Linewidth-Broadened Fabry-Perot Cavities for Future Gravitational Wave Detectors

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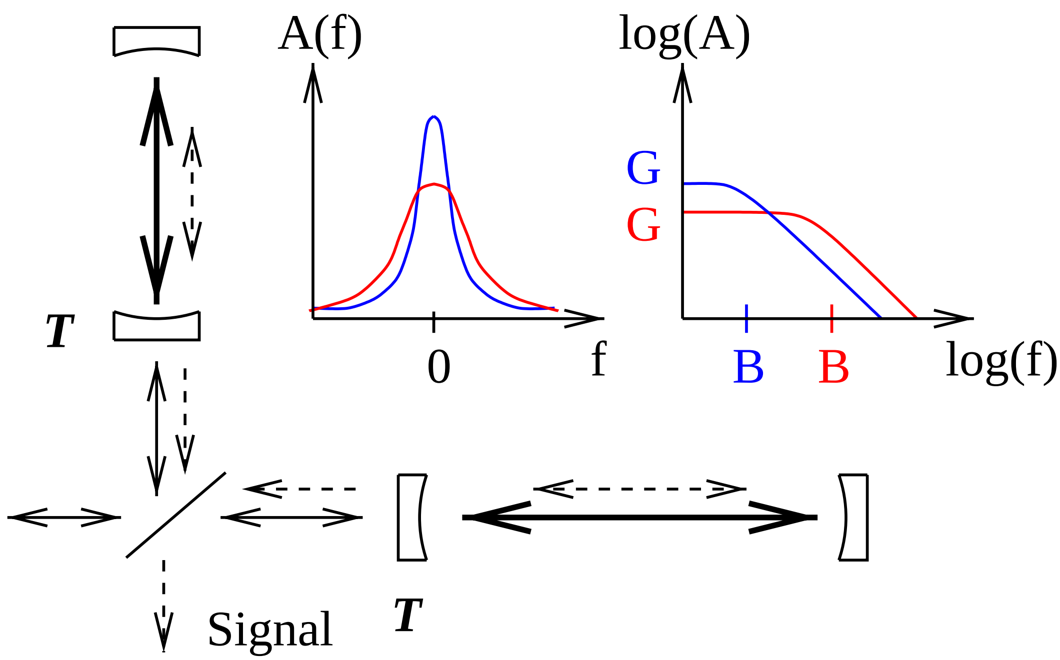
THE PROBLEM

LIGO I:



Bandwidth limited by Gain:

($T =$ Intensity Transmittance)

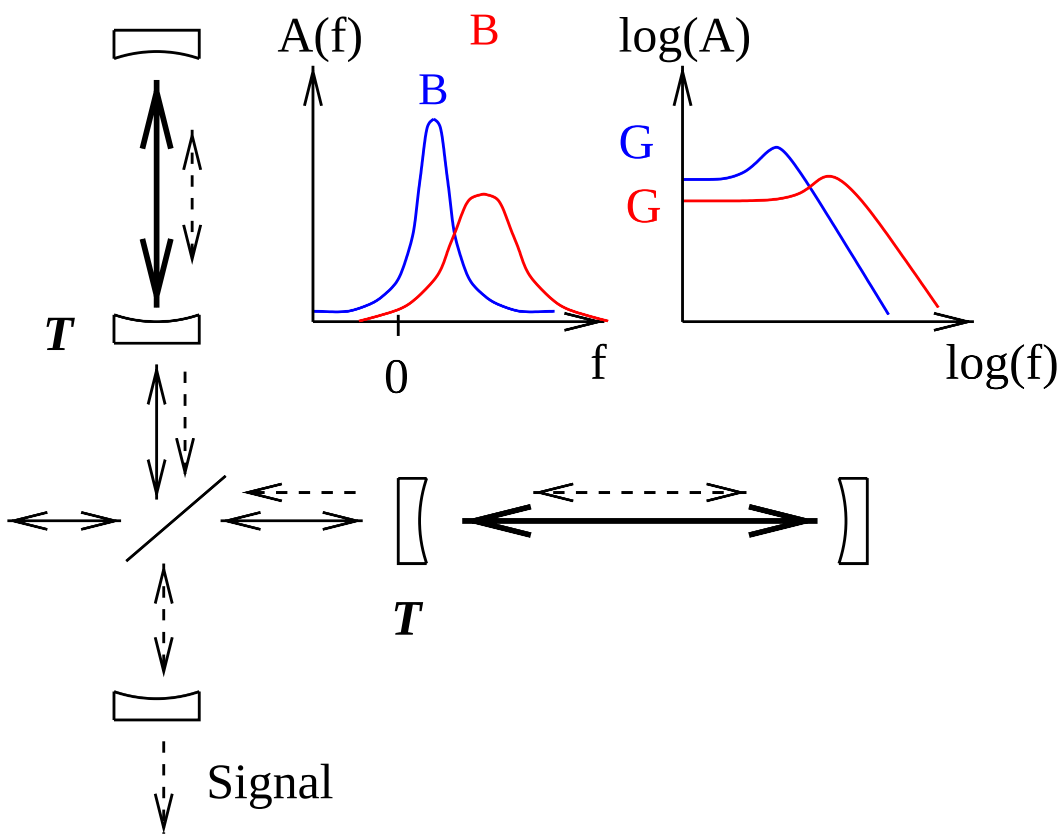
$$B \propto T \qquad G \propto 1/T$$

$$\Rightarrow$$

Reason for Power Recycling
(and Signal Recycling in Adv. LIGO)

The Problem

Advanced LIGO:

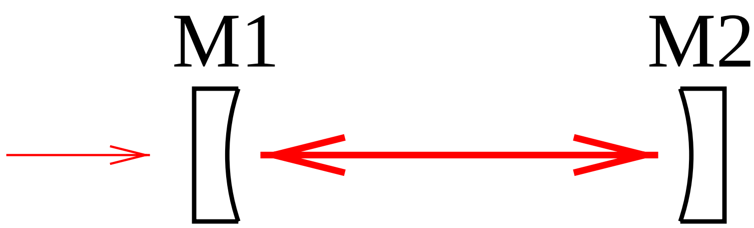


Bandwidth still limited by Gain:

$$B \propto T \qquad G \propto 1/T$$

THE PROBLEM

Simple Cavity:



$$E_{cav} = \frac{t_1}{1 - r_1 r_2 e^{i2\phi_{1W}}} E_{in}$$

ϕ_{1W} : **one-way phase shift** $= \dfrac{2\pi L}{\lambda}$

Bandwidth: $FWHM \approx \frac{FSR}{F}$ **and**

$F = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2} \approx \frac{\pi}{T} \Rightarrow FWHM \propto T$

