Innovative vibration-cancellation method for a pulse tube cryocooler

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- Elastic deformation of pipe: a source of vibration
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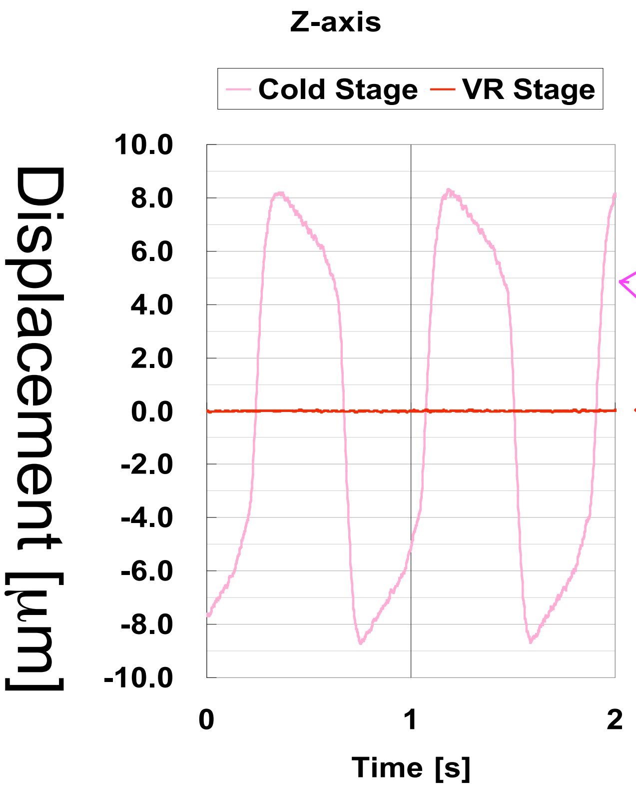
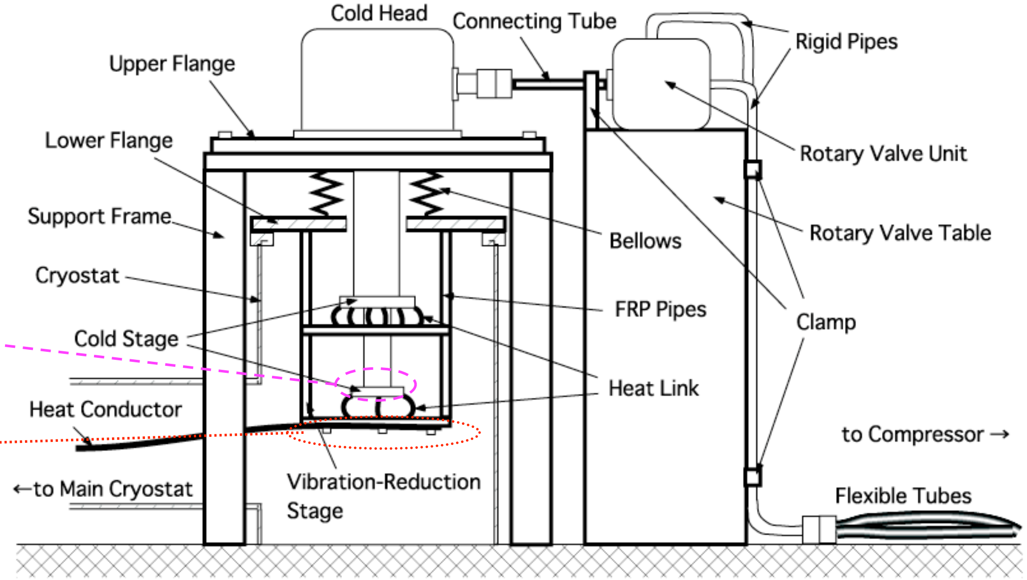
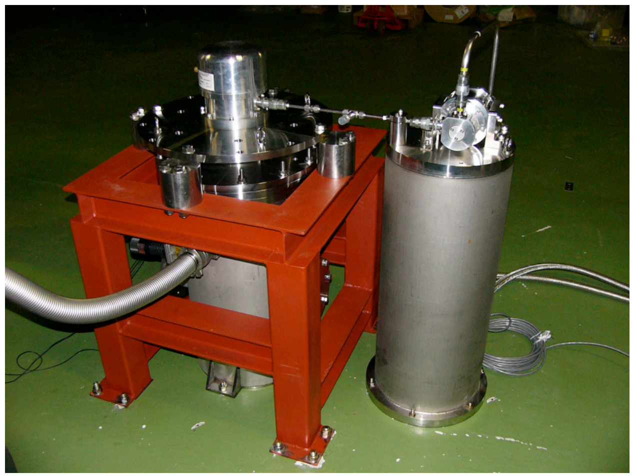
Example of PT Cryocooler system with vibration-reduction stage







Amplitude of 2nd VR stage
Δz=±50 nm（99.7% Reduction）

Cryocooler system with V.R. stage

Excellent reduction of vibration

Need additional somewhat complicated structure

Method of vibration cancellation

Utilize a vibration as a counter force

Possibly realize compact cryocooler system

Experimental proof of a basic idea

Elastic deformation of pipe

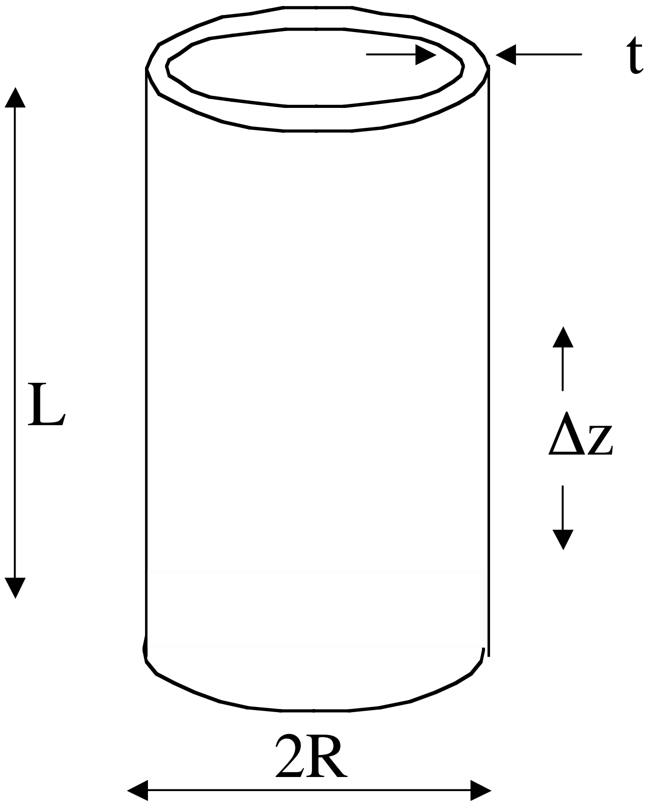
-- an origin of cold stage vibration --

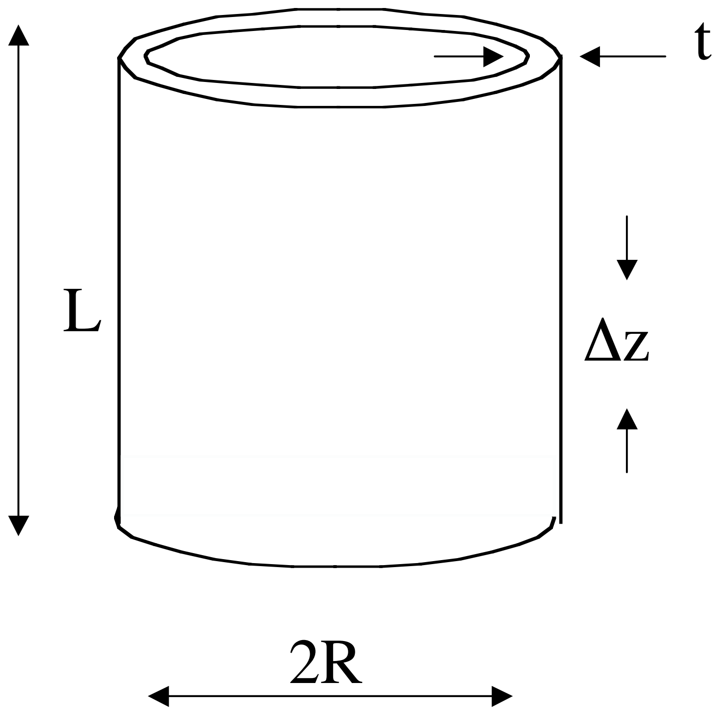
$$\Delta z = \left(\frac{1}{2} - \nu\right)\frac{RL\Delta p}{Et}$$

