ALPS II cavity control with a surrogate field: model and experiment

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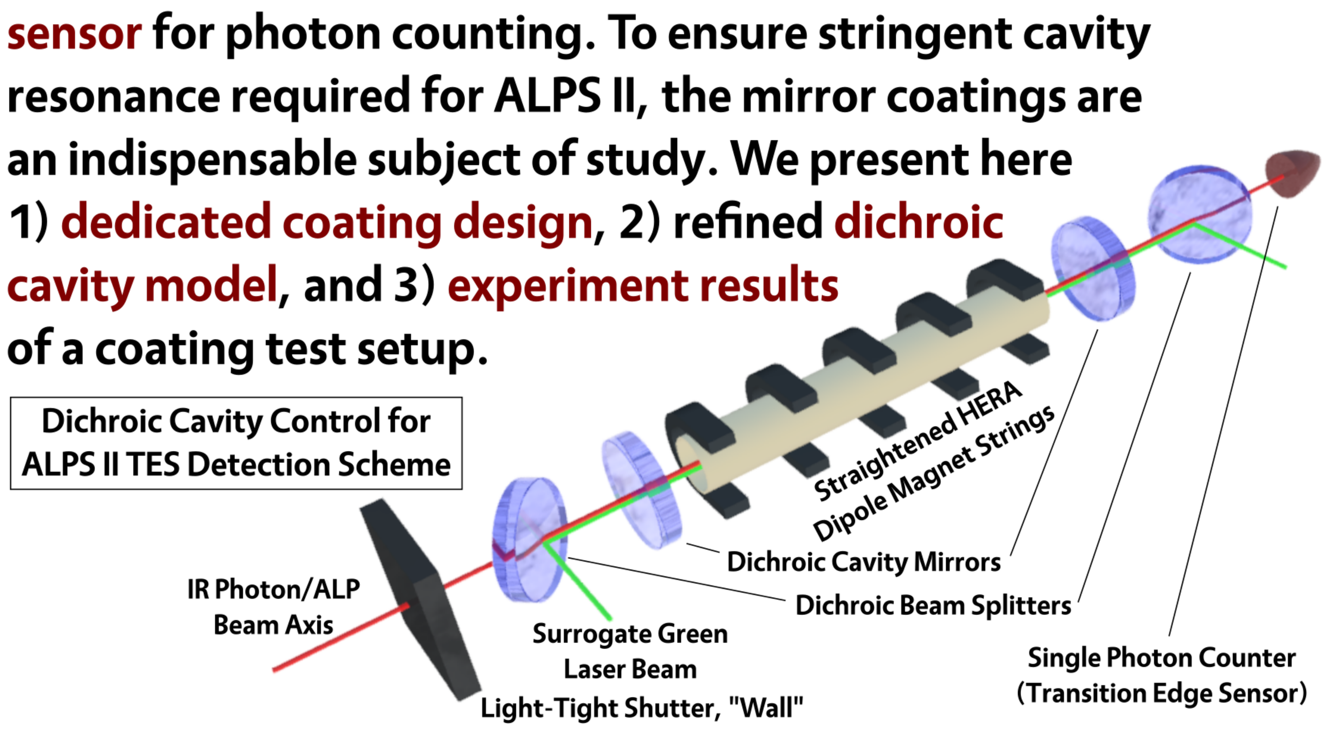
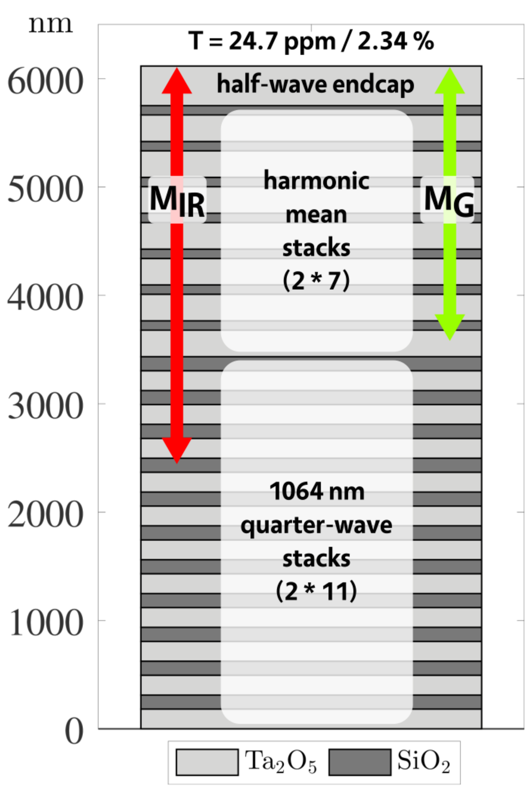
Introduction