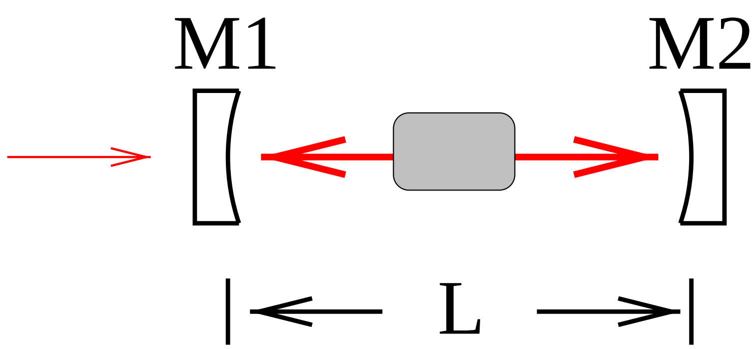
Gain:

$$G = \frac{T}{1 + R^2 - 2R\cos(2\phi_{1W})} \propto \frac{1}{T}$$

on resonance

The Idea

Modify Optical Path length:



If $$\frac{\partial\phi_{1W}(\lambda)}{\partial\lambda} = 0$$

the cavity would be resonant for all frequencies

a 'White-light' cavity

Gain $\propto 1/T$ **unlimited Bandwidth !**

THE QUESTION

Is it possible to have

$$\frac{\partial \phi_{1W}}{\partial \lambda} = 0$$

over a reasonable frequency range (± 10 kHz) ?

How ?

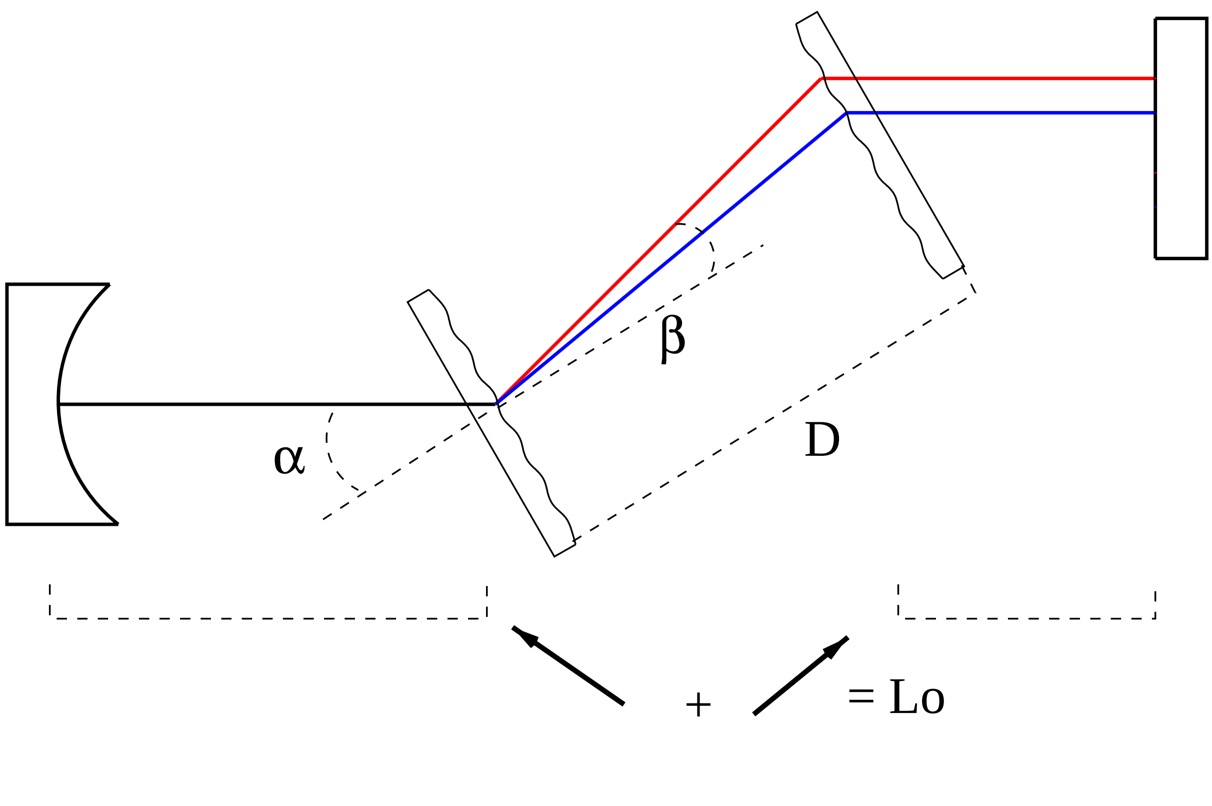
1. **Dispersion in special atomic resonances** [a]
2. **Angular dispersion in gratings or prisms**
3. **Mirror coatings**
4. **Triangular Cavities** [b]
5. **etc.**

[a] A. Wicht et al. Opt. Comm. 179 (2000) p. 107-115

[b] G. Mueller at UF email:mueller@phys.ufl.edu

The Concept

Cavity with Grating Compressor:



$$L(\lambda) = Lo + \frac{D(1+\sin(\alpha)\sin(\beta(\lambda)))}{\cos(\beta(\lambda))}$$

The Concept

White light condition:

$$\frac{\partial \Phi}{\partial \lambda} = \frac{\partial}{\partial \lambda}\left(\frac{2\pi L(\lambda)}{\lambda}\right) \Rightarrow \frac{L(\lambda)}{\lambda} = \frac{\partial L(\lambda)}{\partial \lambda}$$

or

$$\frac{\partial L}{\partial \lambda} \equiv \frac{\partial L}{\partial \beta}\frac{\partial \beta}{\partial \lambda} = \frac{L(\lambda)}{\lambda}$$