Δp : inner pressure
E : Young's modulus
ν : Poisson's ratio

stretching

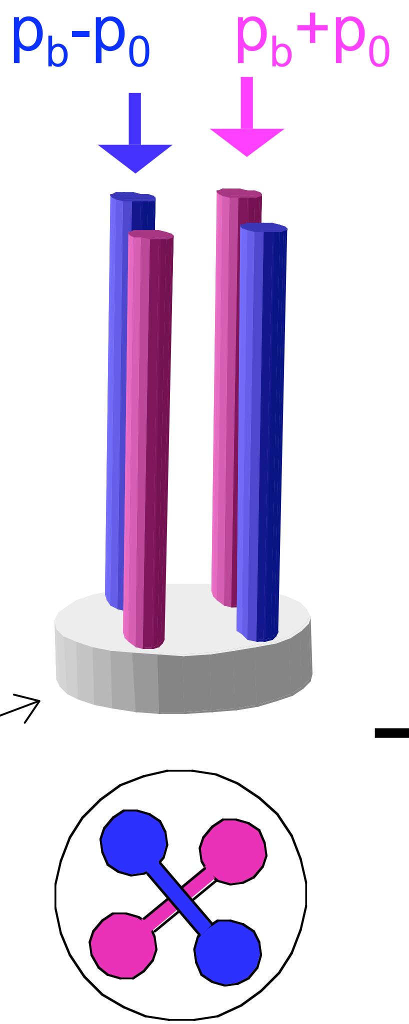
bulging





A method of vibration cancellation

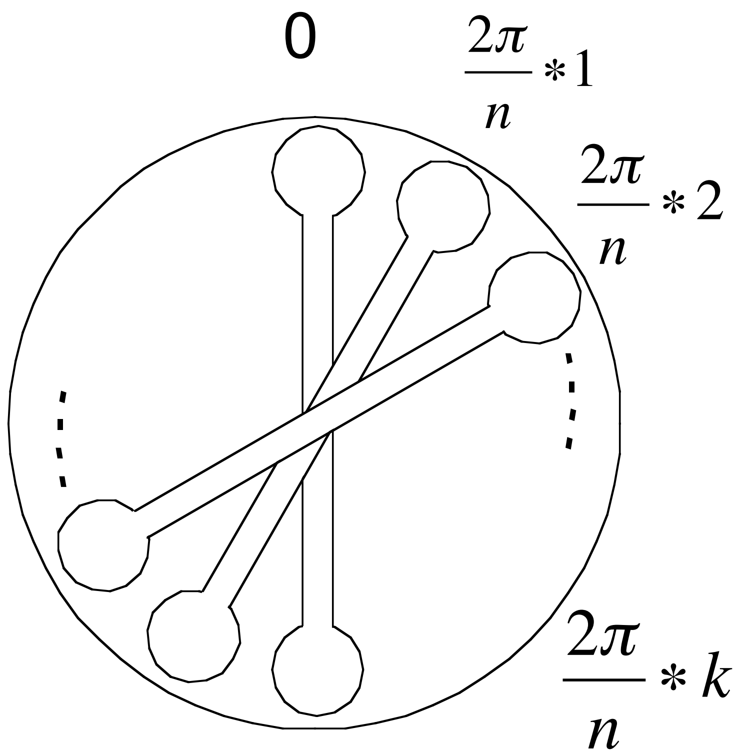
Pulse tube
Regenerator
--> pair



Cold Stage

n-pairs

Phase shift of driving puressures



Canceling vibration of cold stage

k-th pair $p(t) = p_0 \exp\left[i\left(\omega t + \frac{2\pi}{n}k\right)\right] \quad \rightarrow \quad \Delta z_k = \Delta z_0 \exp\left[i\left(\omega t + \frac{2\pi}{n}k\right)\right]$

Identical 2n-pipes --> n-pairs

$$\Delta z_0 \equiv \left(\tfrac{1}{2} - \nu\right)\frac{p_0 RL}{tE}$$

$$\Delta z_{ColdStage}(t) = \sum_{k=1}^{n} \Delta z_0 \exp\left[i\left(\omega t + \frac{2\pi}{n}k\right)\right]$$

$$= \left(\Delta z_0 \exp[i\omega t]\right) \sum_{k=1}^{n} \exp\left[i\frac{2\pi}{n}k\right]$$

$$= 0 \qquad \because) \quad \sum_{k=1}^{n} \exp\left[i\frac{2\pi}{n}k\right] = 0$$

$$\left(k, n \in N, \quad k \le n\right)$$

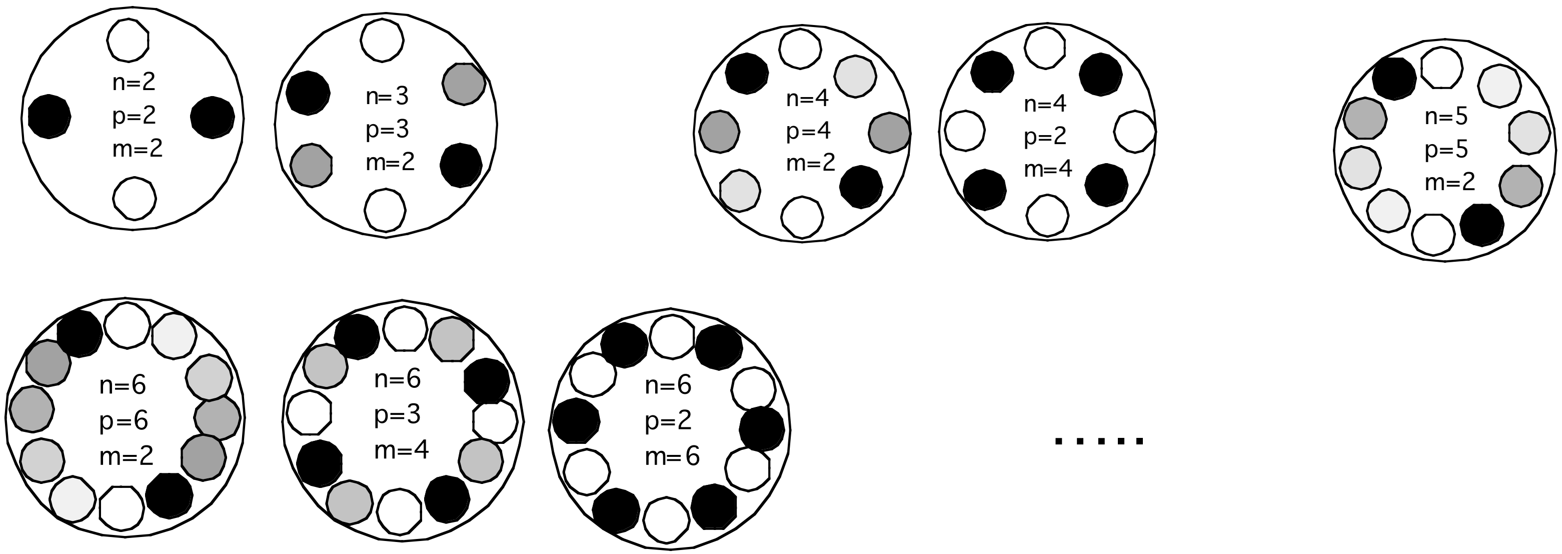
General class of cancellation

2n : Number of pipes

2π/p : step of phase shift

When $\frac{2n}{p} = m, \quad m \in Z \rightarrow \sum_{k=0}^{2n} \exp[i\frac{2\pi}{p}k] = \frac{1-\exp[2\pi i\frac{2n}{p}]}{1-\exp[i\frac{2\pi}{p}]} = 0$

Applicable sets of (n, p, m) for top-loading type pulse tube cryocooler.