ALPS II aims at ALP-photon coupling sensitivity $g_{a\gamma\gamma}$ of $2\cdot10^{-11}$ GeV^{-1} that translates into some 2 photons/day in the experiment design. Aggressive optical resonant gain (~ $2\cdot10^{8}$) is anticipated and a dichroic cavity control scheme is proposed to be in line with the transition edge sensor for photon counting. To ensure stringent cavity resonance required for ALPS II, the mirror coatings are an indispensable subject of study. We present here 1) dedicated coating design, 2) refined dichroic cavity model, and 3) experiment results of a coating test setup.



Dichroic Mirror Coating and Cavity

- Coating temperature dependence optimized
- Manufacture error (random, systematic, chirp) Monte Carlo analysis



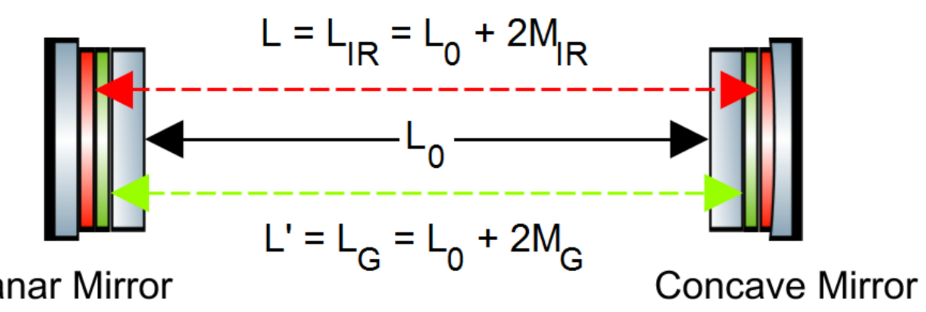
Resonance condition

$$\nu = \frac{c}{2(L_0+M)}\cdot\left(N + 2\cdot\frac{\psi_\Delta}{2\pi}\right)$$

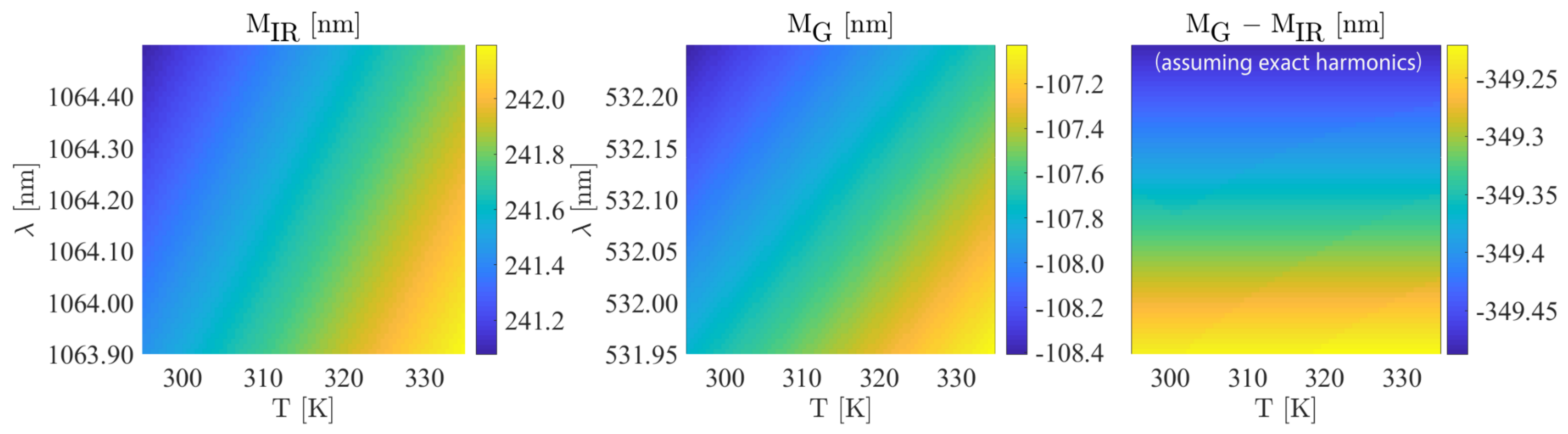
Coating reflection phase

$$M(\lambda, T) = \frac{1}{2}\cdot\frac{\phi_M(\lambda,T)}{2\pi}\cdot\lambda$$

- Penetration depth and cavity resonance



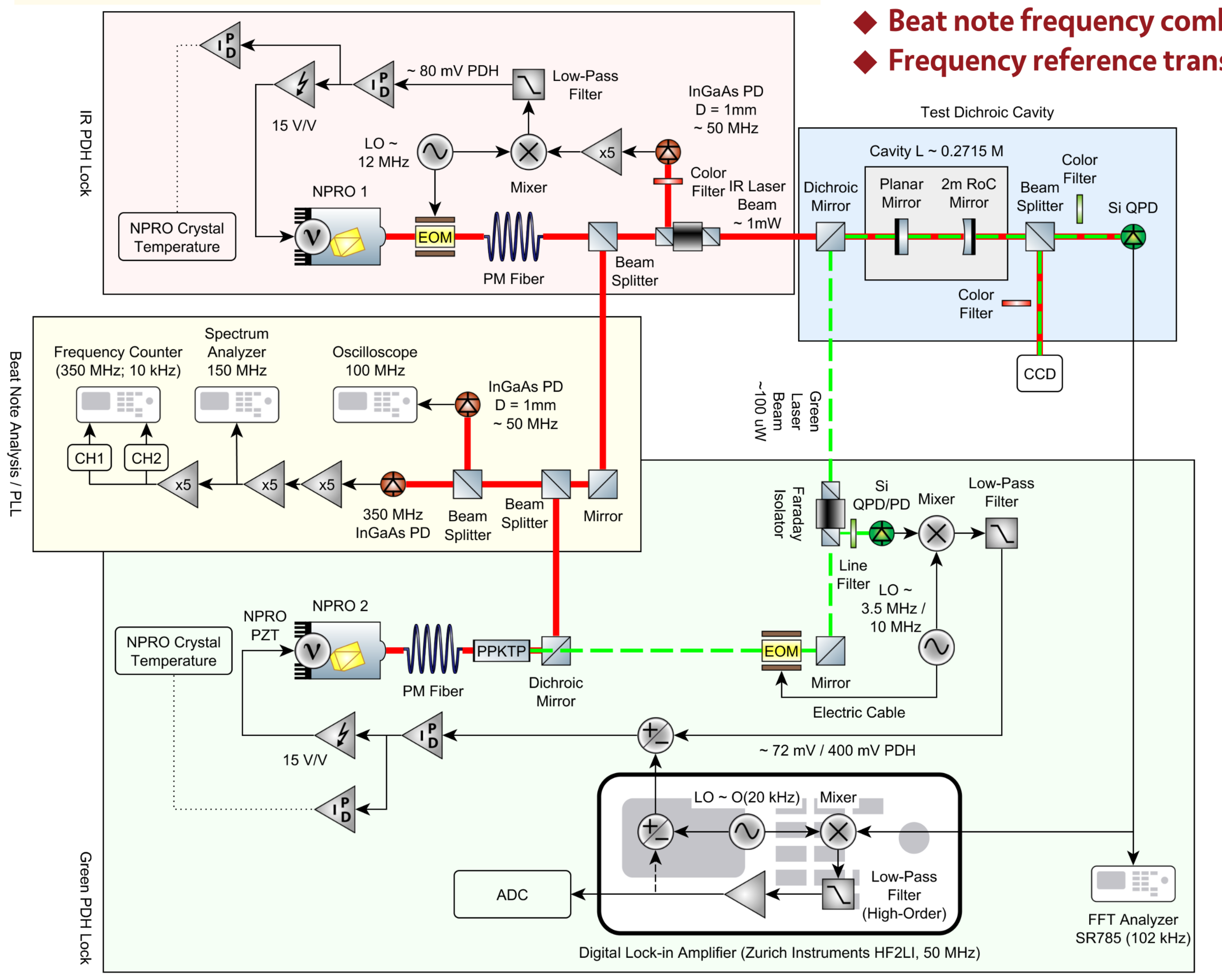
- Test coating temperature and wavelength dependence

