A Laser Heterodyne Polarimeter to Search for VMB with ALPS IIc Hardware

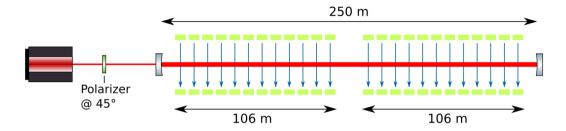
Harold Hollis

Dark Cosmos Group

Feburary 8, 2021



ALPS IIc hardware for VMB experiment



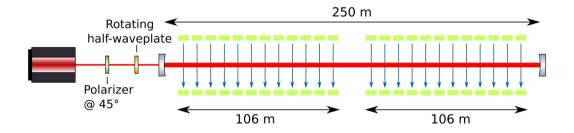
For incident light polarized linearly at 45° to \vec{B} :

- 212 m HERA dipole string: $\psi_1 \approx 6.9 \times 10^{-14} \, \mathrm{rad}$
- Cavity multiplier: $G_{\rm cav} \approx 8 \times 10^4$
- $\psi_N = G_{\text{cav}} \cdot \psi_1 \approx 8 \times 10^4 \cdot \psi_1 \approx 5.5 \,\text{nrad}$
- How to sense this?

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Make ψ Time Dependent

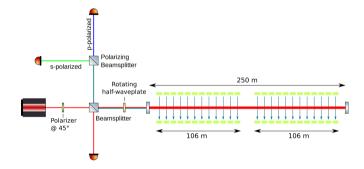


• Insert rotating half waveplate to rotate incident polarization through angle $\theta(t)$

• Now
$$\psi_N(\theta) = \psi_N \sin(2\theta)$$
 where $\theta(t) = 2\omega_\pi \cdot t$

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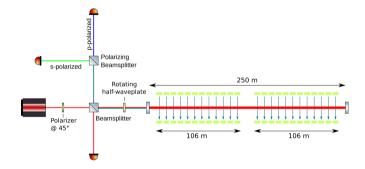
Split Reflected Light's Polarization Components



- Light reflects from the cavity back through the rotating half-waveplate.
- This 'de-rotates' the rotation given by the forward pass through.

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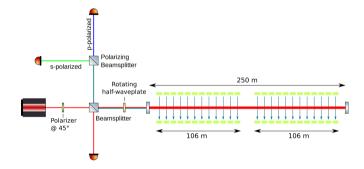
Split Reflected Light's Polarization Components



- Reflected light from the beamsplitter is split into the s-pol and p-pol components.
- $\bullet\,$ Relative phase of these components varies with angular frequency $4\cdot\omega_\pi$

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Split Reflected Light's Polarization Components

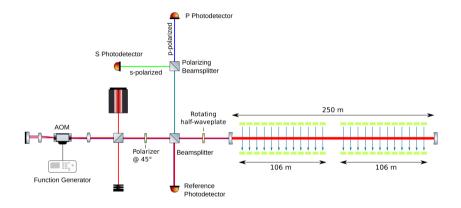


- Amplitude of relative phase variation is $4 \cdot \psi_N$.
- Use laser heterodyne method to read out this phase variation.

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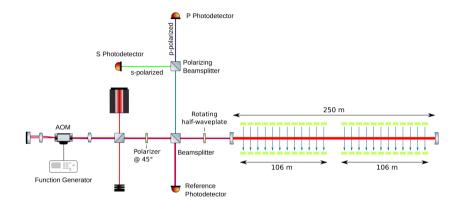
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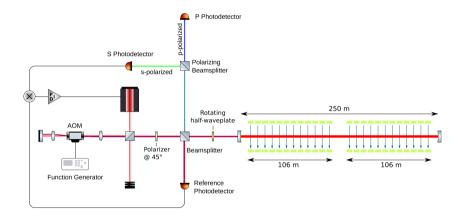
- Double-pass AOM produces two overlapped fields with fixed frequency offset Ω .
- Frequency offset field is non-resonant in cavity.

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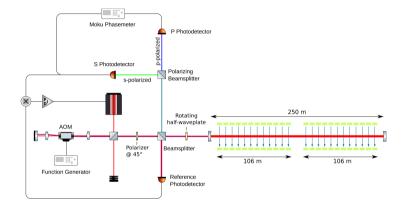
- The frequency offset fields produce a beatnote on the photodetectors.
- Beatnotes from Reference and S photodectors used to lock laser to cavity.

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- The laser is locked to keep the s-polarized component (before rotation) resonant.
- The p-polarized component is alternately above and below resonance.