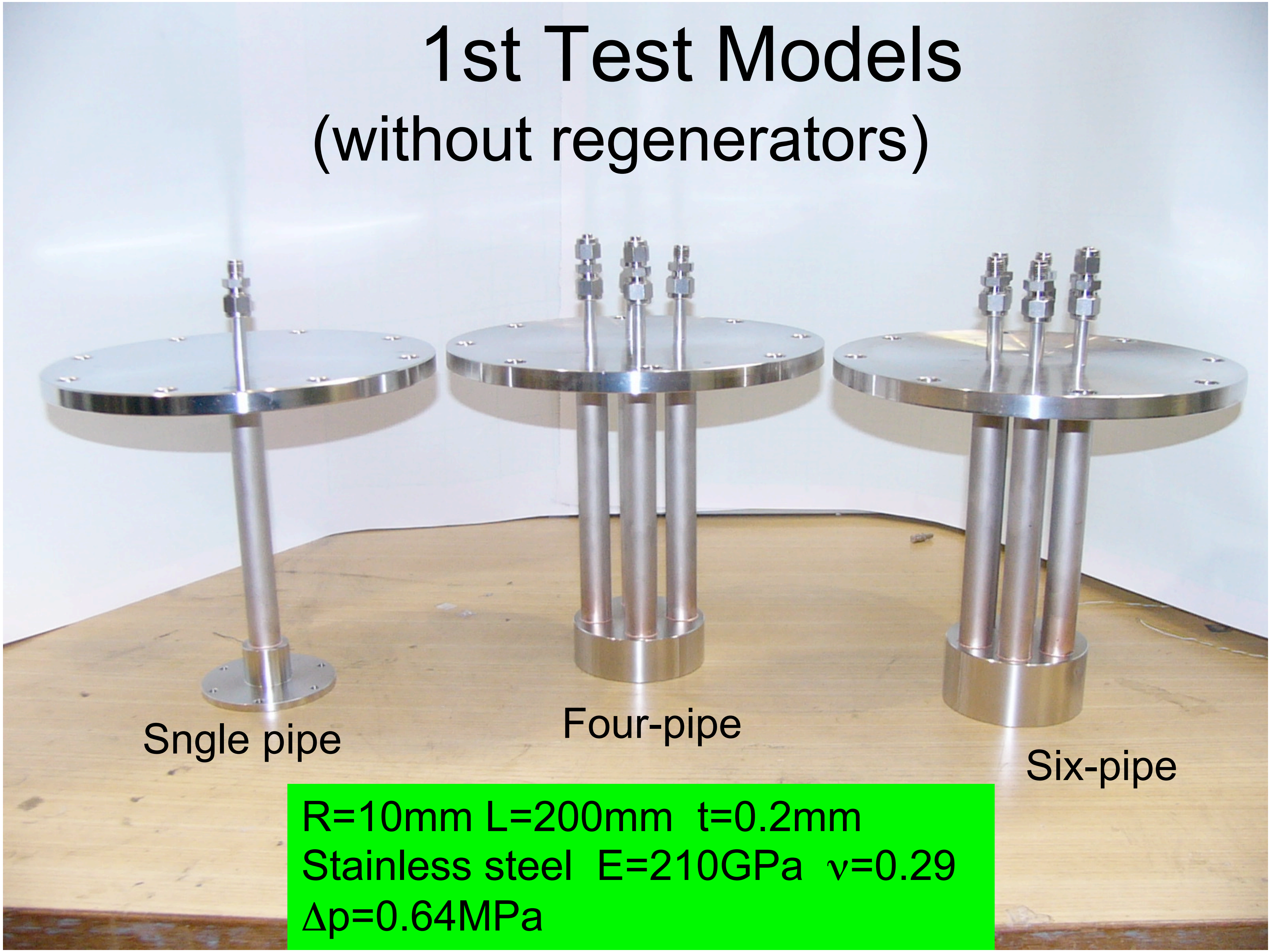


Demonstration of the vibration-cancellation method

- 1st models : no regenerator
  single-pipe (equivalent to n=1),
  four-pipe (n=2),
  six-pipe (n=3)

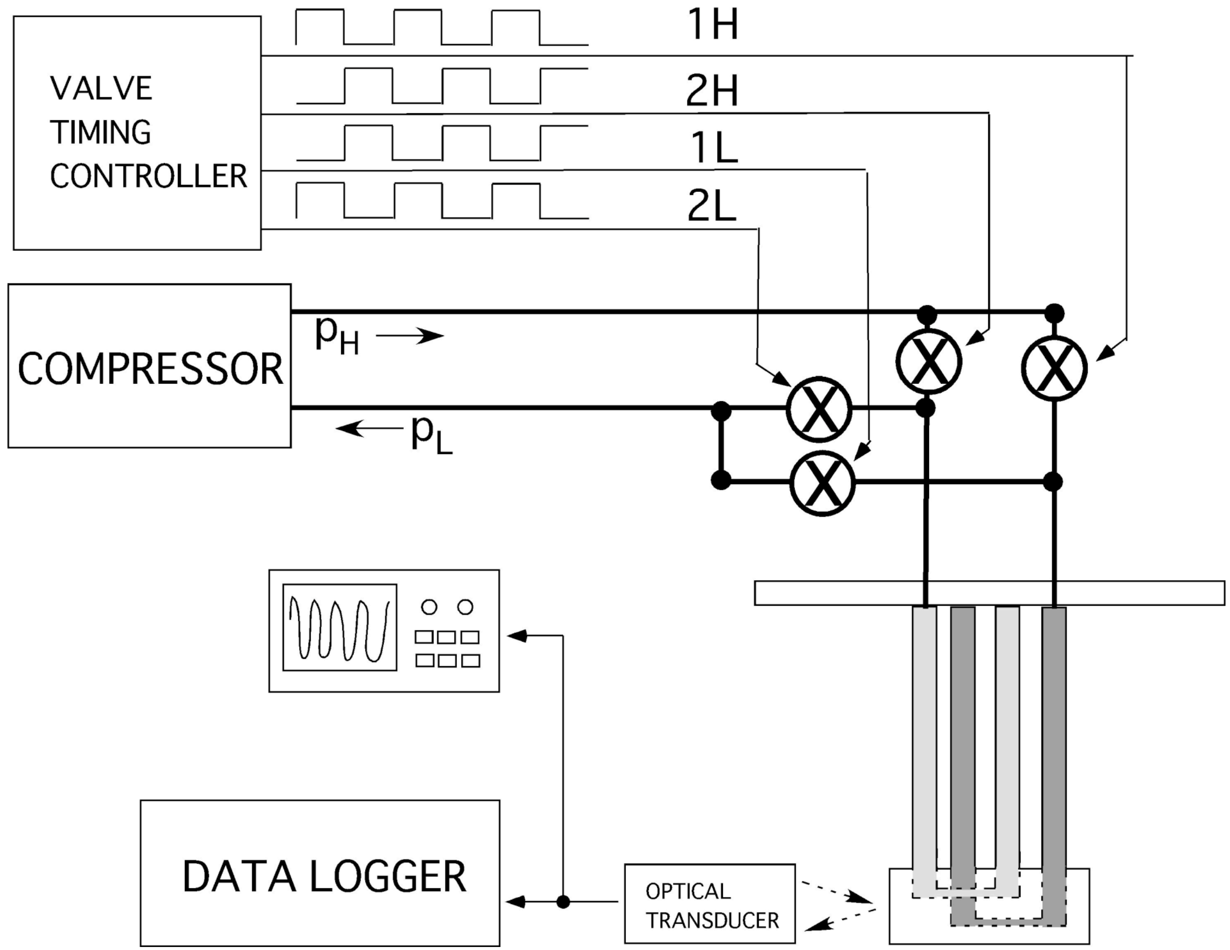
- 2nd model : with regenerator cartridge
  and buffer tank
  four-pipe (n=2)

1st Test Models
(without regenerators)