Determines the necessary $\frac{\partial \beta}{\partial \lambda}$
Defined as well by the grating equation:

$$\sin(\alpha) + \sin(\beta) = \frac{m\lambda}{d}$$

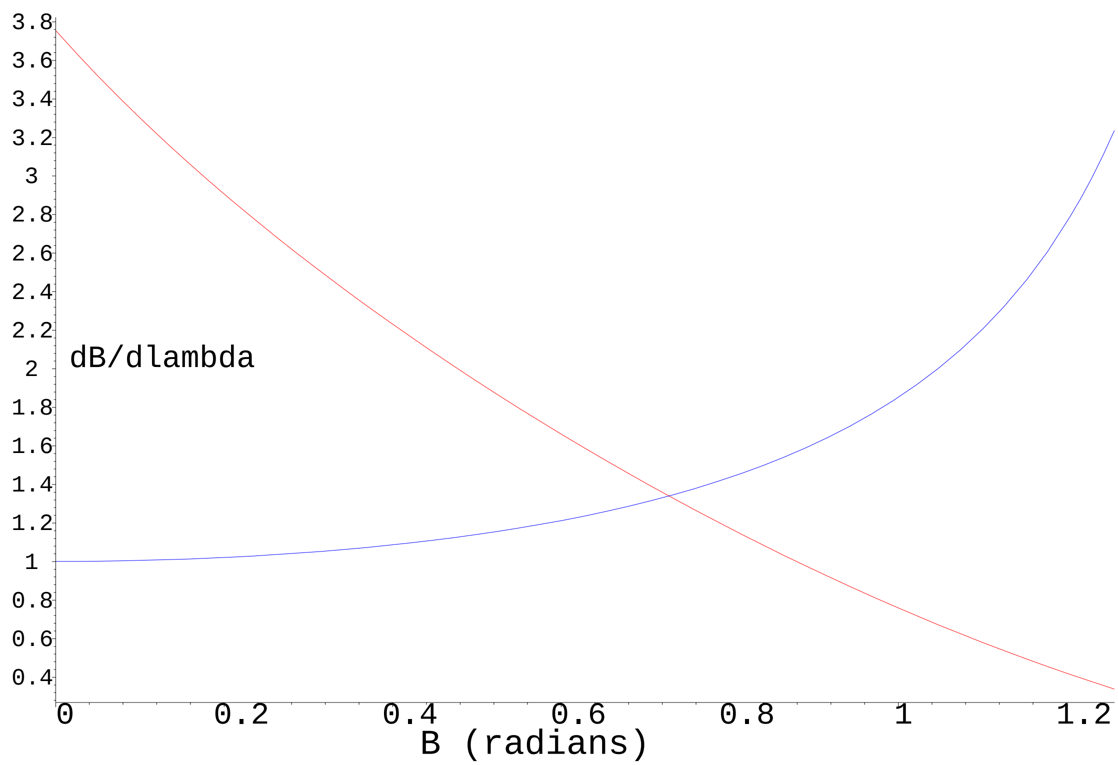
where m is order and, d is groove spacing

$$\frac{\partial \beta}{\partial \lambda} = \frac{m}{d \cos \beta}$$

The Concept

Compare required $\frac{\partial\beta}{\partial\lambda}$ with grating dispersion $\frac{\partial\beta}{\partial\lambda}$