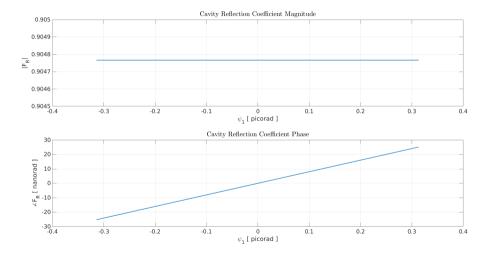
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- Phase of p beat signal is compared to phase of s beat signal with a phasemeter.
- The amplitude of the time varying phase difference is proportional ψ_N .

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Output of P Photodetector is proportional to (ignoring noise)

$$E_{LO}e^{i(\omega+\Omega)t} + F_r(\delta)E_Me^{i\omega t}|^2 =$$

$$E_{LO}^2 + |F_r(\delta)|^2 E_M^2$$

$$+ 2E_{LO}|F_r(\delta)|E_M\cos(\Omega t + \angle F_r(\delta))$$

where $\delta=4\psi_1$ is the round-trip differential phase shift and

$$\angle F_r(\delta) = 4\psi_N \cdot \cos(4\omega_\pi \cdot t + \phi)$$

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- Ideally, the cavity's resonance frequencies are independent of polarization.
- The resonance condition

$$\nu_m = \frac{c}{2L_C} \left(m + \frac{\phi_G - \phi_m}{\pi} \right) \tag{1}$$

includes the reflection phase of the cavity mirrors (assumed identical here).

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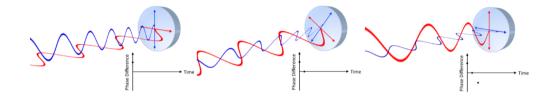


Image Credit: Baum, Clair (2016)

- But the cavity mirror's reflection phase ϕ_m does depend on polarization.
- This 'mirror birefringence' is roughly 6 orders of magnitude greater than VMB
- How to separate VMB from mirror birefringence?

• Modulate the magnet current such that the magnetic field strength is, e.g.,

$$B = 5.3 \operatorname{T} \cdot (1 + 0.01 \cos(\omega_m \cdot t))$$

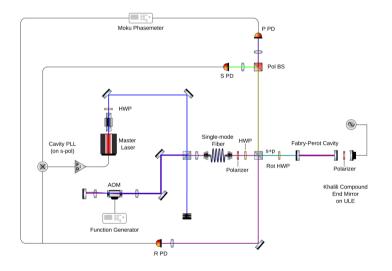
• then the maximum ellipticity is of the form

$$\psi_N \approx 5.5 \,\mathrm{nrad} + 110 \,\mathrm{prad} \cdot \cos(\omega_m \cdot t)$$

resulting in phase modulation sidebands at $4\omega_{\pi} \pm \omega_{m}$ with amplitude $220 \, \mathrm{prad}$

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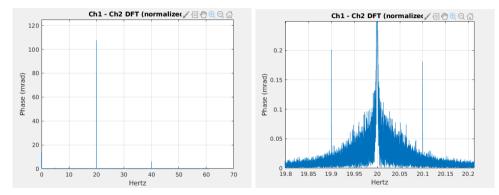
UF Tabletop Cavity Birefringence Testbed



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Harold Hollis A Laser Heterodyne Polarimeter to Search for VMB 16 / 24

100 mHz Khalili modulation



- Continue Development of Tabletop Experiment
- Study Use of Light in Transmission
- Schedule

