The shape of things to come:

interferometer topologies that use reflection gratings

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2005 Aspen winter conference on gravitational waves
LIGO DCC# G050020-00-Z

Driving issues behind interferometer design

Initial LIGO

Limited by available power

Power recycling is a key technology

Advanced LIGO

Limited by thermal loading

Resonant Sideband Extraction is a key technology

Beyond Advanced LIGO

Limited by optical losses

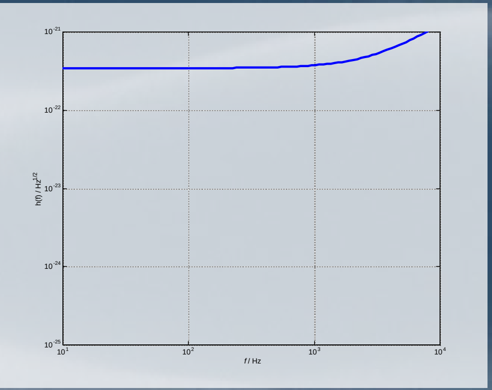
Low-efficiency reflection gratings are a key technology

A look at key technologies: power recycling

A Michelson interferometer‘s sensitivity is independant of the interference condition

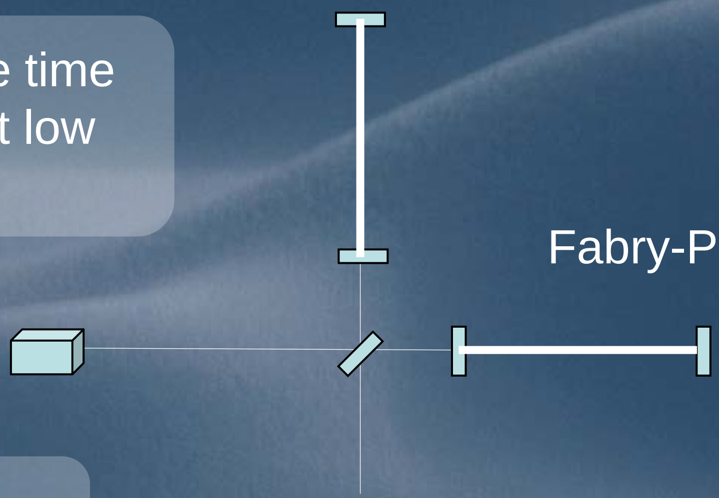
Sensitivity is limited by storage time of arms

Michelson interferometer



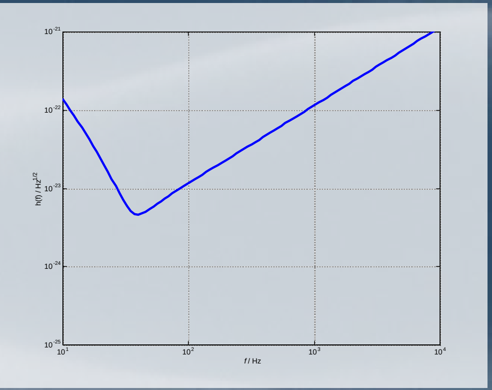
A look at key technologies: power recycling

Increasing arm storage time improves sensitivity at low frequencies



Fabry-Perot Michelson

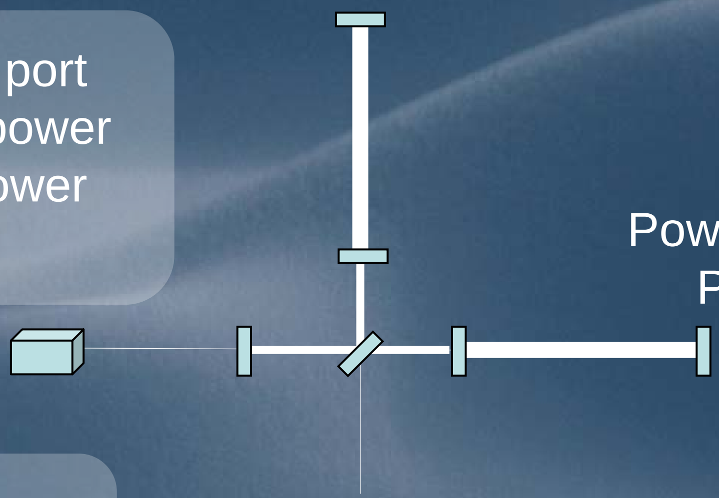
Sensitivity is limited by available laser power



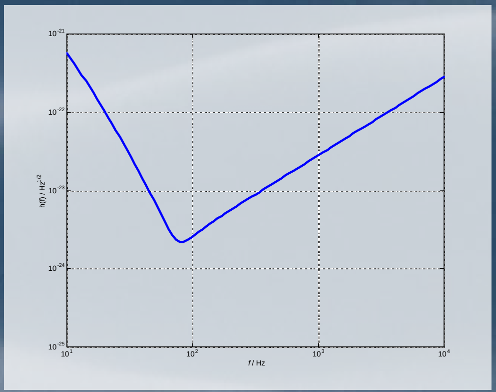
A look at key technologies: power recycling