Comparison of Chromatic Flare

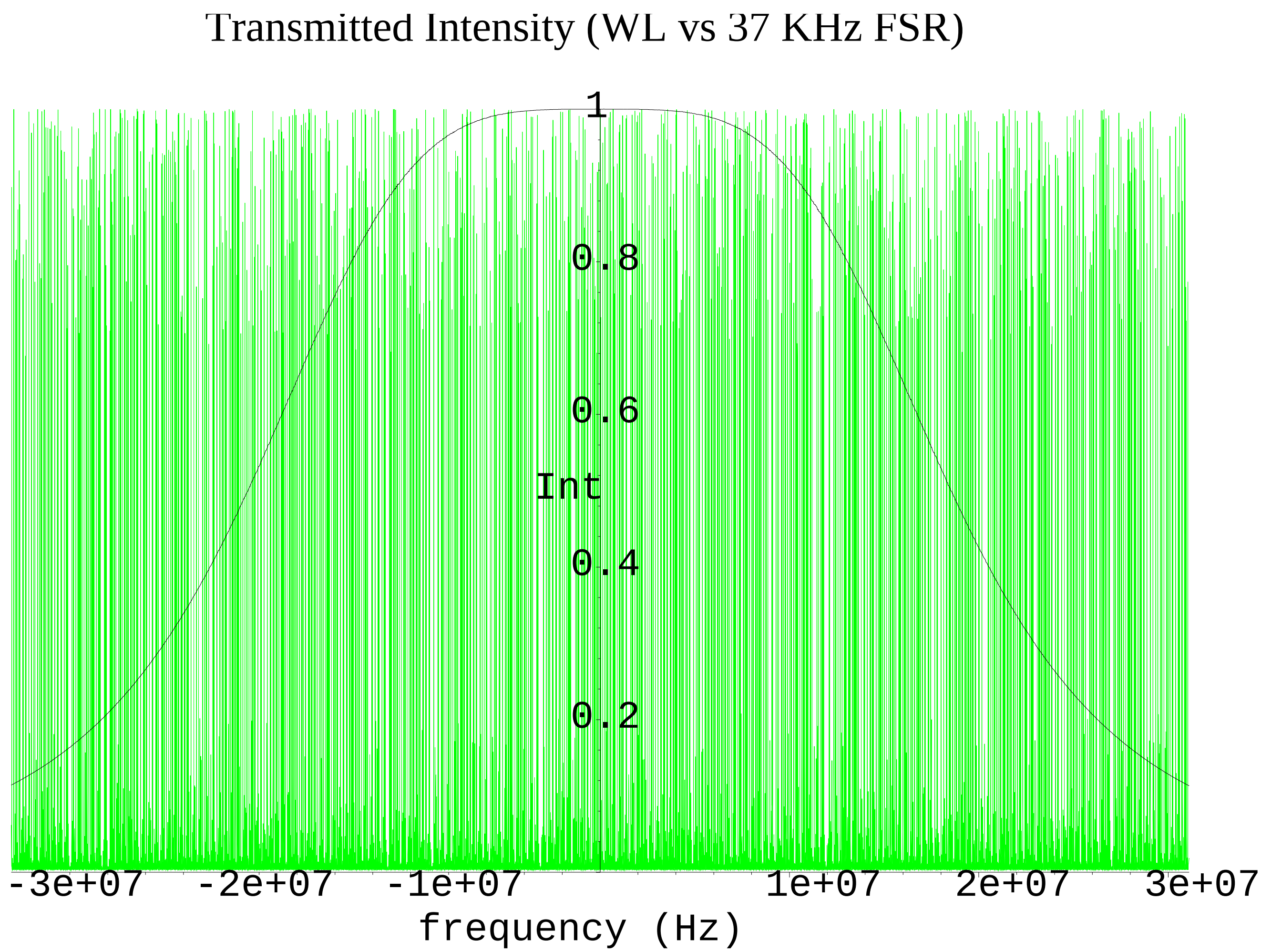


In vicinity of intercept, $\frac{\partial\Phi}{\partial\lambda} \approx 0$

Question: Can it beat the standard cavity bandwidth?

THE CONCEPT

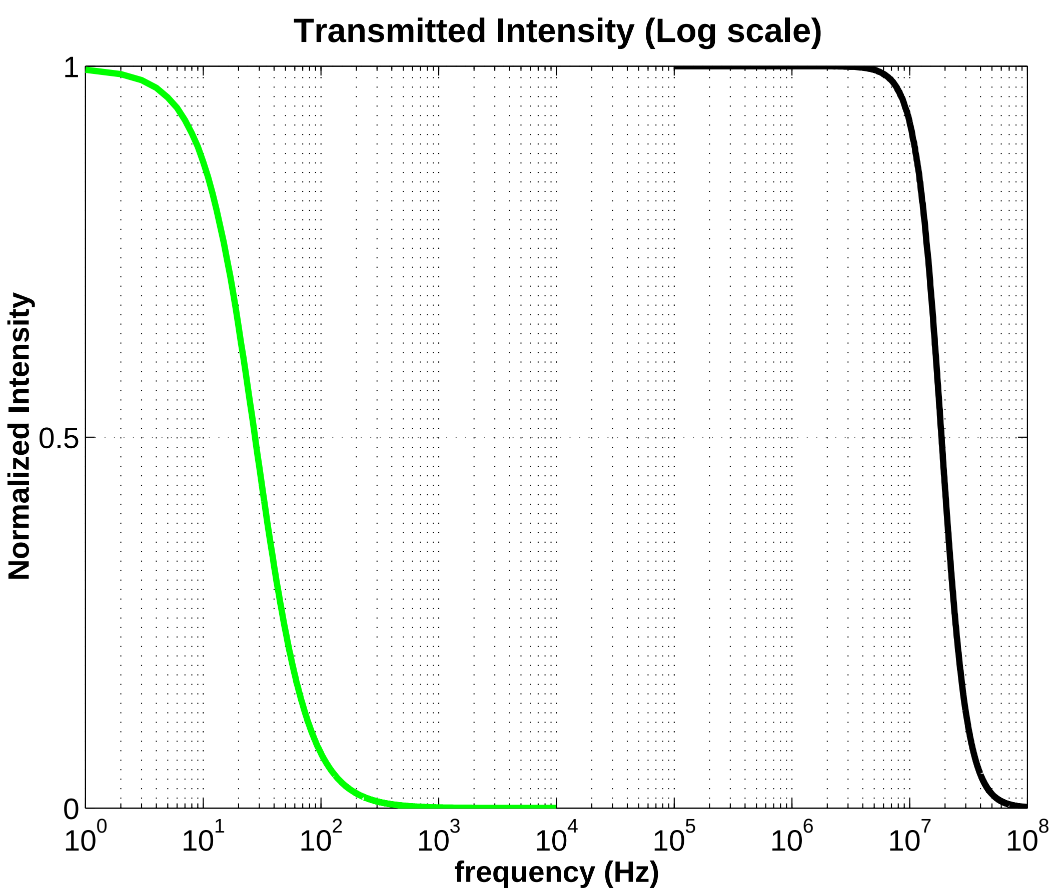
Answer: Yes and how!



With $Lo = 3990$ **m,** $D = 30$ **m,**
$\alpha = 45^\circ$**,** $\beta_0 = 46^\circ$**,** $\lambda_0 = 1064$ **nm,** $T = 0.5\%$

