Miniature PT Cryocooler Activated by Resonant Piezoelectric Compressor and Passive Warm Expander

C1OrG-02
CEC/ICMC 2017, Madison WI

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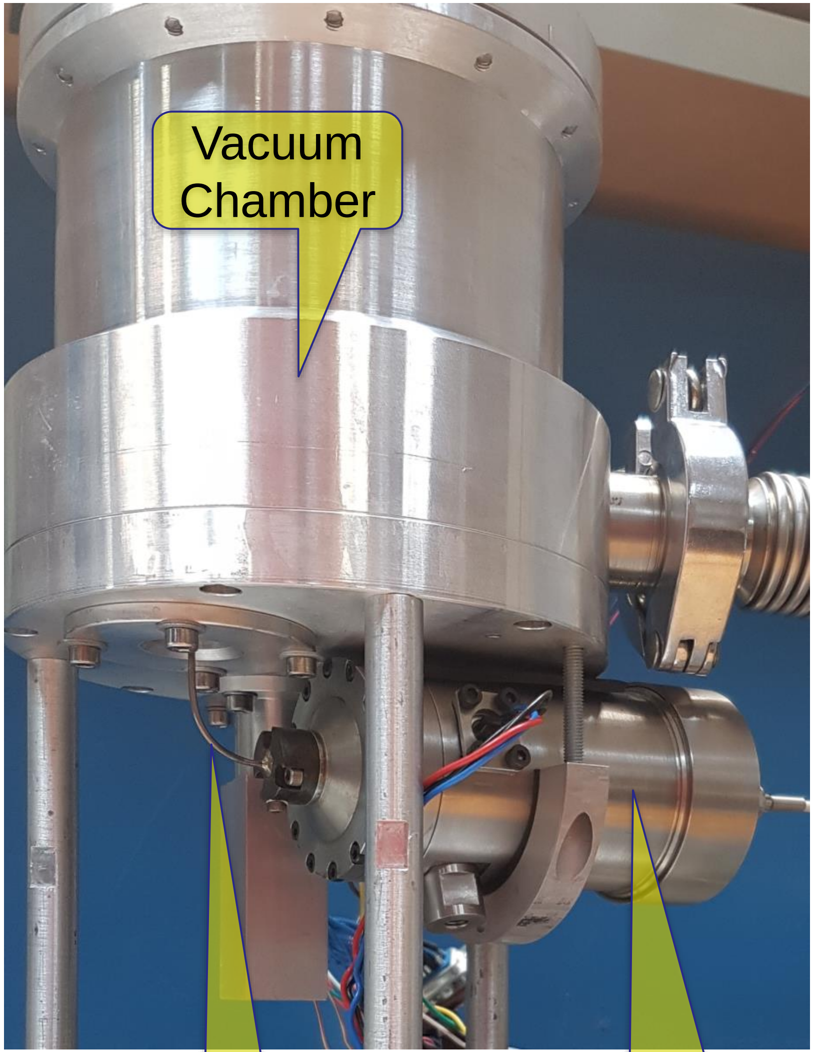
Background

- A miniature Pulse Tube (PT) cryocooler, namely MTSa, noted by a 12 mm long regenerator, was presented earlier. MTSa driven by conventional compressor and equipped by an Inertance Tube (IT) provided 400 mW of cooling at 110 K, while operating at 103 Hz with filling pressure of 40 Bar and a pressure ratio of 1.3. The no-load temperature was measured at 99 K.
- MTSb is a modular version of MTSa, which allows maximum flexibility in experiments with different equipment. Due to imperfections of the modular assembly, the MTSb reaches a no-load temperature of 105 K, while the nominal 400 mW of cooling is achieved at about 115 K.
- A functional linear compressor driven by a PZT stack-type actuator operating at mechanical resonance and suitable for driving the MTS series cryocoolers was demonstrated at CEC-ICMC 2015.
- A proposed passive mechanical Warm Expander (WE) replacing the IT for phase shifting was first shown at ICC19. A number of detected problems did not allow matching the PT requirements; therefore, the WE system had to be significantly improved.
- This work concentrates on redesigning the WE system accompanied by the modified theory, and on the subsequent integration of the PT components.