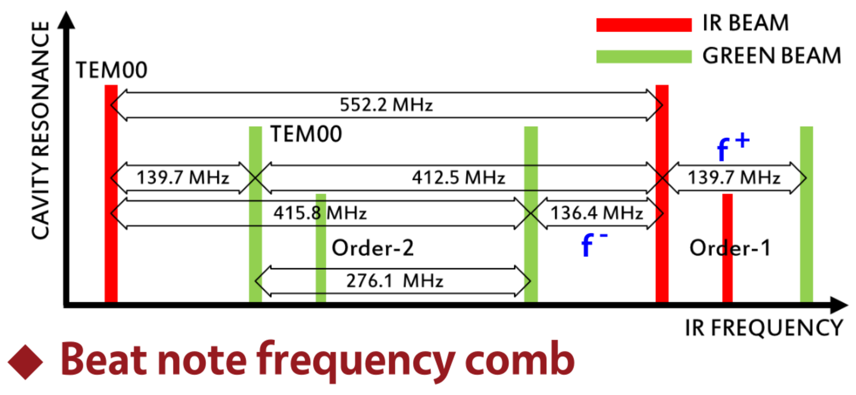


Test Dichroic Cavity Setup, Beat Note Frequency Comb and Temperature Dependence Measurements

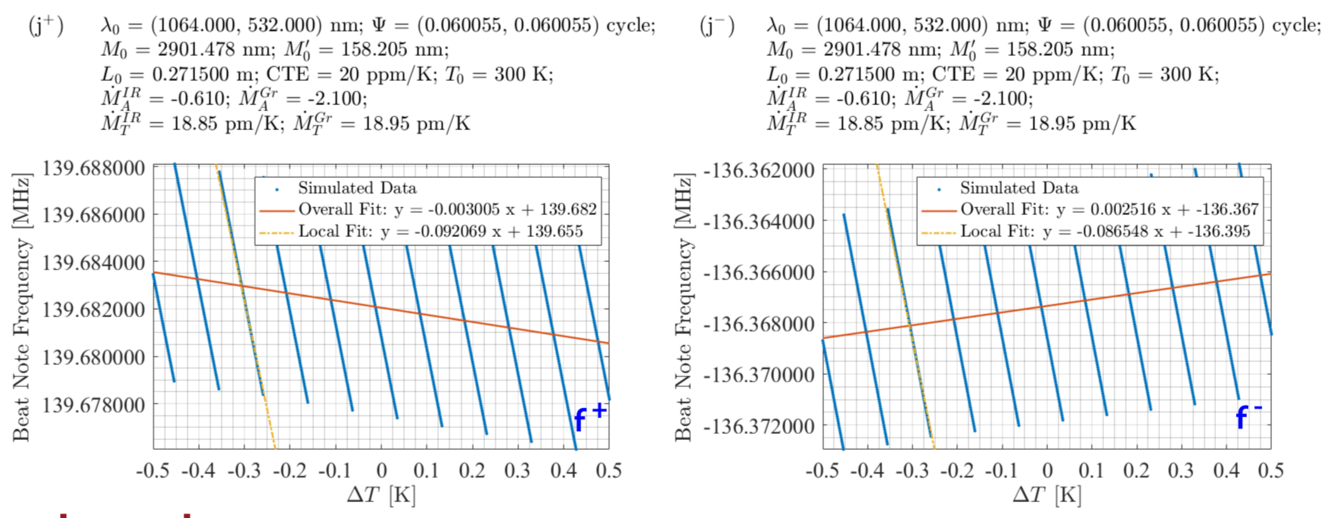
- Plano-concave linear cavity in low-vacuum
- Aluminum spacer with heat foil and temperature sensors
- Pound-Drever-Hall locks in IR and quasi-harmonic green
- IR beat note carries info on cavity dichroic properties:

$$f \equiv \nu' - \nu = \frac{c}{2L'}\cdot\frac{(N'+2\Psi')}{2} - \frac{c}{2L}\cdot(N+2\Psi)$$