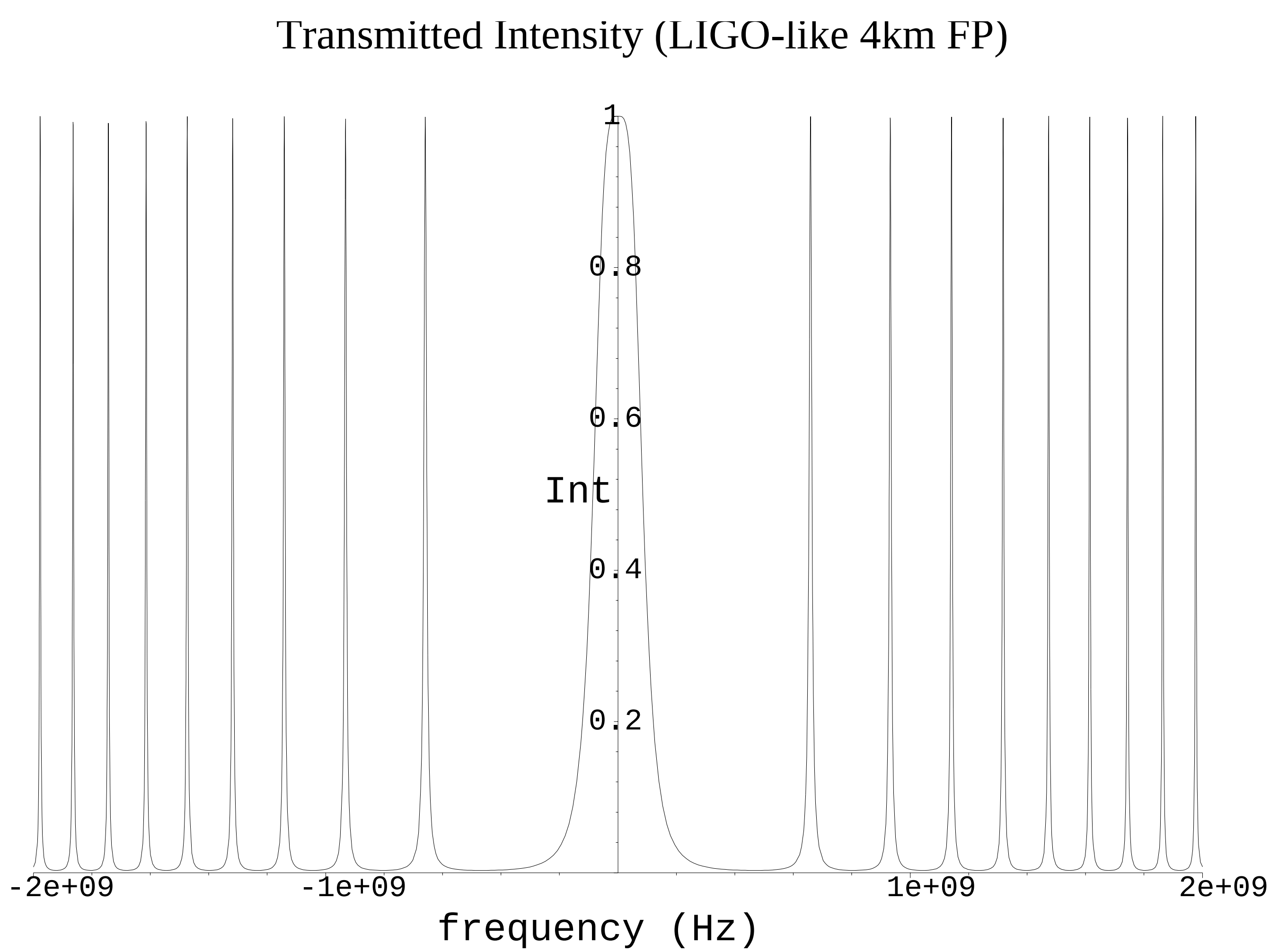
the FWHM of the resonance increases from 60 Hz to 36 MHz.