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Schedule

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4 v2.1	235 days	Mon 2/8/21	Fri 12/31/21	1		
Design	60 days	Mon 2/8/21	Fri 4/30/21			
 Procurement 	30 days	Mon 5/3/21	Fri 6/11/21	ř – 1		
Optics	30 days	Mon 5/3/21	Fri 6/11/21			
Vacuum	30 days	Mon 5/3/21	Fri 6/11/21	Development	Schodulo	
Electrical	20 days	Mon 5/3/21	Fri 5/28/21	Development	Schedule	
Mechanical	30 days	Mon 5/3/21	Fri 6/11/21		-	
Build	10 days	Mono/14/21	Fri 6/25/21	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	l Start	Finish
Comissioning	20 days	Mon / d D			Start	
Data Runs	115 days	Mon 7/26/21	Fri 12/31/21			
4 v2.2	376 days 60 days	M-1/26/23	1/2/23	Experiment v2.1	Feb 2021	Dec 2021
Design	50 days	Mont / AL	netop	Experiment v2.1		Dec 2021
Optics	30 days	Mon 10/18/21	Fri 11/26/21			
Vacuum		Par	ber v2	1	Jan 2022	May 2022
Electrical		Mon 10/18/21	Fri 11/26/21	· -		101ay 2022
Mechanical		Mon 10/18/21	Fri 11/26/21			
Build		Mon 1/2	pletop	Experiment v2.2	Aug 2021	Dec 2022
Comissioning	20 days	Mon 2/14/22	Fri 3/11/22		1.00 -0	200 2022
Data Runs	211 days	Man 314/22	Mpp 1/2/23	2	1am 2022	May 2022
4 Paper v2.1	80 days	Men 1/3	ber v2	. ∠	Jan 2023	May 2023
Initial Draft	30 days	Mon 1/3/22			-	3
Review	10 days	Men 2/14/22	പിലിക	sign Doc	Jan 2023	July 2023
Submit/Revise/ Publish	40 days	Man 2/38,22		igii Duc		July 2025
4 Paper v2.2	40 days	Tu 1/8/23	Mon 2/27/23			
Initial Draft	30 days		curem	ient	July 2023	July 2024
Review	10 days	Tue 1/3/23	Mon 1/16/23		J	- J
Submit/Revise/ Publish	40 days	Tue 1/3/23	Mon 2/27/23			
 Final Design 	128 days	Tue 1/3/23	Thu 6/29/23			+
Initial Design Document	30 days	Tue 1/3/23	Mon 2/13/23			
Final Design Document	98 days	Tue 2/14/23	Thu 6/29/23			
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Backup Slides

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For r_1 , r_2 real, the cavity reflection coefficient is given by:

$$F_r(\phi) = \frac{r_1 - r_2 e^{i\phi}}{1 - r_1 r_2 e^{i\phi}} = \frac{(r_1 - r_2 \cos \phi - ir_2 \sin \phi) (1 - r_1 r_2 \cos \phi + ir_1 r_2 \sin \phi)}{|1 - r_1 r_2 e^{i\phi}|^2}$$

where ϕ is the round-trip accumulated propagation phase. For ϕ small enough, the numerator is approximately

$$(r_1 - r_2 - ir_2\phi)(1 - r_1r_2 + ir_1r_2\phi)$$

Grouping real and imaginary parts, the numerator becomes

$$(r_1 - r_2) (1 - r_1 r_2) + r_1 (r_2 \phi)^2 - i (1 - r_1^2) r_2 \phi$$

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For $r_2 = 1$, the numerator is

$$(r_1 - 1)(1 - r_1) + r_1(\phi)^2 - i(1 - r_1^2)\phi = r_1\phi^2 - (1 - r_1)^2 - i(1 - r_1^2)\phi$$

and phase of the reflection coefficient is then approximately

$$\angle F_r \approx \tan^{-1}\left(\frac{1-r_1^2}{(1-r_1)^2}\phi\right) = \tan^{-1}\left(\frac{1+r_1}{1-r_1}\phi\right)$$

For $\frac{1+r_1}{1-r_1}\phi$ small enough, the phase of the reflection coefficient is approximately

$$\angle F_r \approx \frac{1+r_1}{1-r_1}\phi \approx \frac{2\sqrt{r_1}}{1-r_1}\phi = \frac{2\mathcal{F}}{\pi}\phi$$

where we have used $2\sqrt{r_1}\approx 1+r_1$ for $(1-r_1)$ small

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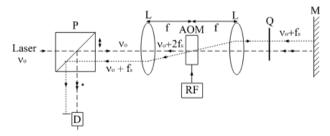
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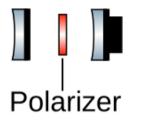
Fig. 2. Experimental setup: P, polarizing cube beam splitter; D, detector; L, lens; f, focal length; M, mirror; Q, 1/4 wave plate; and f_s , frequency of the acoustic wave. Laser beams with frequencies v_0 and $v_0 + 2f_s$ are collinear and overlap on the detector.



thorizontally polarized light
 vertically polarized light

Khalili Compound End Mirror

• Signal injection: How to introduce controlled, small cavity BF?



- A Khalili compound end mirror for variable reflection phase ϕ
- Originally proposed to reduce coating thermal noise in LIGO
- Displace final end mirror by (small) $\Delta l \rightarrow \Delta \phi \propto \Delta l$
- $\Delta \phi$ equivalent to changing cavity optical length
- Add polarizer between mirrors gives polarization dependent changes in optical length