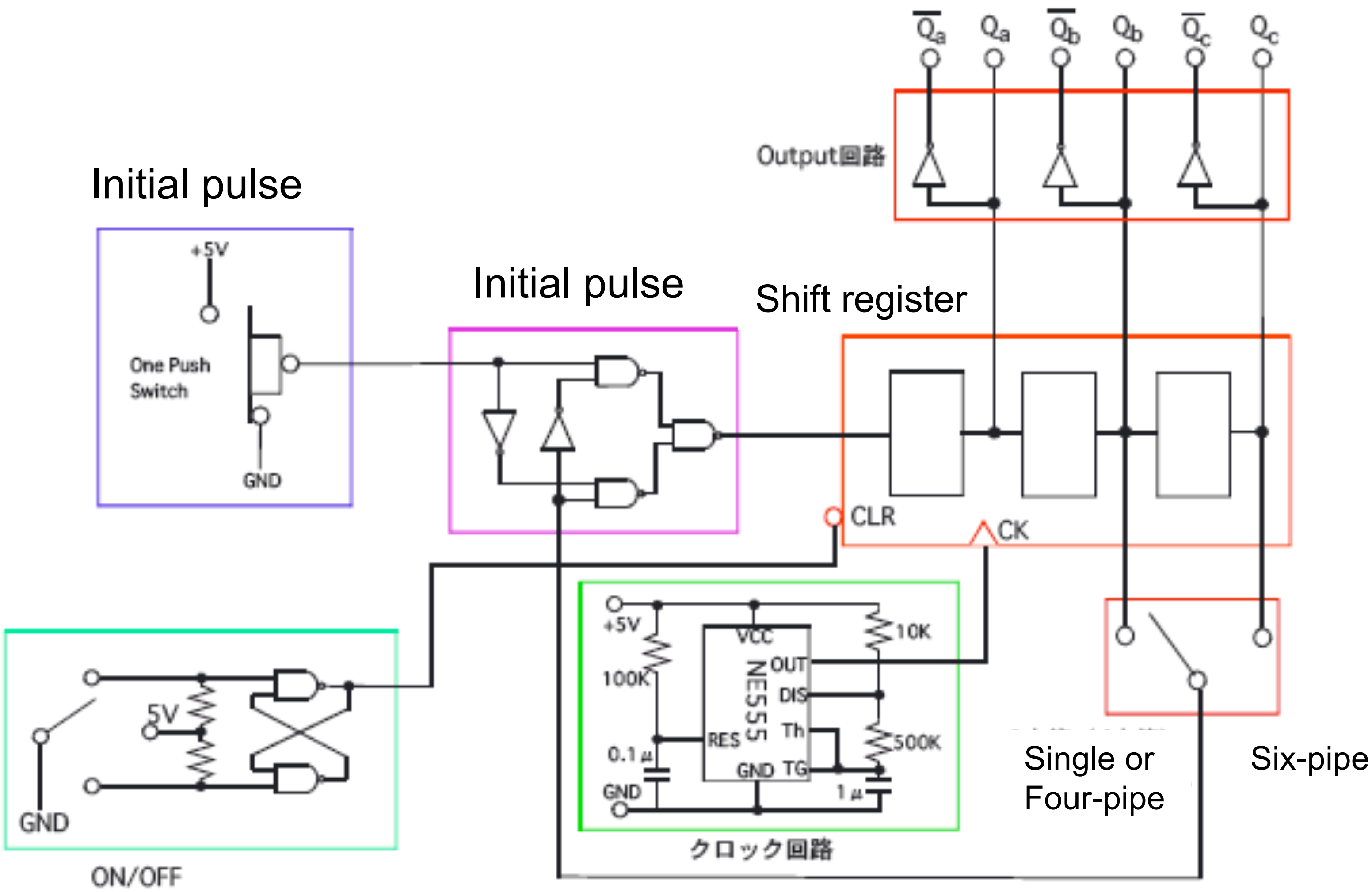


R=10mm L=200mm t=0.2mm
Stainless steel E=210GPa ν=0.29
Δp=0.64MPa

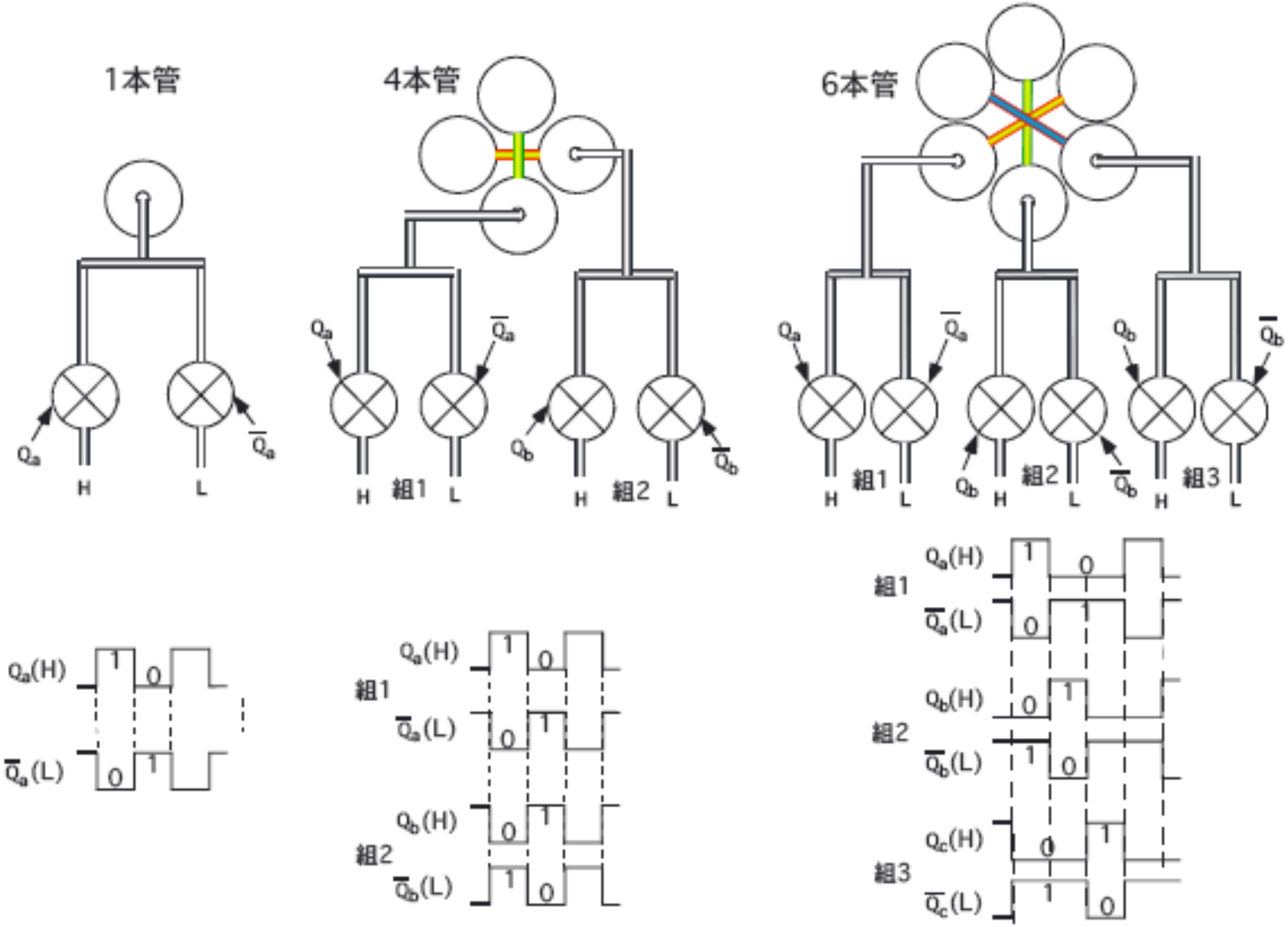
Experimental setup



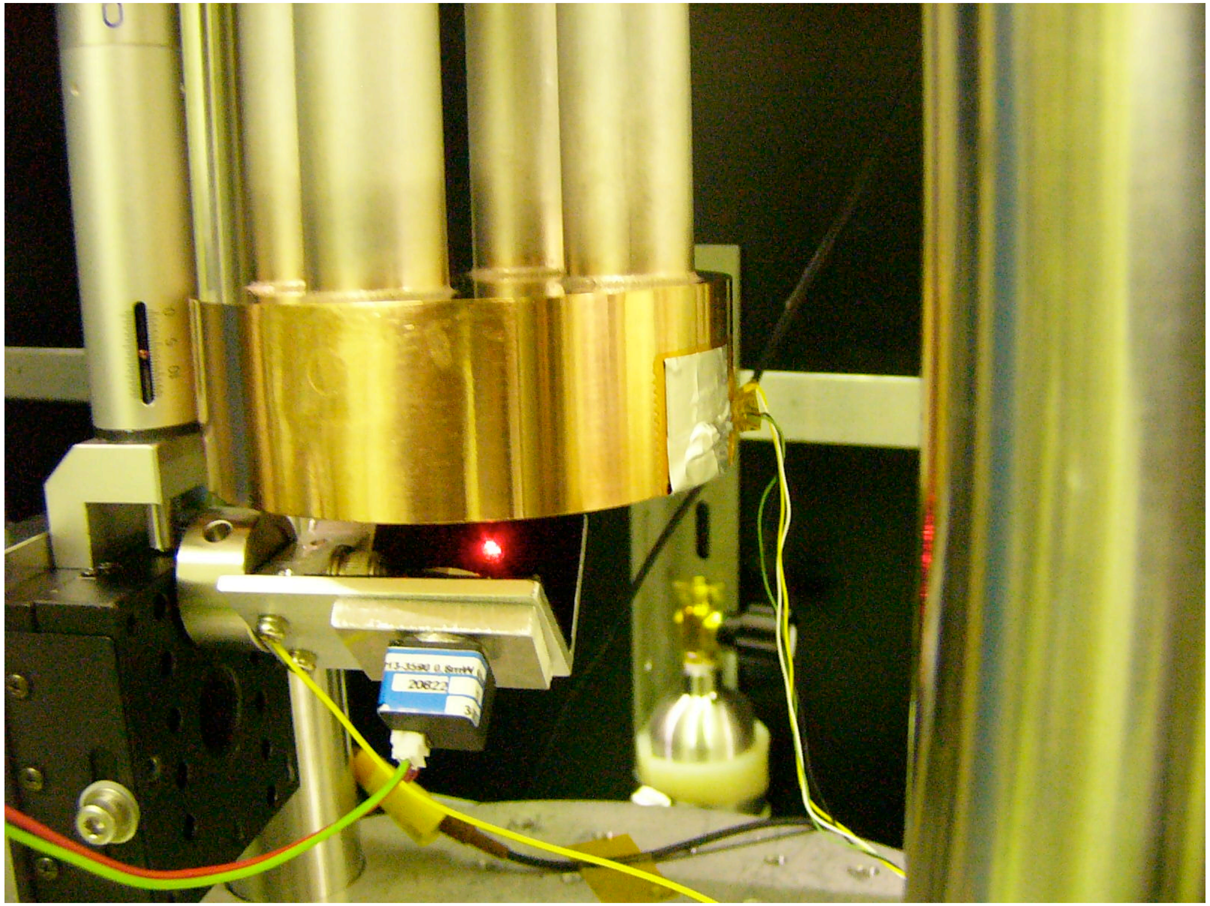
Pulse generator

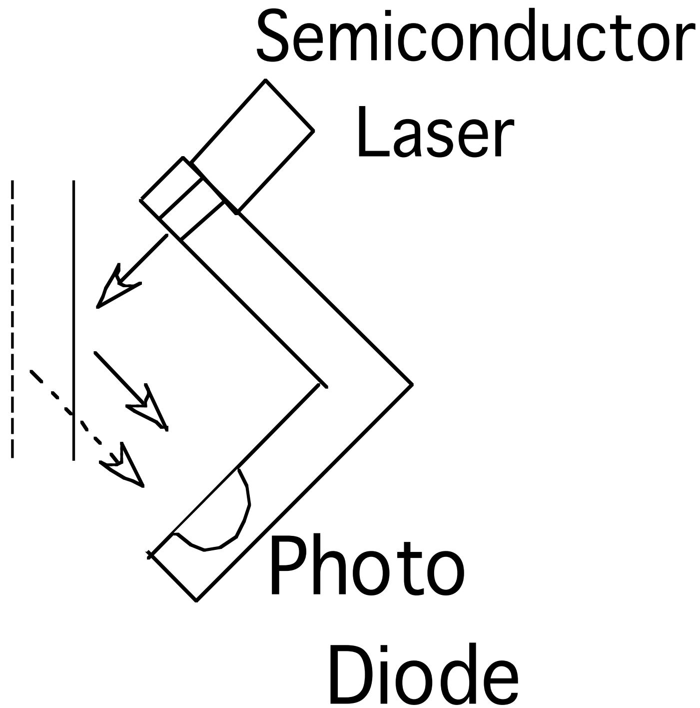


Valve connection



Optical transducer

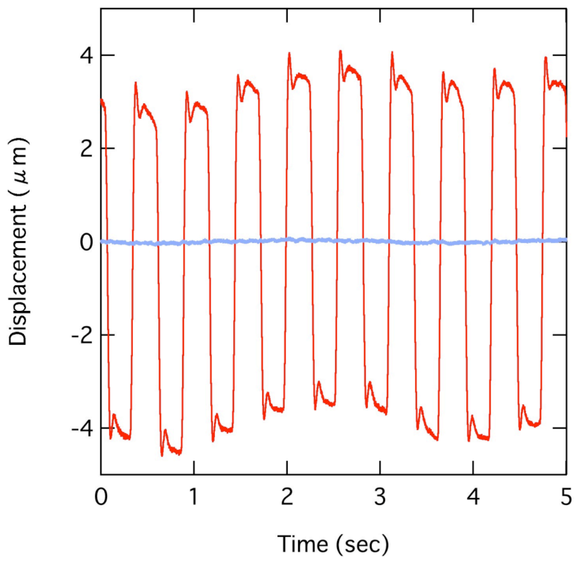




Experimental results (Δz)

Cold Stage Vibration of the 1st Test Models