Another view



$$T = 0.5\%$$

And another view

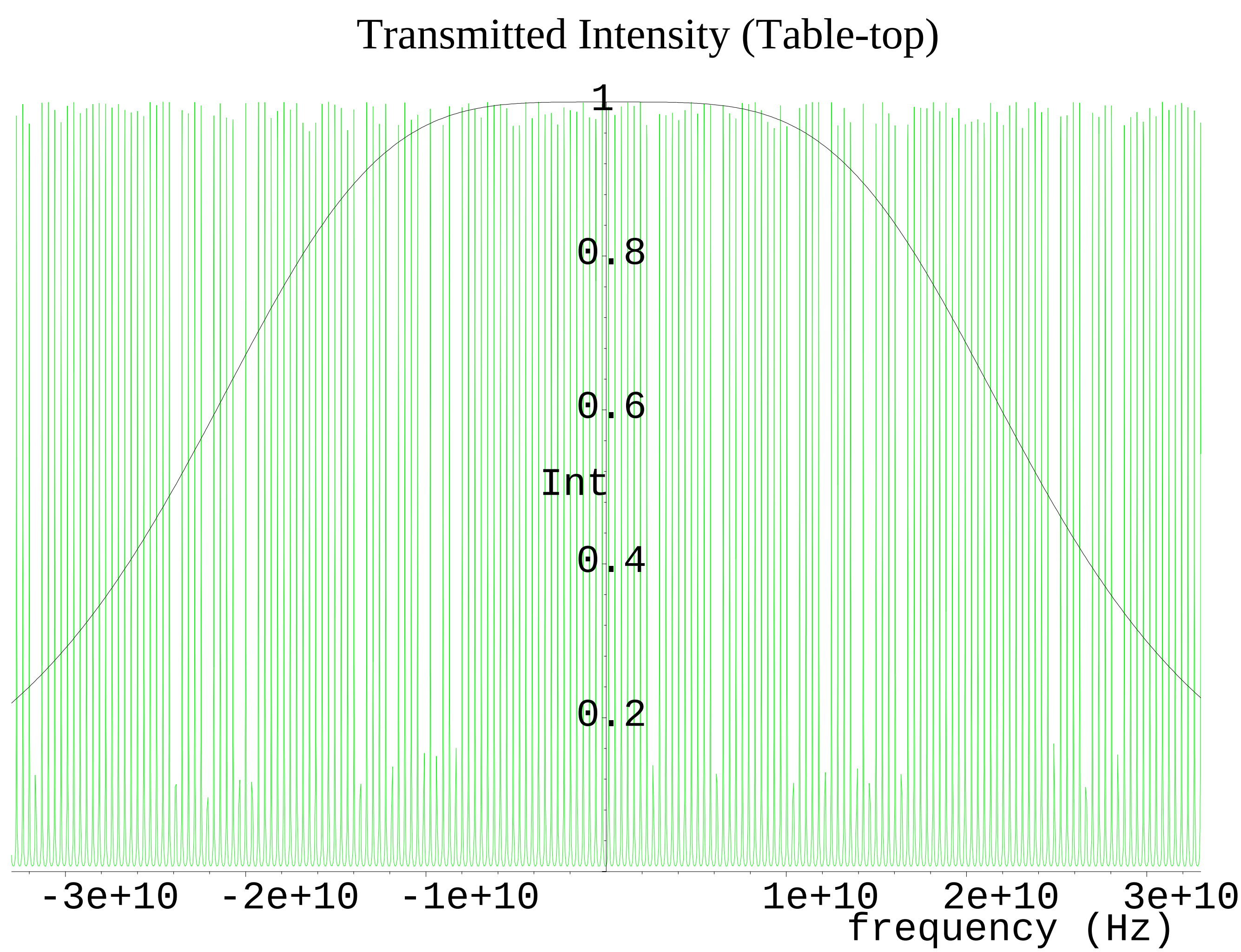


$$T = 10\%$$

THE PLAN

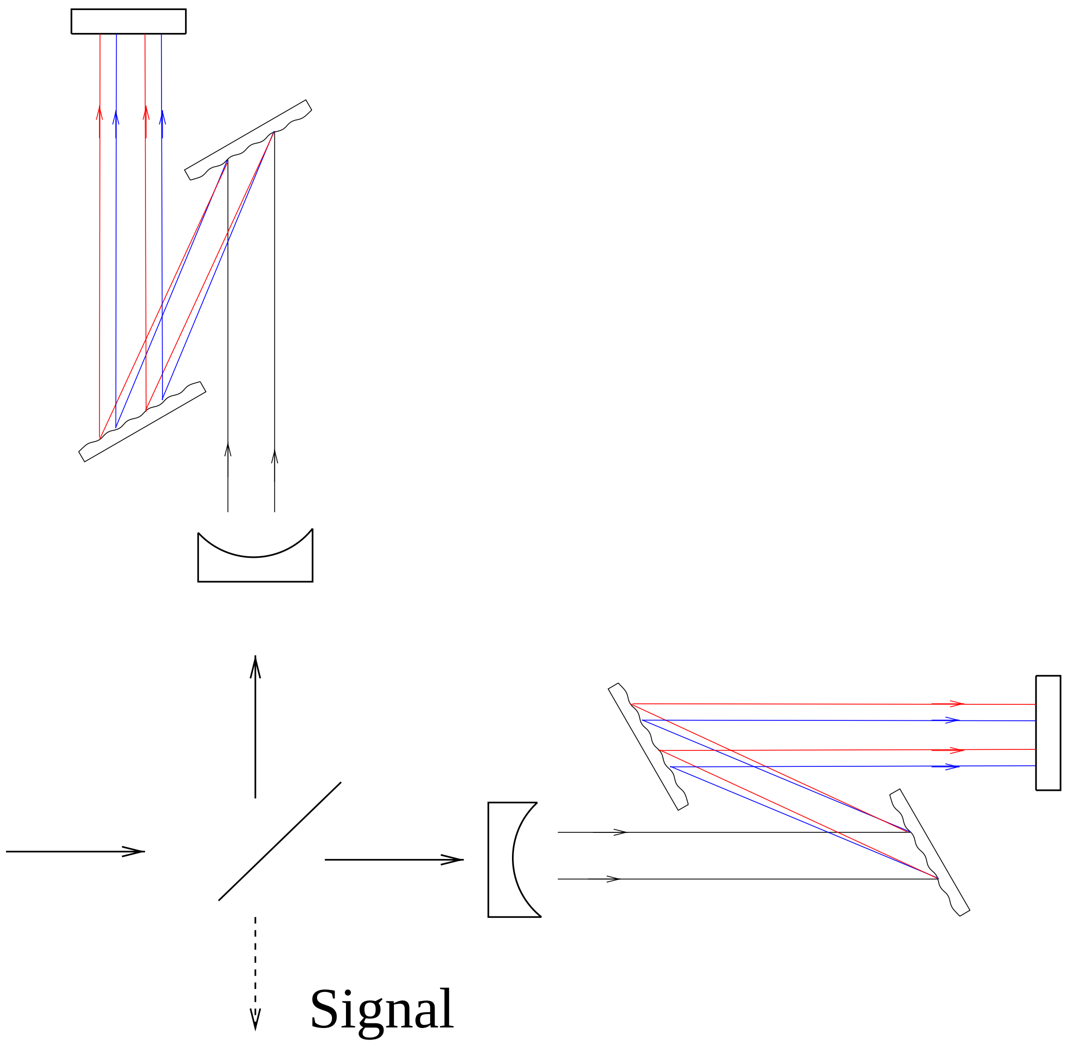
A table-top scale proof of principle

Step 1: Single white-light cavity



With $Lo = 23$ **cm,** $D = 10$ **cm,**
$\alpha = 41^\circ$**,** $\beta_0 = 41^\circ$**,** $\lambda_0 = 1064$ **nm,** $T = 10\%$
Resonance has FWHM of 100 GHz (vs 20 MHz)

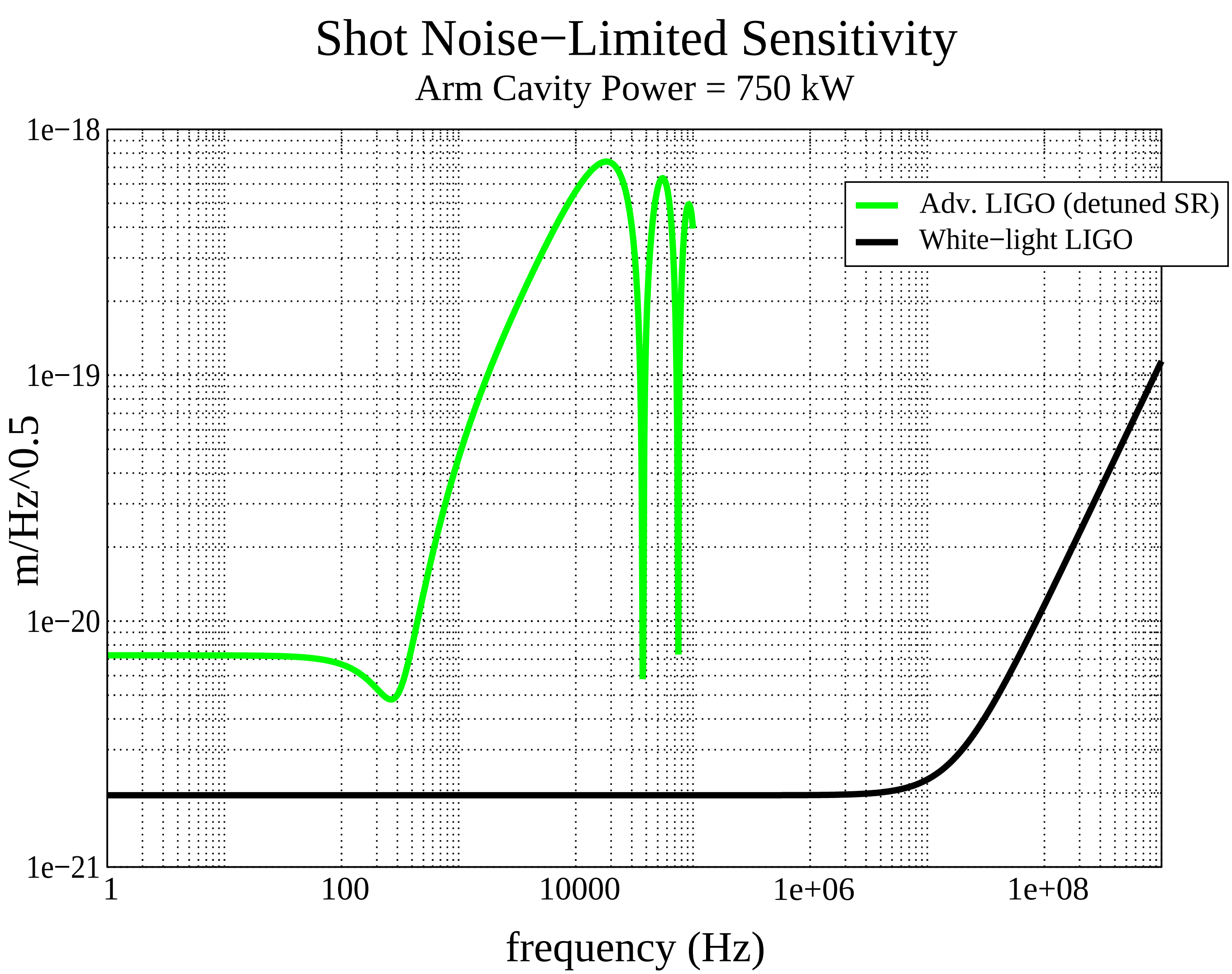
Step 2: Full Michelson interferometer with two white light cavities