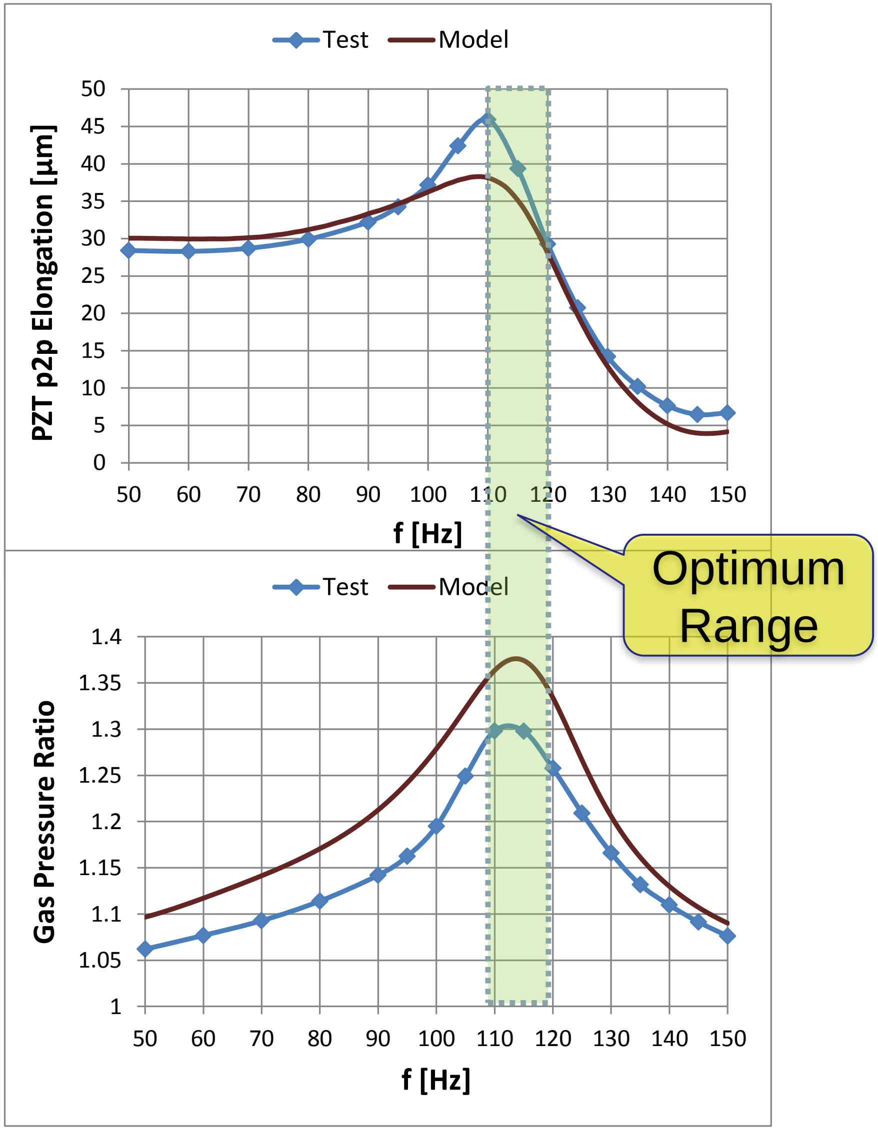
Resonant PZT Compressor



Vacuum Chamber

Transfer Line

PZT Compressor

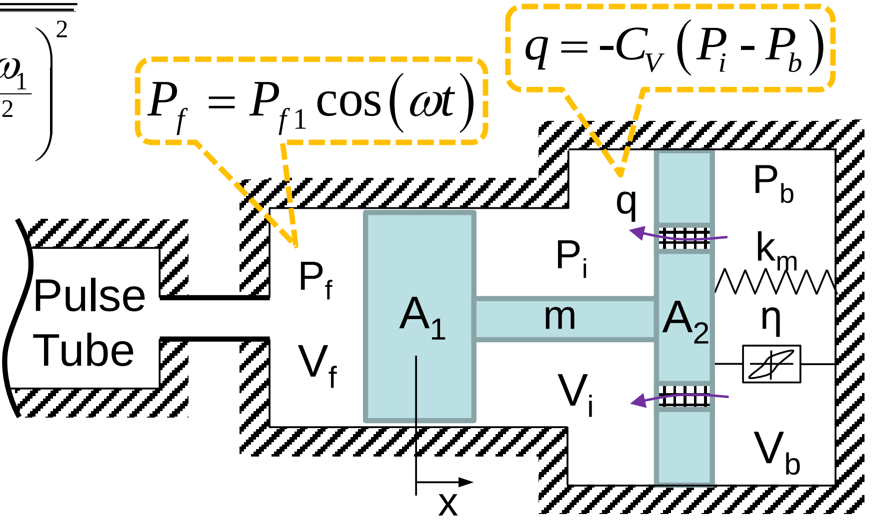


Optimum Range

Data for 60% of the maximum voltage

Linear Model of the Warm Expander

$$\begin{cases} x_1 = \dfrac{P_{f1}A_1}{\sqrt{\left(\eta k_m + \omega\dfrac{c_1 - k_1/\omega_1}{1+(\omega/\omega_1)^2}\right)^2 + \left(k_m - \omega^2 m + \dfrac{k_1 + \omega^2 c_1/\omega_1}{1+(\omega/\omega_1)^2}\right)^2}} \\[2ex] \tan\theta = \dfrac{\eta k_m + \omega \underbrace{\boxed{\dfrac{c_1 - k_1/\omega_1}{1+(\omega/\omega_1)^2}}}_{c(\omega)}}{k_m - \omega^2 m + \underbrace{\boxed{\dfrac{k_1 + \omega^2 c_1/\omega_1}{1+(\omega/\omega_1)^2}}}_{k_{\text{int}}(\omega)}} \end{cases}$$



$$\boxed{P_f = P_{f1}\cos(\omega t)}$$

$$\boxed{q = -C_V\,(P_i - P_b)}$$

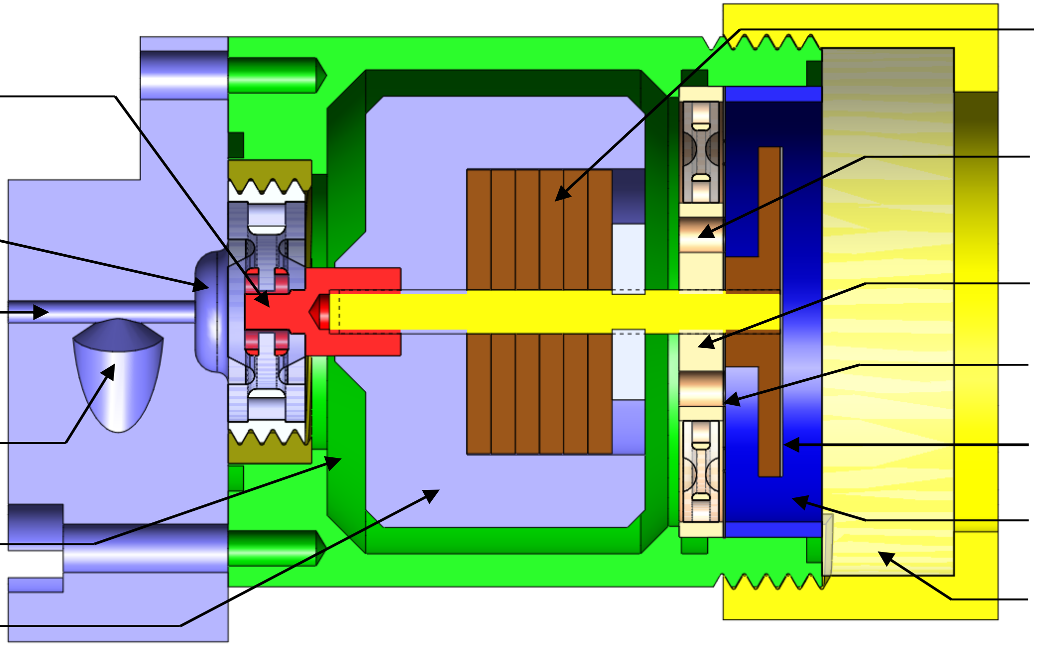
Where:

$$\omega_1 = C_V \gamma P_0\left(\frac{1}{V_{i0}} + \frac{1}{V_{b0}}\right), \quad c_1 = \frac{(A_2 - A_1)^2 V_{b0} + A_2^2 V_{i0}}{C_V\,(V_{i0} + V_{b0})}, \quad k_1 = \frac{\gamma P_0 A_1^2}{V_{i0} + V_{b0}}, \quad k_g = \frac{P_{f1}A_1^2\,|\cos\theta_0|}{V_{f1}}$$