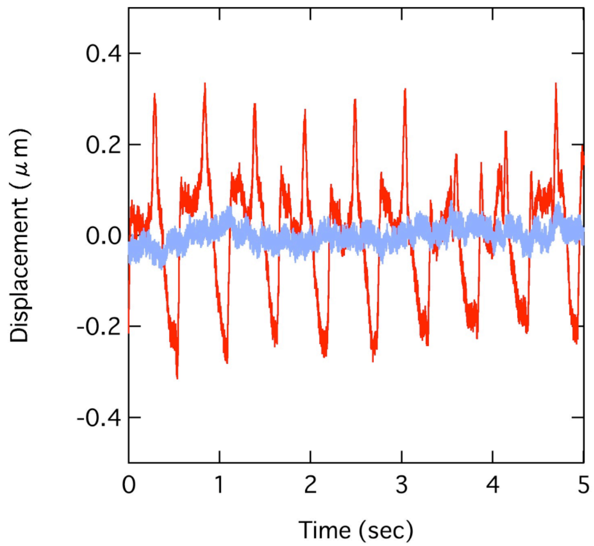
Single pipe



$$\Delta z_0^{RMS} = 3.4\mu m$$

$$\Delta z_{Noise}^{RMS} = 0.029\mu m$$

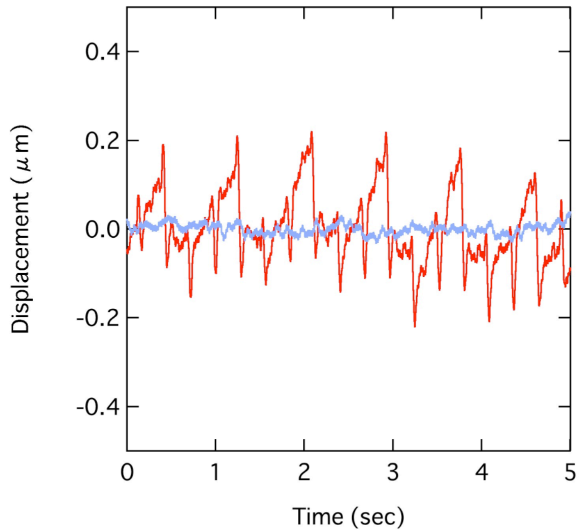
Four pipes



$$\Delta z_0^{RMS} = 0.13\mu m$$

$$\Delta z_{Noise}^{RMS} = 0.023\mu m$$

Six pipes

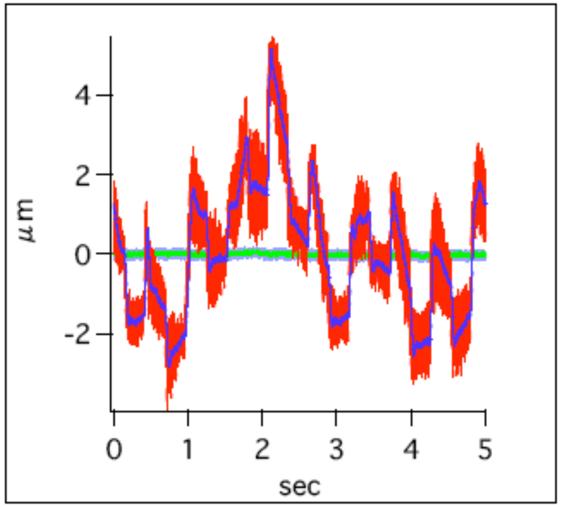


$$\Delta z_0^{RMS} = 0.082\mu m$$

$$\Delta z_{Noise}^{RMS} = 0.012\mu m$$

Experimental results (Δx)