Detecting at the dark port allows the circulating power to be enhanced by power recycling

Recycling factor is limited by thermal load on beamsplitter

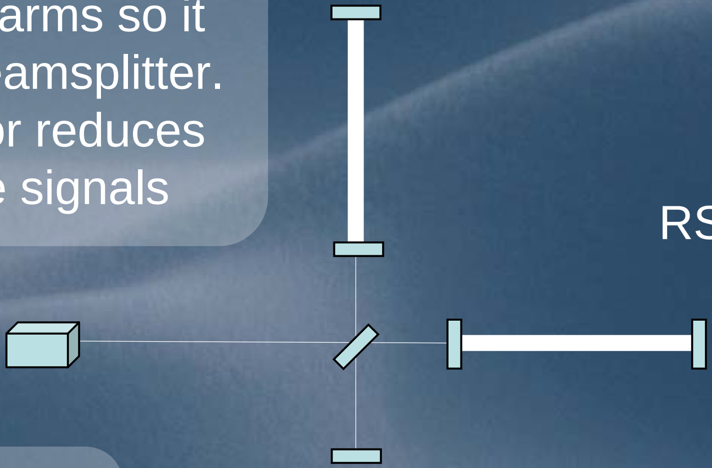


Power-recycled Fabry-Perot Michelson



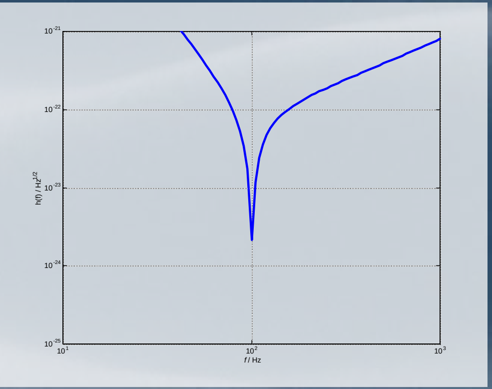
A look at key technologies: Resonant Sideband Extraction

Power is stored in the arms so it doesn‘t overload the beamsplitter. Signal Extraction Mirror reduces the bandwidth for the signals



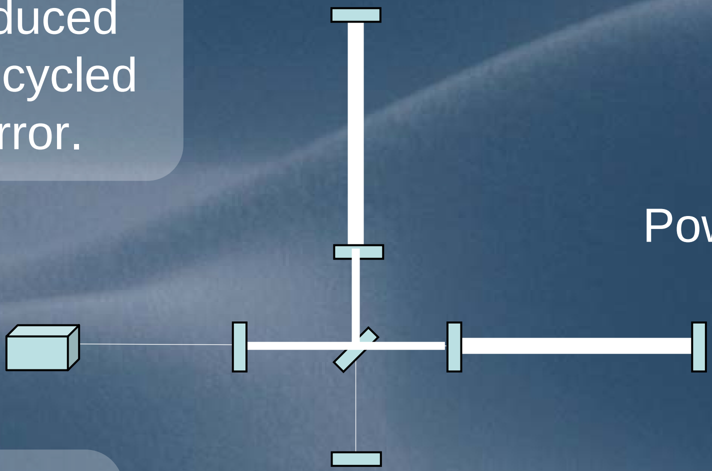
RSE interferoemter

Bandwidth enhancement is limited by loss in the signal extraction cavity



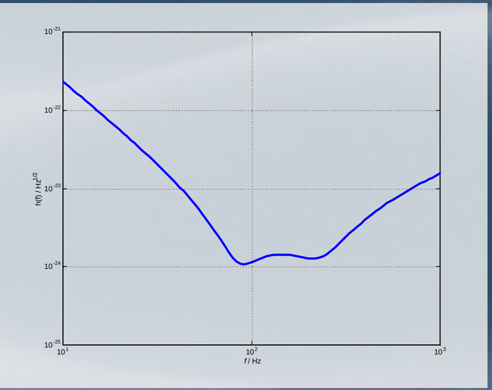
A look at key technologies: power-recycled RSE

Arm cavity finesse is reduced and reflected power is recycled by power-recycling mirror.