Prediction of C_V and *m* for the PT operating at ω_0, and requiring P_{f1}, V_{f1} and θ_0 at the warm end:

$$\boxed{\begin{cases} C_V \approx \dfrac{\omega_0}{k_g\,|\tan\theta_0| - \eta k_m}\left(A_2 - \dfrac{V_{b0}}{V_{i0} + V_{b0}}A_1\right)^2 \\[2ex] m \approx \dfrac{k_g + k_m + k_1}{\omega_0^2} + \dfrac{c_1}{\omega_1} \end{cases}, \qquad -180^\circ < \theta_0 < -90^\circ}$$

Design of the Warm Expander



A_1 piston-diaphragm-cylinder assembly

V_f

Connection to PT

Pressure gauge aperture

V_i

Main mass

Weights and nut

Aperture for porous material (x6)

A_2 assembly

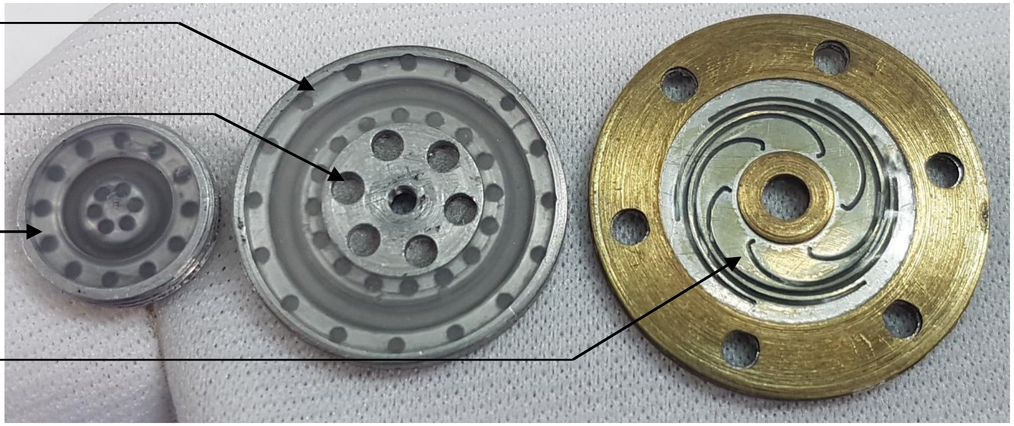
Flexural bearing

Mirror

V_b

Glass window