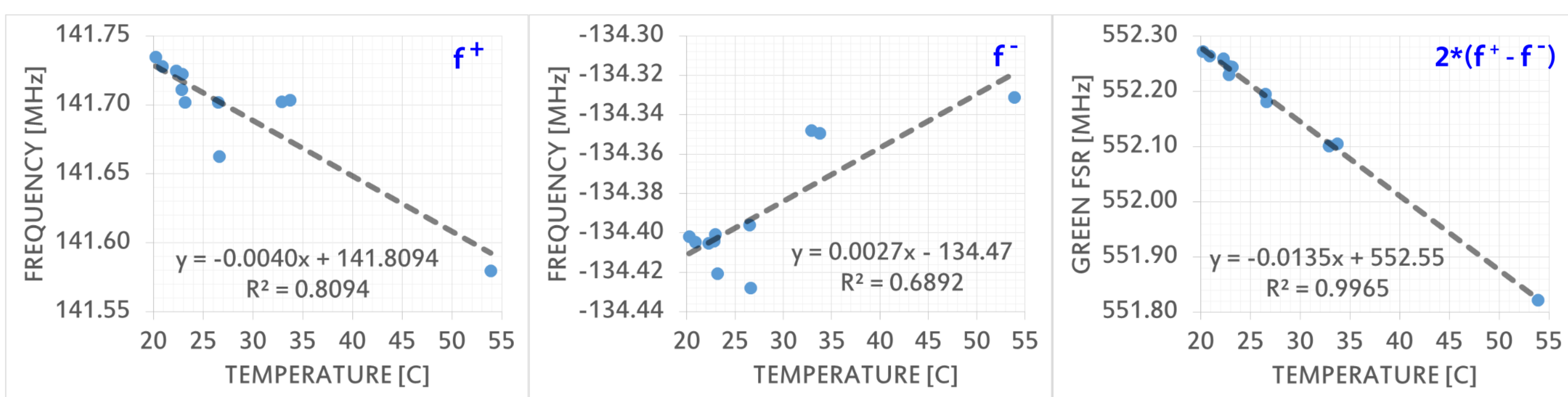




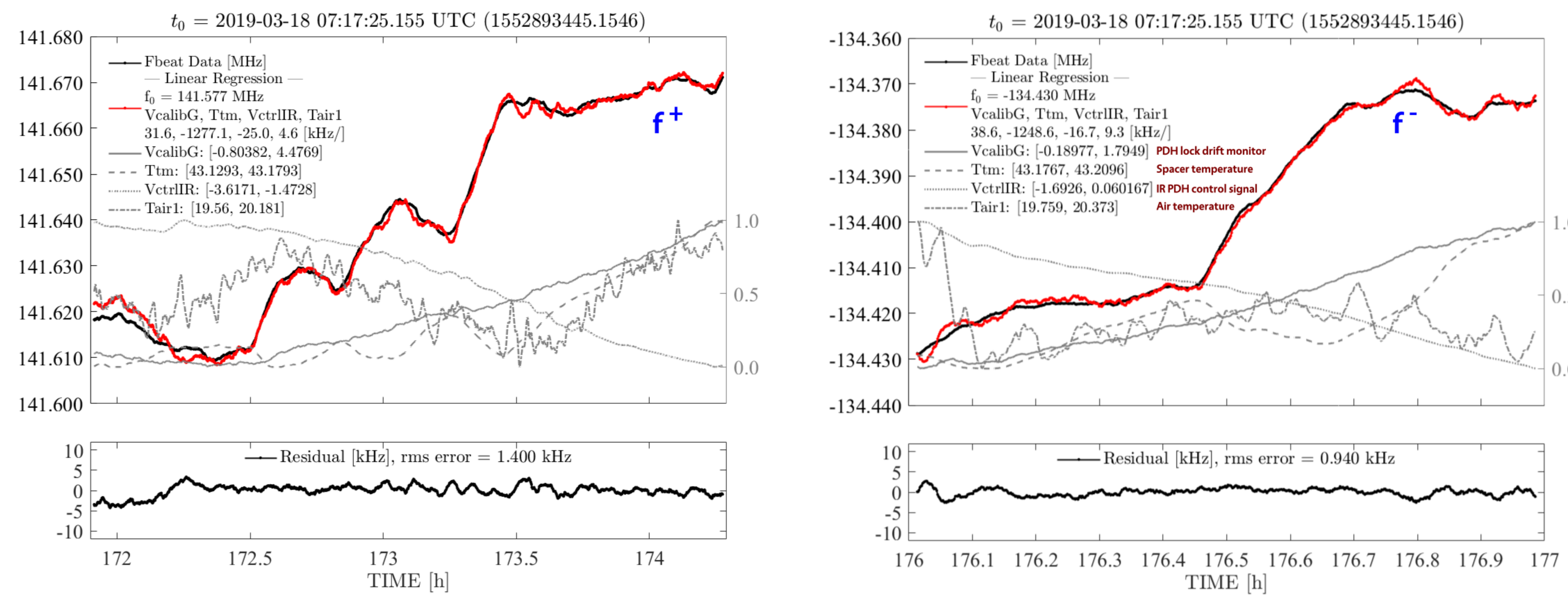
- Beat note frequency comb
- Frequency reference transfer application?
- Numerical simulation on beat note frequency vs. temperature