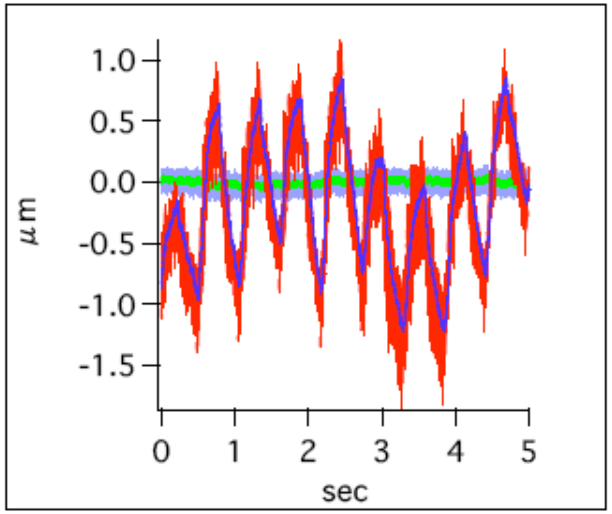
Single pipe



$$\Delta x_0^{RMS} = 1.6\mu m$$

$$\Delta x_{Noise}^{RMS} = 0.029\mu m$$

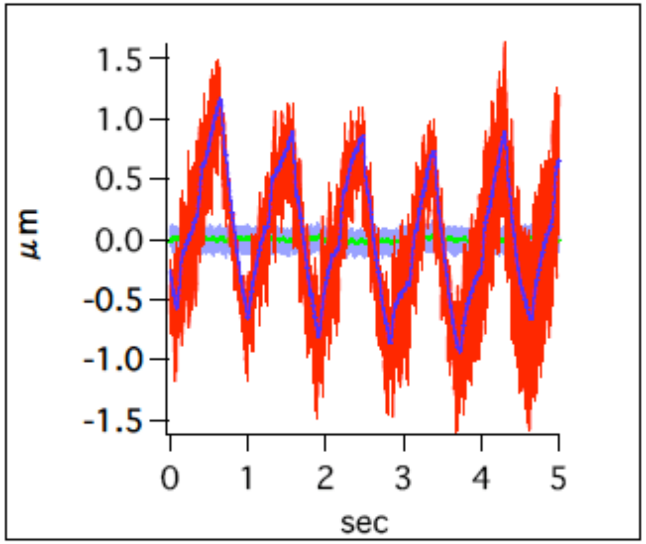
Four pipes



$$\Delta x_0^{RMS} = 0.53\mu m$$

$$\Delta x_{Noise}^{RMS} = 0.023\mu m$$

Six pipes