Parameters of the WE were optimized for operation at 110 Hz with MTSb cryocooler



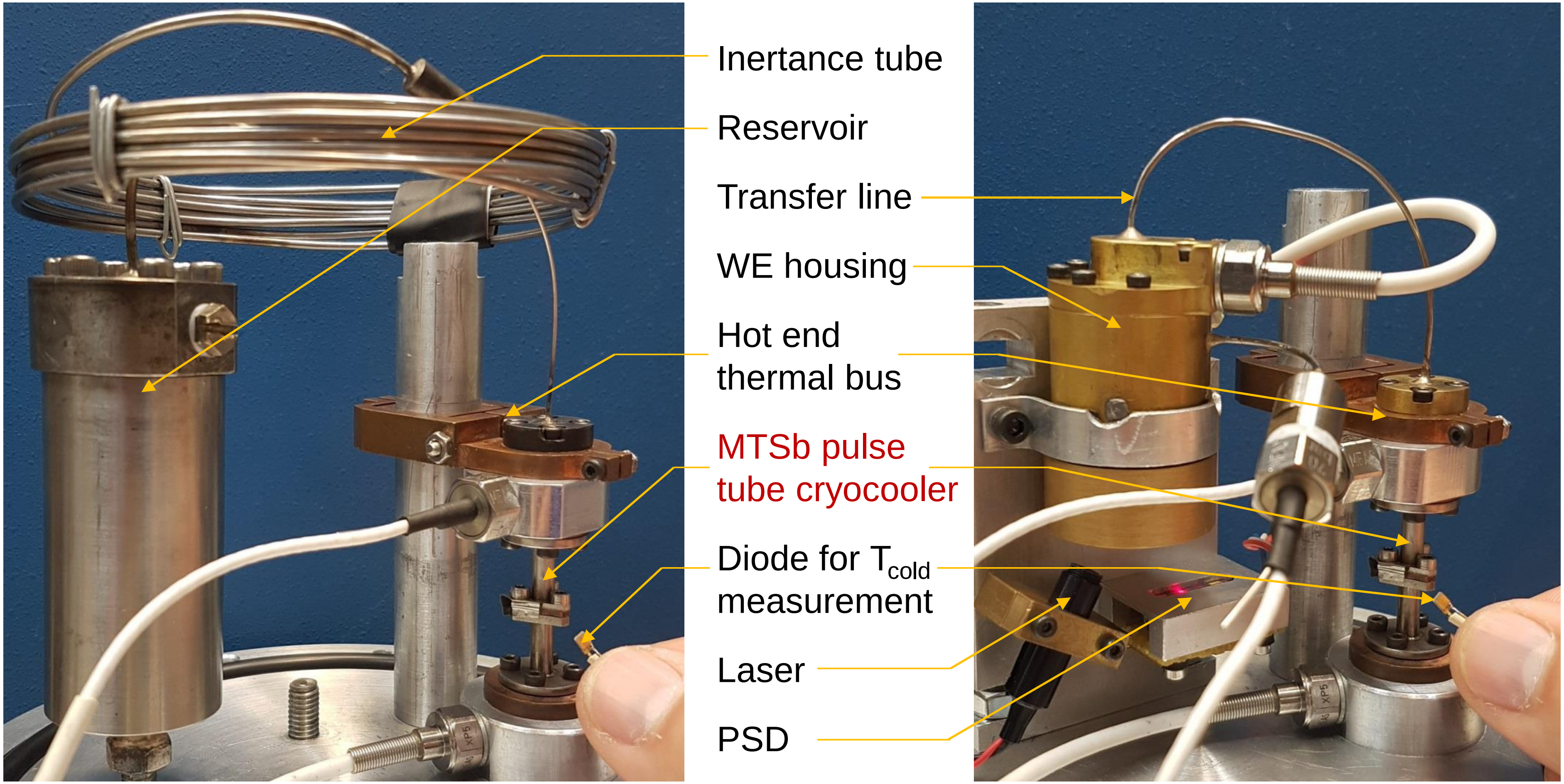
A_2 assembly, Ø14mm

Random stainless steel fiber disks

A_1 assembly, Ø5mm

Compressing diaphragm of the PZT compressor, Ø12.5mm

MTSb Equipped with IT and WE Systems



Inertance tube

Reservoir

Transfer line

WE housing

Hot end thermal bus

MTSb pulse tube cryocooler

Diode for T_{cold} measurement

Laser

PSD

Results

From SAGE™:

- P_{f1} = 4.4 bar
- x_1 = 1.36 mm
- θ_0 = -150°

From WE design:

- k_m = 7.0 N/mm
- η = 0.1
- V_{i0} = 2.0 cc
- V_{b0} = 1.2 cc

Theoretical estimation:

- f_0 = 110 Hz
- C_V = 5.99 mm^3/s/Pa
- m = 27.9 gr

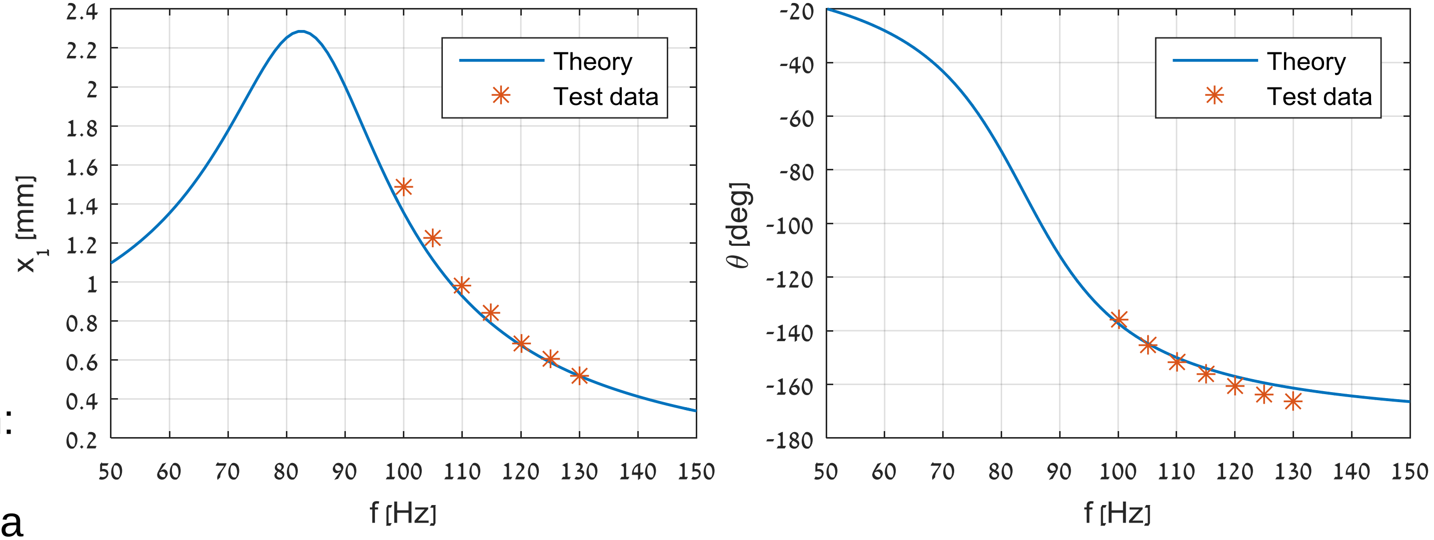
Trial and error optimization:

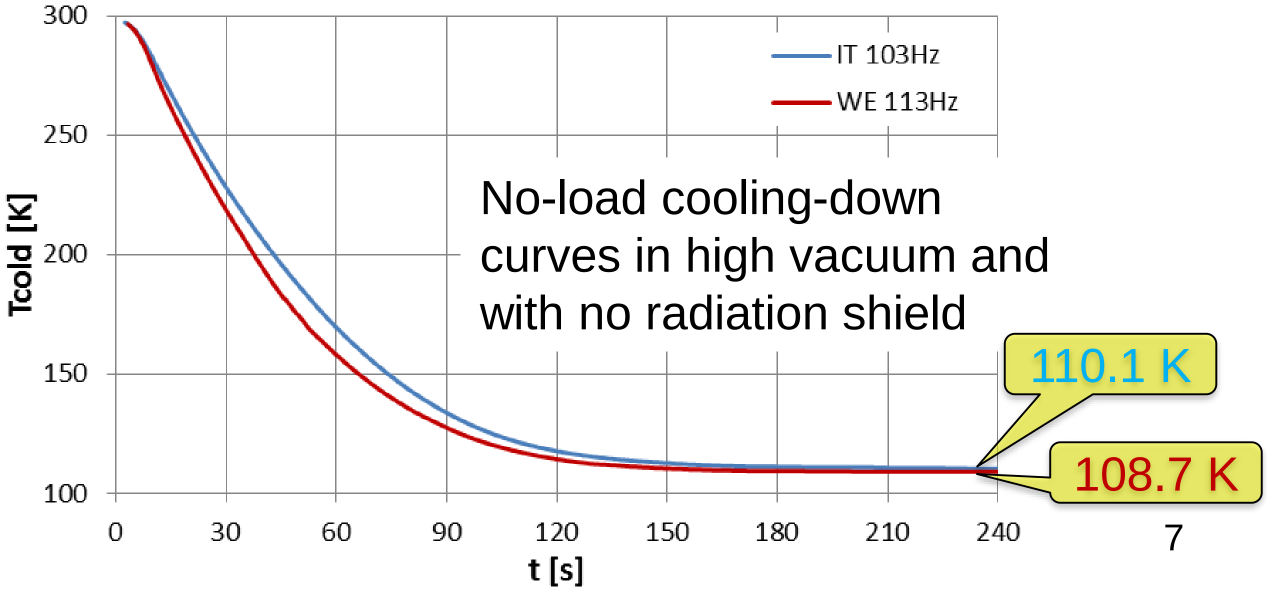
- f_0 = 113 Hz
- C_V = 7.0 mm^3/s/Pa
- m = 30 gr

Actual *x* at 113 Hz:

- x_1 = 1.4 mm
- θ = -155°

Frequency responses for P_{f1} = 3 bar





No-load cooling-down curves in high vacuum and with no radiation shield

110.1 K

108.7 K

Conclusions

- A passive WE system was successfully redesigned for matching the miniature PT cryocooler (MTSb) requirements.
- The MTSb cryocooler was successfully integrated with a resonant piezoelectric compressor and the recently developed passive warm expander at the frequency of 113 Hz.
- The cold end temperature of the cryocooler decreased by 1.4 K after the IT system was replaced by the WE system despite the enhanced frequency.
- The WE structure is much more compact relative to the IT-reservoir assembly. Without the measurement equipment the external dimensions of the WE housing may be easily reduced to 33×Ø25 mm.
- A modified linear model developed for the WE was successfully validated, and determined to be very useful for the initial estimation of the WE parameters. Fine tuning of the PT-WE performances requires either additional trial-and-error optimization, or extension of the model for nonlinear effects.

Thank you for your attention