- Gross temperature dependence

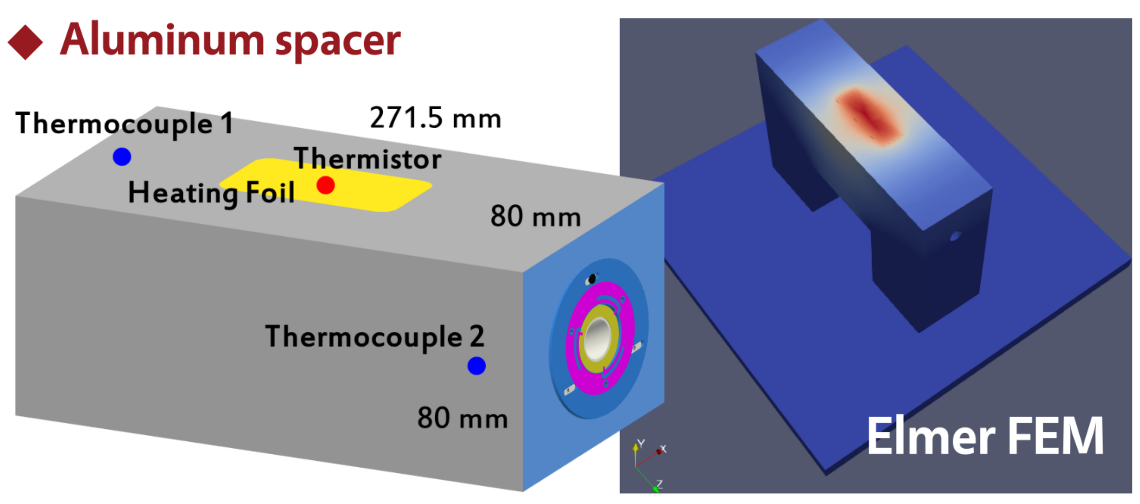


- Fine temperature dependence with linear regression analysis



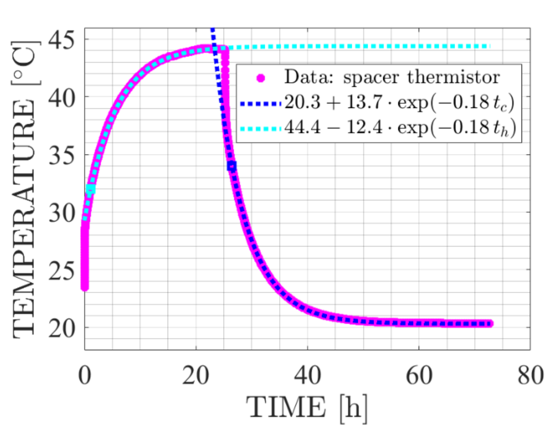
Cavity Thermodynamic Property

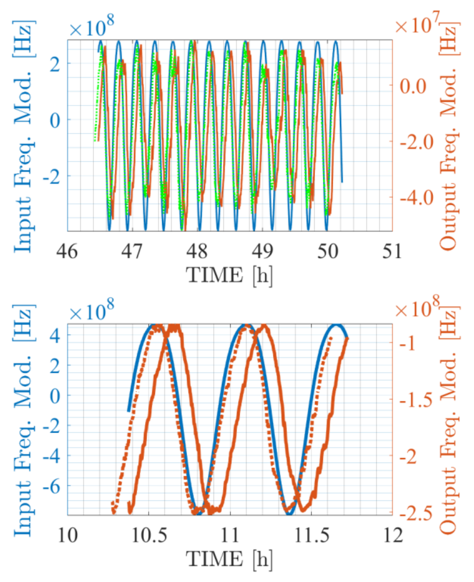
- Aluminum spacer



- Thermal time constant ~ 5.6 h

Phase lag ~ 65°@0.5 mHz, 70°@1 mHz (amplitude transfer ~ 10 %)





Beat Note Frequency Stability

	Differential Penetration Depth	Differential Temperature Dependence	Differential Wavelength Dependence
Couping $(\partial f/\partial T)$	$\frac{c}{2L_0}\left(N-\frac{N'}{2}+\Psi+\frac{\Delta\phi}{2\pi}\right)\cdot\mathrm{CTE}$	$\frac{c}{L_0}\cdot\frac{-\Delta\dot{M}_T}{\lambda^{\mathrm{IR}}}$	$\frac{c}{L_0}\cdot\Delta\dot{M}_\lambda\cdot(-\mathrm{CTE})$
Remark	$L_0(T)$ and $M(T)$ are described separately and therefore do not necessarily scale proportionally with temperature; $f(L(T))$.	Coating reflection phase is temperature dependent and affects f; $f(L(M(T)))$.	$f(L(M(\lambda(L(T)))))$.
Analytical estimate	-2.79 kHz/K for f^+ $+2.73$ kHz/K for f^-	-208 Hz/K	$+19.43$ kHz/K
Numerical simulation	-2.78 kHz/K for f^+ $+2.74$ kHz/K for f^-	-208 Hz/K	$+18.26$ kHz/K

Notable parameters: $L_0 = 0.2715\,\mathrm{m}$, CTE $= +20\,\mathrm{ppm/K}$, $\Delta\dot{M}_T \approx +0.1\,\mathrm{pm/K}$, and $\Delta\dot{M}_\lambda \approx -0.440\,\mathrm{pm/pm}$. Note that there are two mirrors per cavity. The ALPS-II requirement of $\leq 1.775\,\mathrm{pm/K}$ on $|\Delta\dot{M}_T|$ translates to some 1.8 kHz/K in the experiment setup.