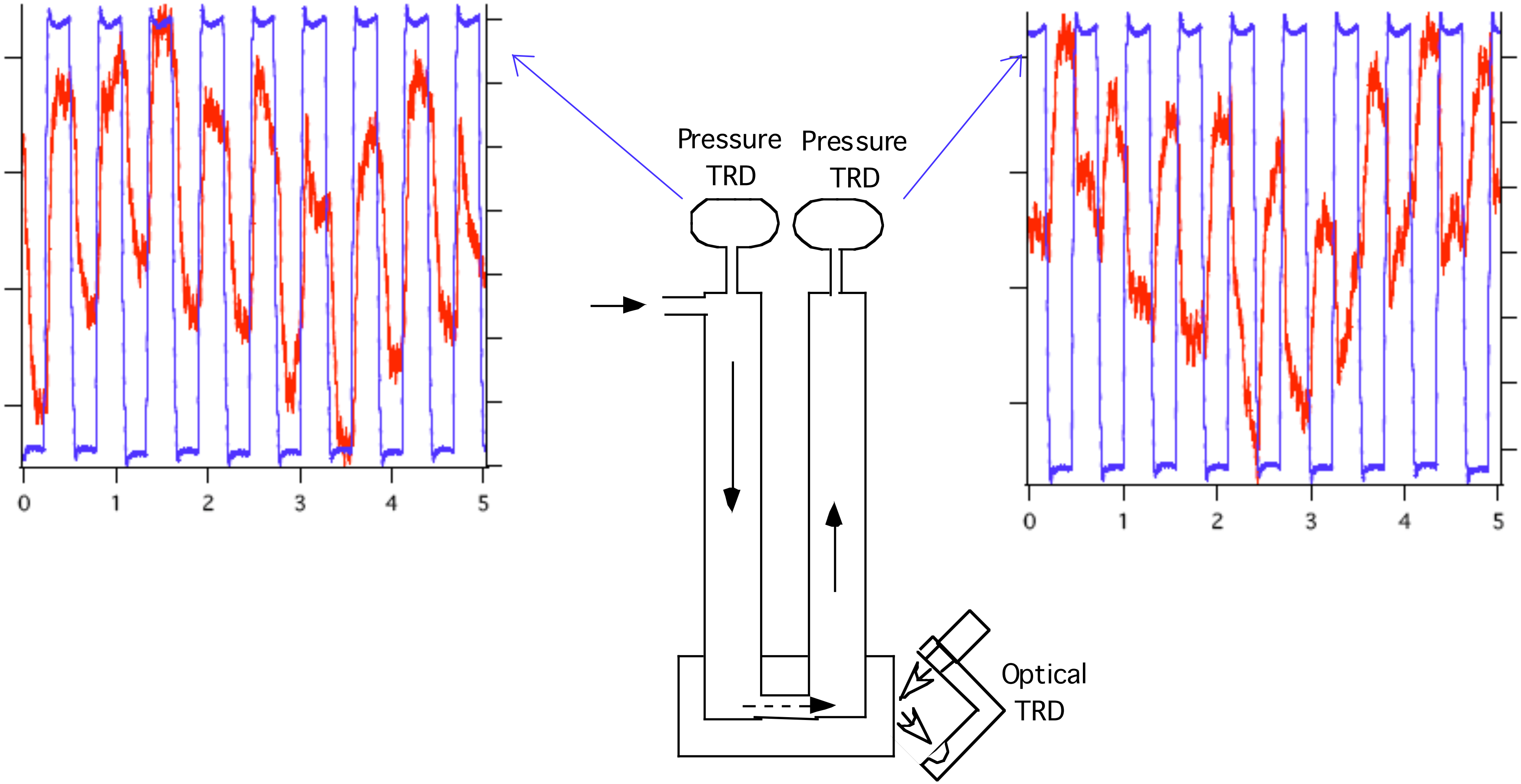


$$\Delta x_0^{RMS} = 0.51\mu m$$

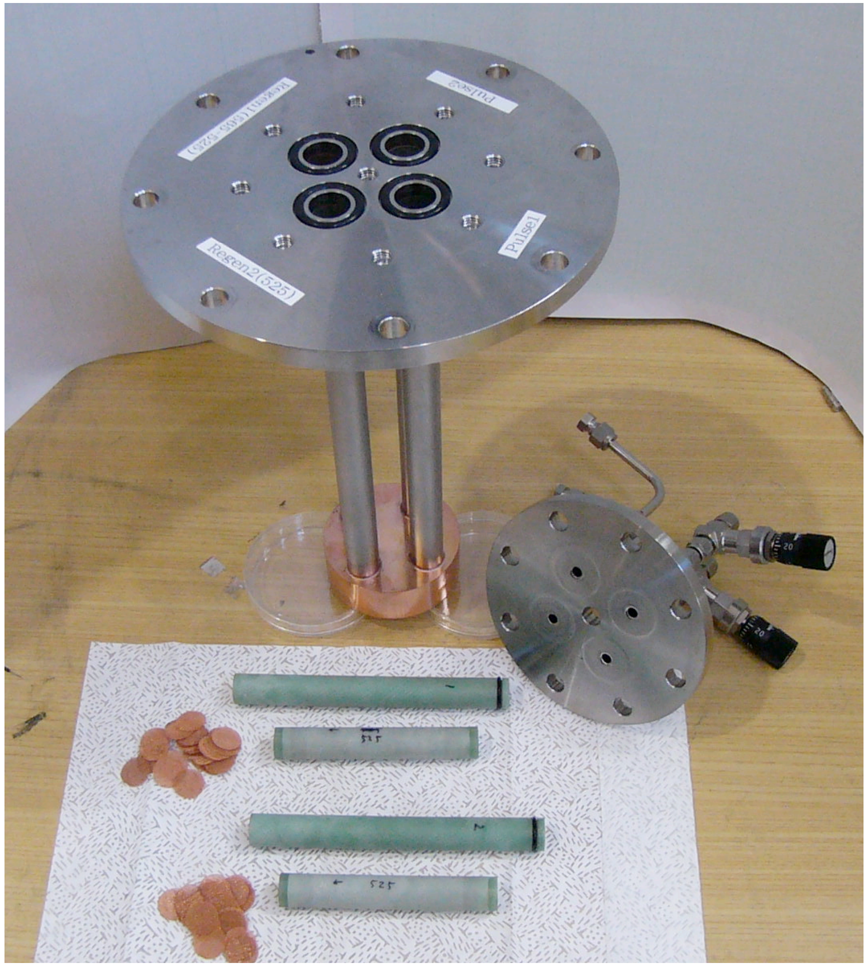
$$\Delta x_{Noise}^{RMS} = 0.012\mu m$$

Effect of time delay

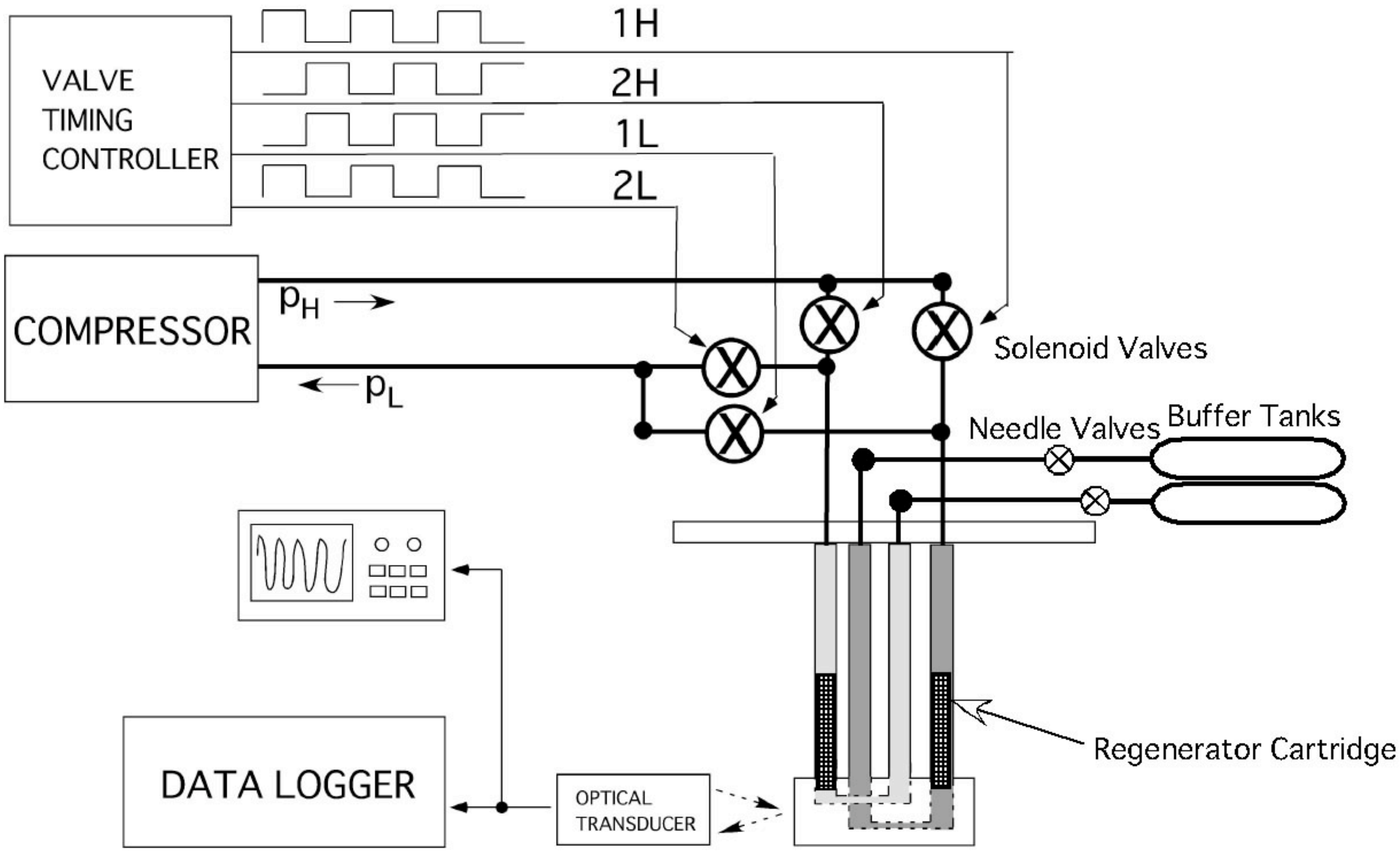
Flow impedance -> Delay -> Lateral motion



