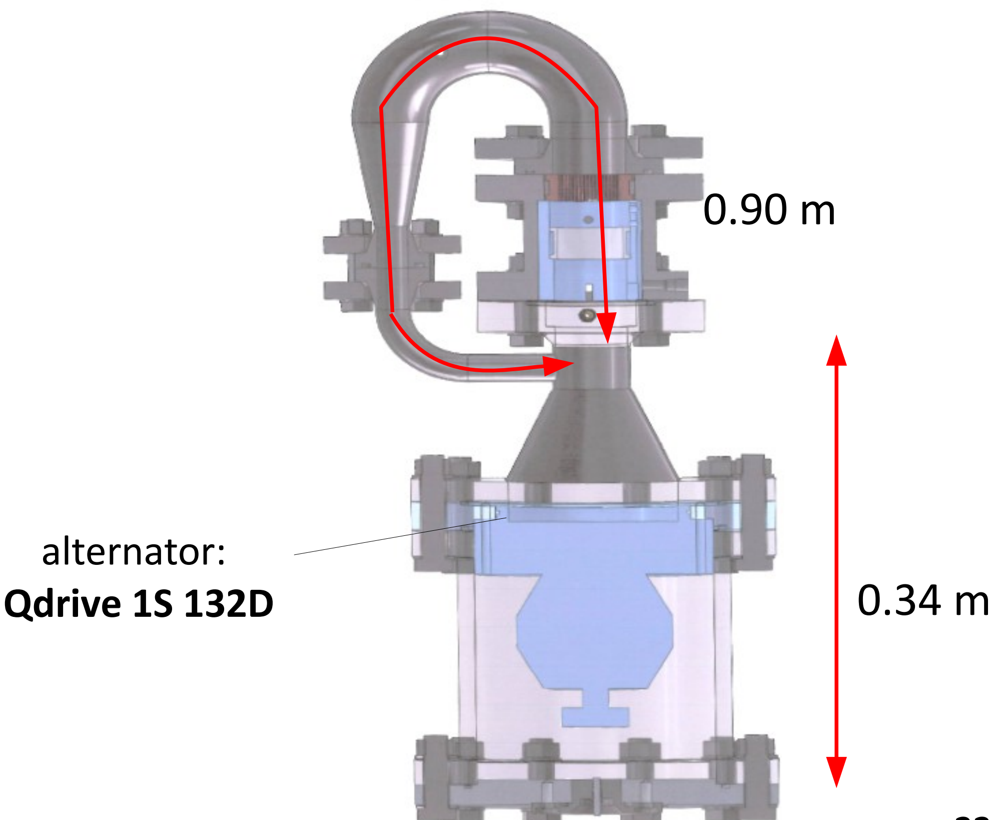
Perspectives

- Active control with two phase-tuned sources: already performed on an annular thermoacoustic engine [1]

[1] C. Desjouy, G. Penelet, and P. Lotton «Active control of thermoacoustic amplification in an annular engine», Journal of Applied Physics, vol. 108, n° 11, 2010.



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



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

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

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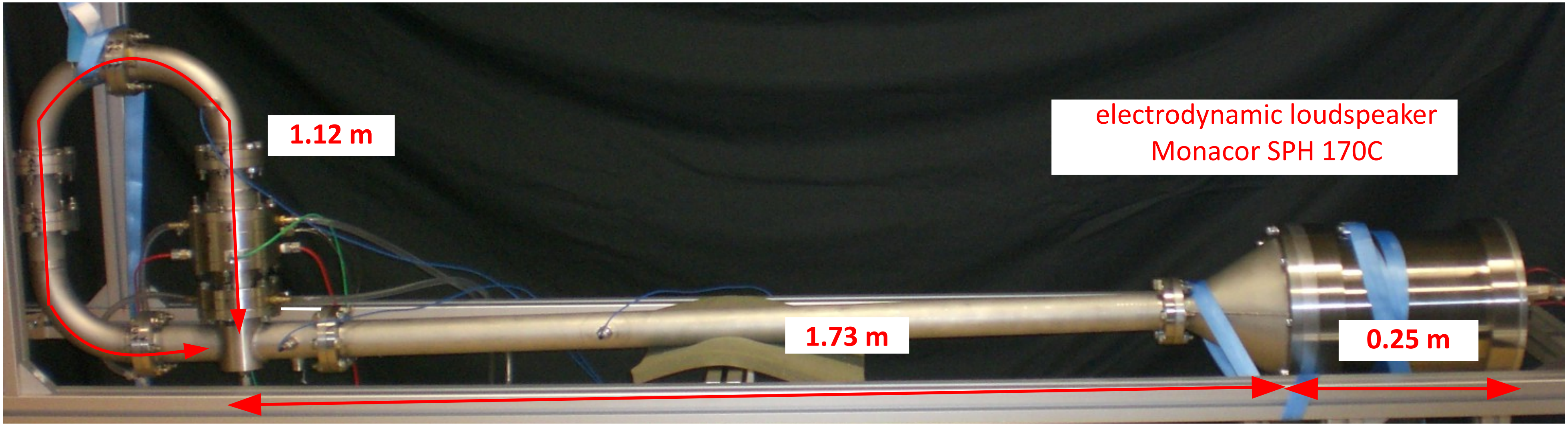

designed with Delta-Ec [W.C. Ward, G.W. Swift & J.P. Clark, J. Acoust. Soc. Am., 123(5) (2008)]

Fluid : **air**
Static pressure : **5 Bars**
Ambient temperature : **295 K**
Frequency: **40 Hz**

Thermoacoustic core : L = 0.093m, d= 5.6 cm
Alternator :
Resonator : L = 1.55 m, d = 4.4 cm
Back cavity : L = 0.26 cm, d = 17 cm
Inertance feedback : L = 0.97 m, d = 4.4 cm
Compliance : L = 0.04 m, d = 5.6 cm