- Iterative numerical calculations match well with analysis
- Experiment dominated by wavelength dependence
- Discrepancy between experiment and model hypothesized to temperature gradient (10x) and manufacture error (5x)
- Re-evaluate coating design optimization objectives
- ALPS II requires <1 Hz beat note frequency stability

Conclusions

Experiment is motivated by ALPS II requirements to measure the temperature dependence of a custom specialty coating. Wavelength dependence and penetration depth difference however also play significant roles that may have to be considered in future coating designs.

Beat note frequency for a doubly-resonant dichroic cavity is modelled and explains well the experiment observations. Numerical simulations are set up to aid further experiment designs including ALPS II and JURA (Joint Undertaking in Research on Axion-Like-Particles).

Although preliminary, coating manufacture tolerance is estimated from the experiment results and complies with vendor specifications.

For ALPS II our experiment suggests coating design and cavity length stabilization be considered as a whole.

Bibliography
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Any Light Particle Search - https://alps.desy.de/

15TH PATRAS WORKSHOP ON AXIONS, WIMPS AND WISPS
Albert-Ludwigs-Universität Freiburg, Germany, 3-7 JUNE 2019

ALPS Collaboration Partners

ALBERT EINSTEIN INSTITUTE HANNOVER
Max Planck Institute for Gravitational Physics and Leibniz Universität Hannover