2nd Test Model

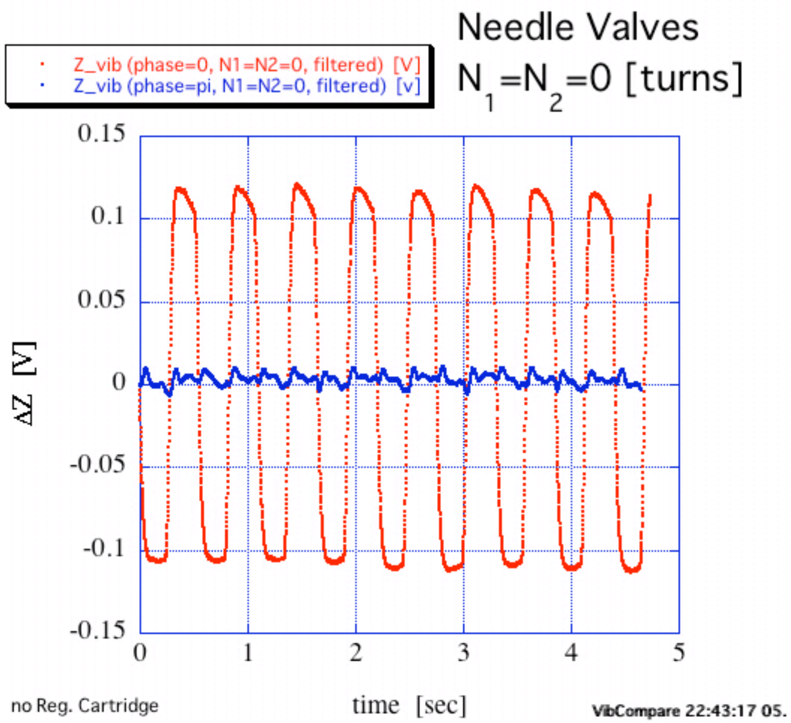


Experimental setup of the 2nd test model

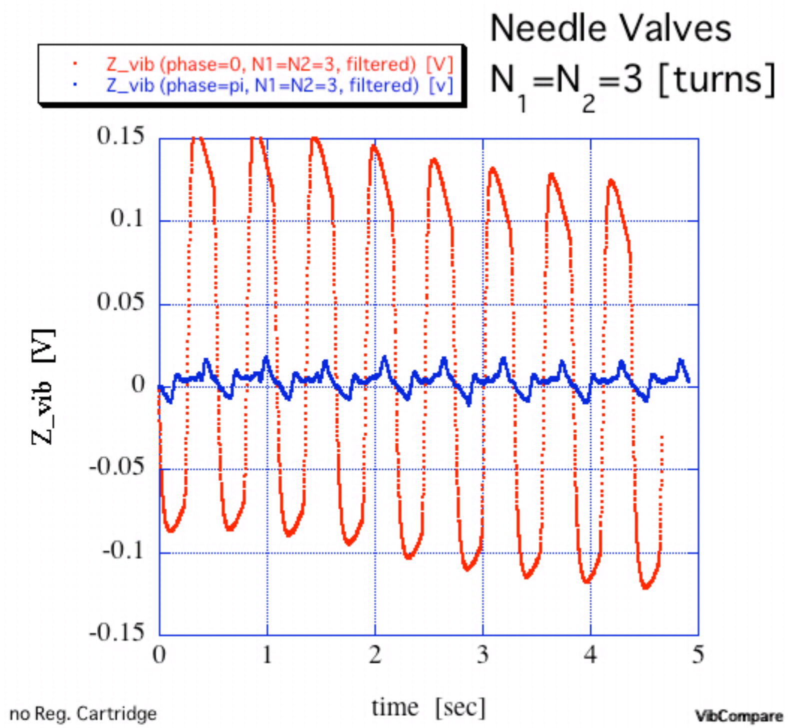


Cold Stage Vibration of the 2nd Test Model

No Regenerator Cartridges

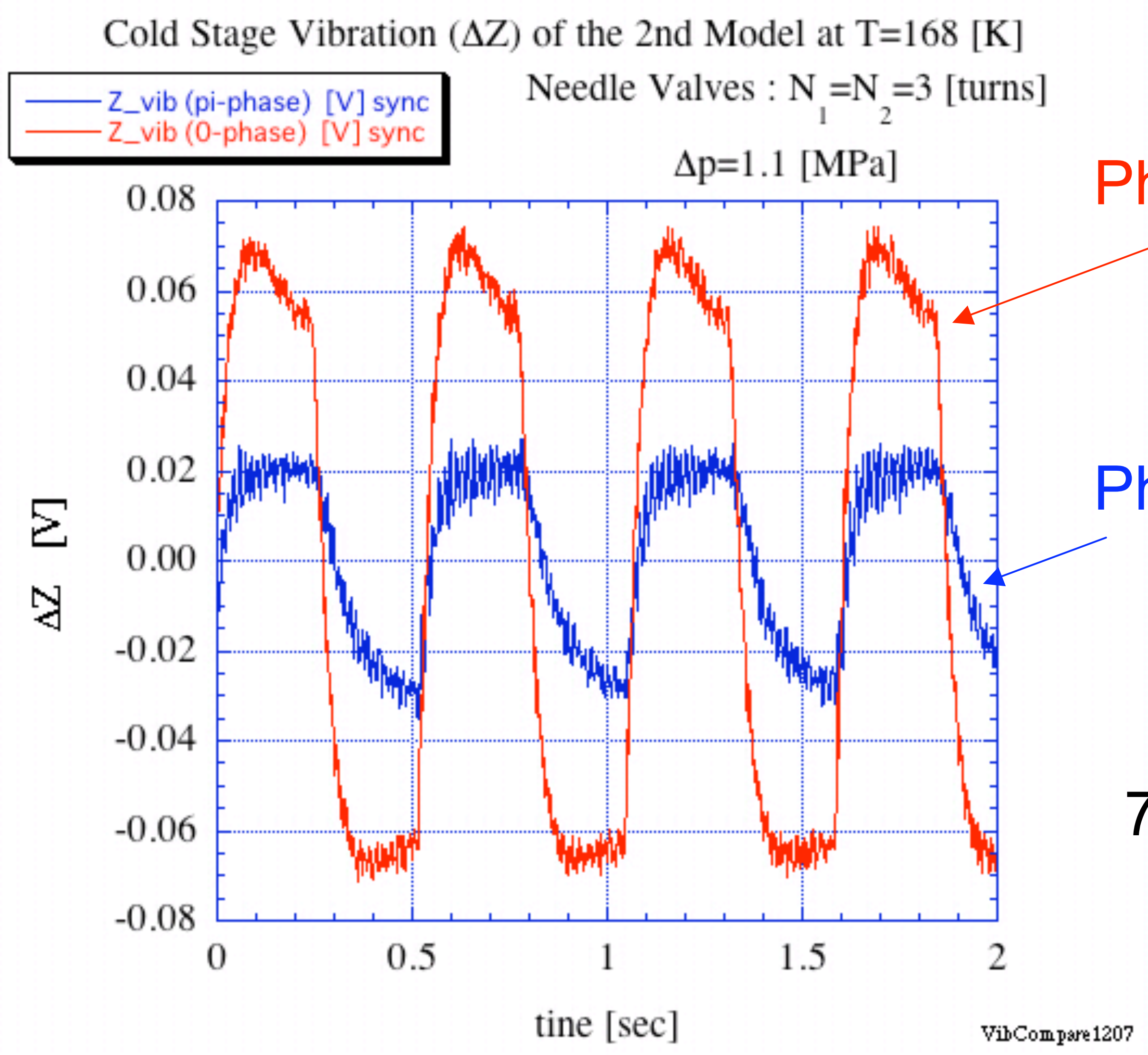


92% Reduction



89% Reduction

Cold Stage Vibration of the 2nd Test Model (with regenerator cartridges)

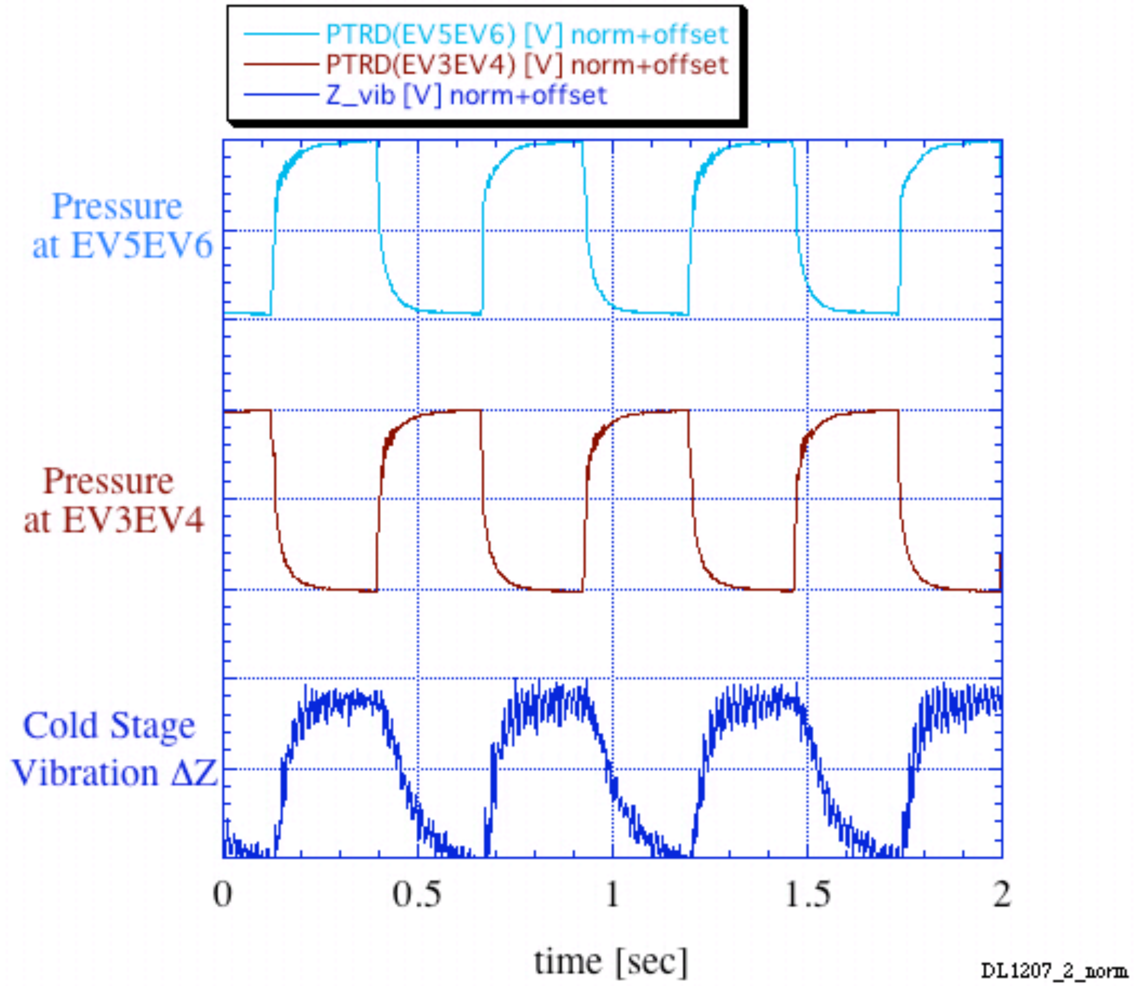


Phase difference =0

Phase difference=π

71% reduction

Driving Pressure and Cold Stage Vibration of the 2nd Test Model (with cartridges)



Summary and conclusion

- Cold stage vibration of 1st test models
  - Δz=3.4μm for the single pipe model
  - Δz=0.13μm for the four pipe model
  - Δz=0.082μm for the six pipe model
- About 98% reduction in the six-pipe model
- Current reduction rate of the 2nd model is about 71 % at T=168 [K].

- The basic idea of the vibration cancellation is applicable for a low vibration PT cryocooler system.
- Improvements of the 2nd model are continued.