Study performance
Study losses in gratings

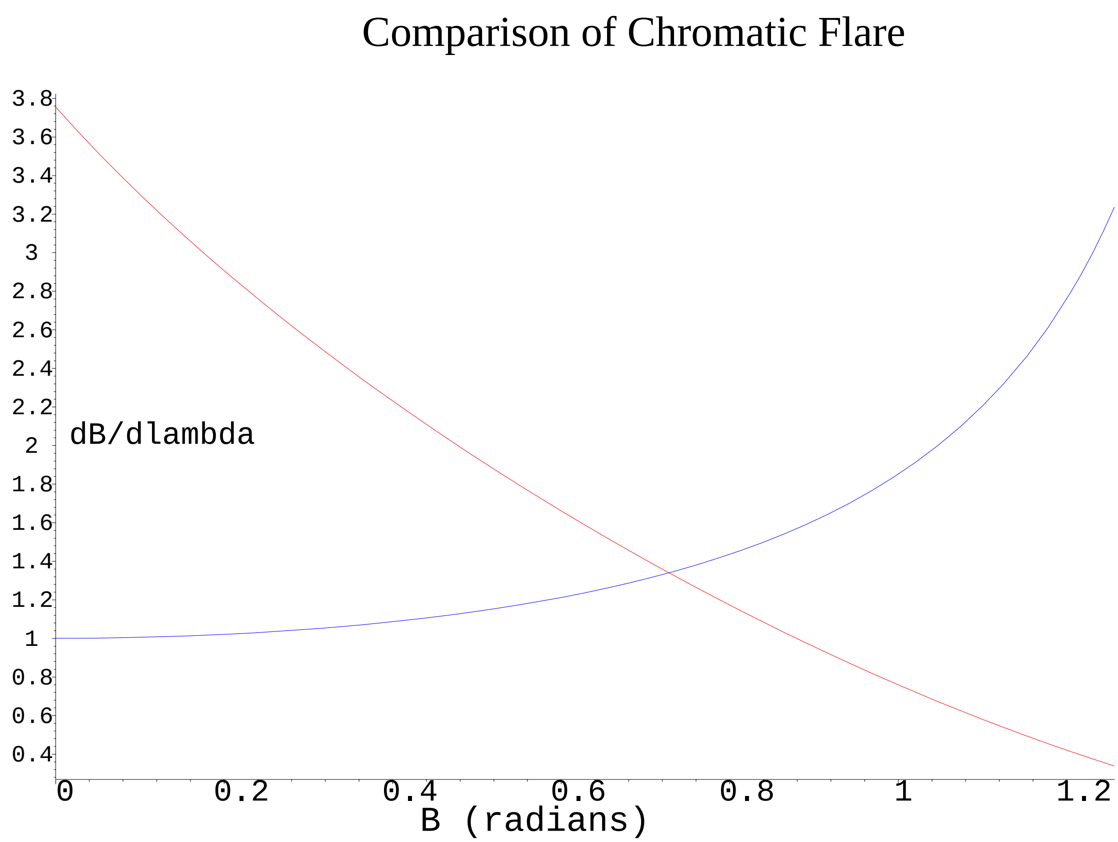
The Plan

Comparison of sensitivities for full IFO



The Concept

Compare required $\frac{\partial\beta}{\partial\lambda}$ with grating dispersion $\frac{\partial\beta}{\partial\lambda}$



In vicinity of intercept, $\frac{\partial\Phi}{\partial\lambda} \approx 0$

Question: Can it beat the standard cavity bandwidth?

THE PLAN

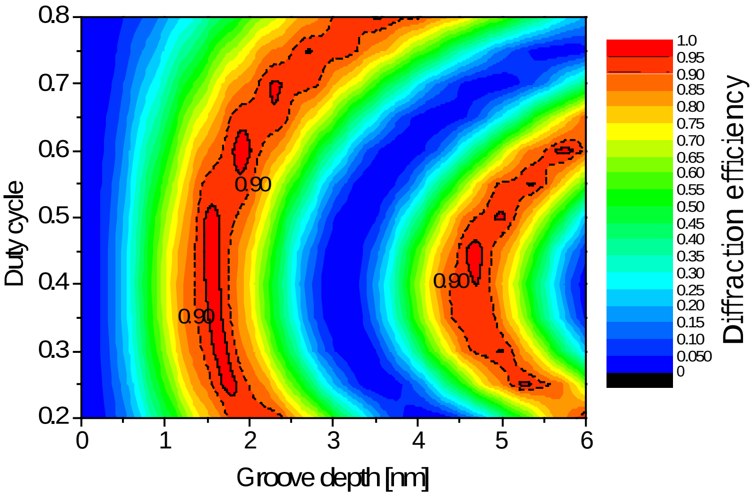
Further investigation needed:

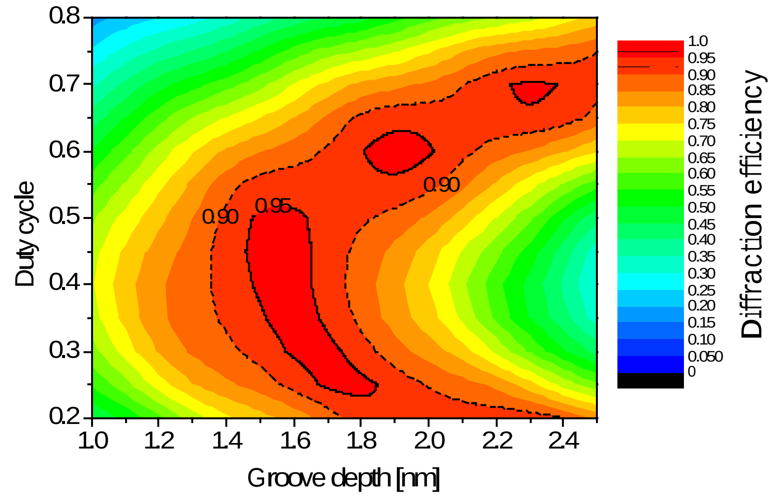
1. **Diffraction grating efficiency**
   - **Uni-Jena $\Rightarrow$ 97% abs. efficiency gratings**
   - **Have also produced $> 99\%$**
   - **Numerical calculations at UF, UJ**
2. **Locking scheme**
   - **3 degrees of freedom**
   - **Table-top: polarization-based control**
   - **LIGO: Reduce bandwidth for RF-based control**
3. **Noise**
   - **Shot noise**
   - **Radiation pressure noise**
   - **Alignment noise**
4. **Subtleties of GW interaction with WL cavity**
5. **What laser source?**

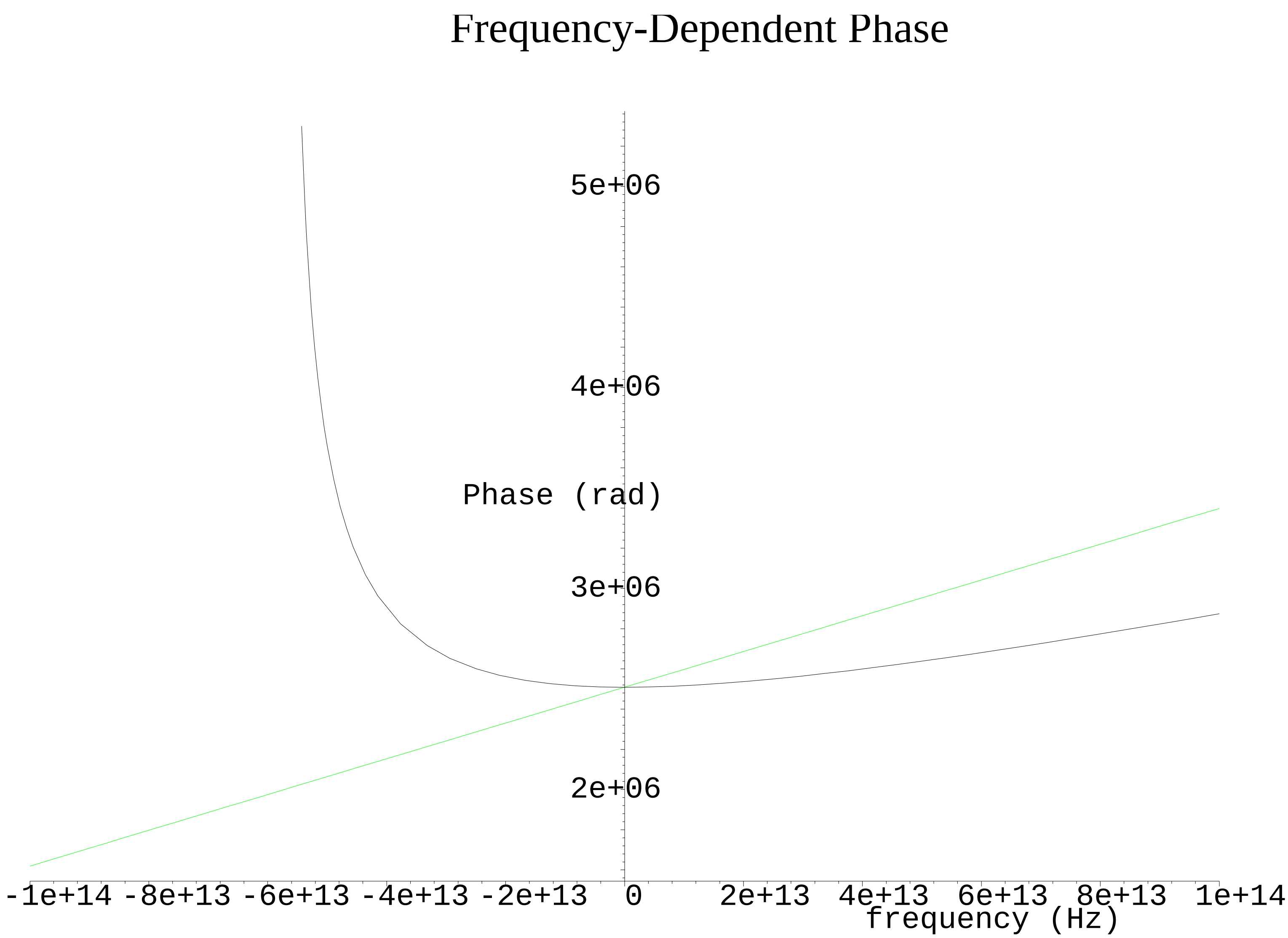
THE PLAN

Uni-Jena’s High-Efficiency Gratings

Groove frequency: 1250 mm
Angle of incidence: 41.5 deg
Polarisation: s- resp. TE- pc






Frequency-Dependent Phase
5e+06
4e+06
Phase (rad)
3e+06
2e+06
-1e+14
-8e+13
-6e+13
-4e+13
-2e+13
0
2e+13
4e+13
6e+13
8e+13
1e+14
frequency (Hz)