Power-recycled RSE

Circulating power is limted by thermal load in beamsplitter



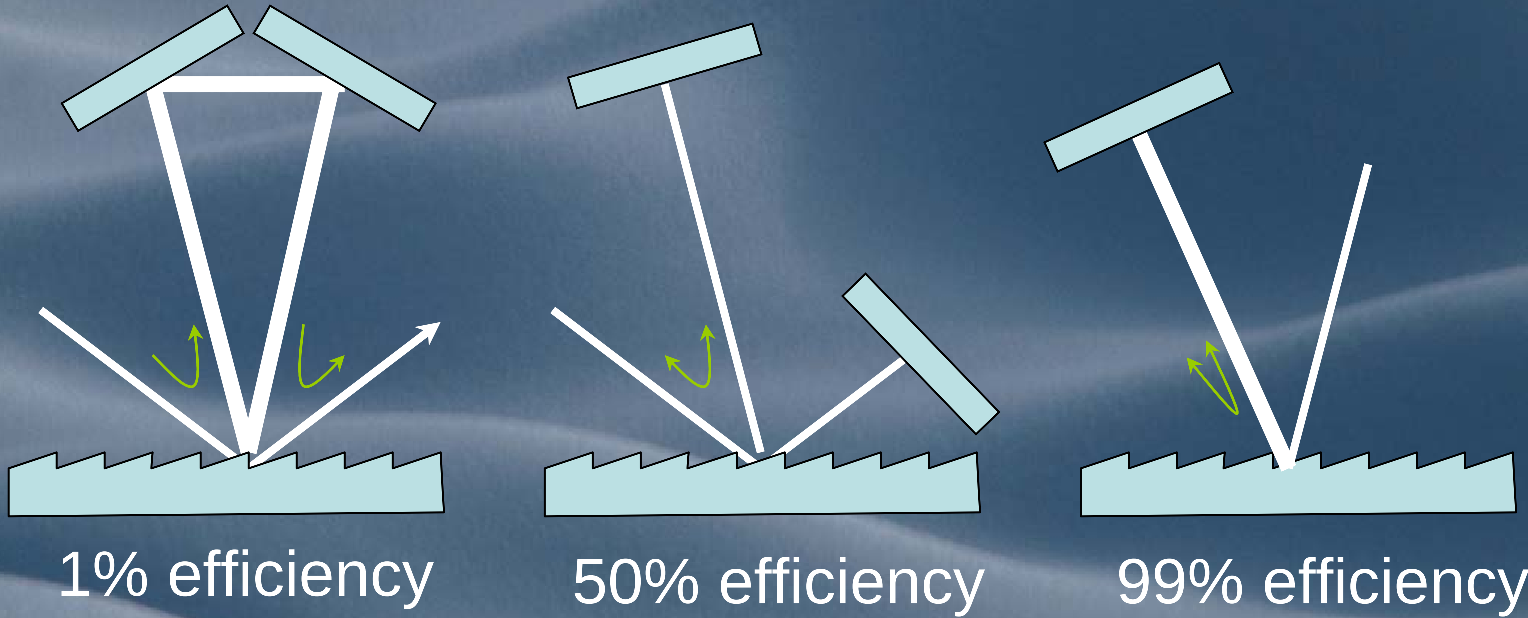
A look at key technologies: reflection gratings

High-reflectivity mirrors with weak reflection gratings can be made with very low loss

How will future detectors be optimized for use with diffractive optics?

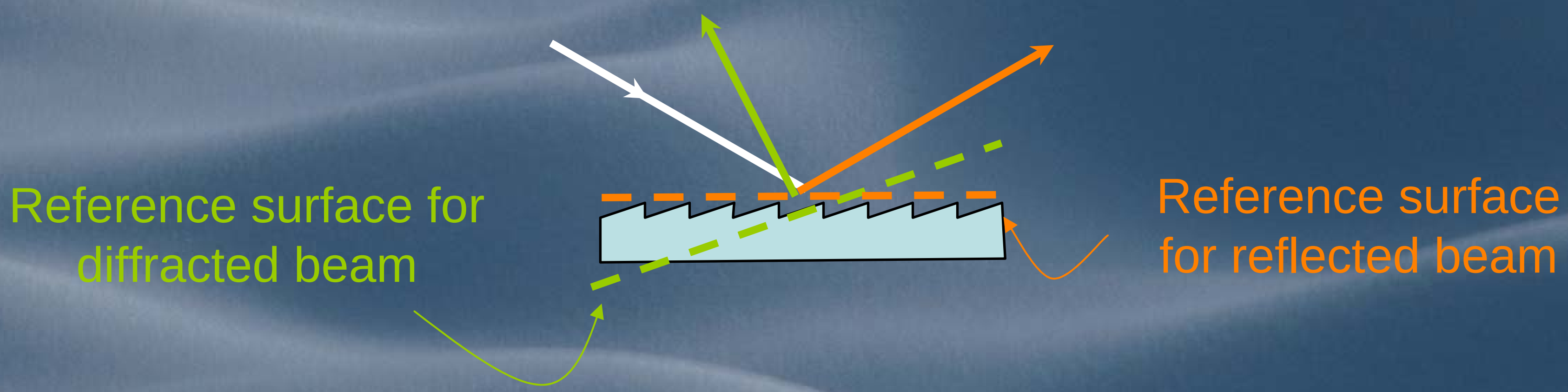
A look at key technologies: reflection gratings

Three basic geometries that use reflection gratings



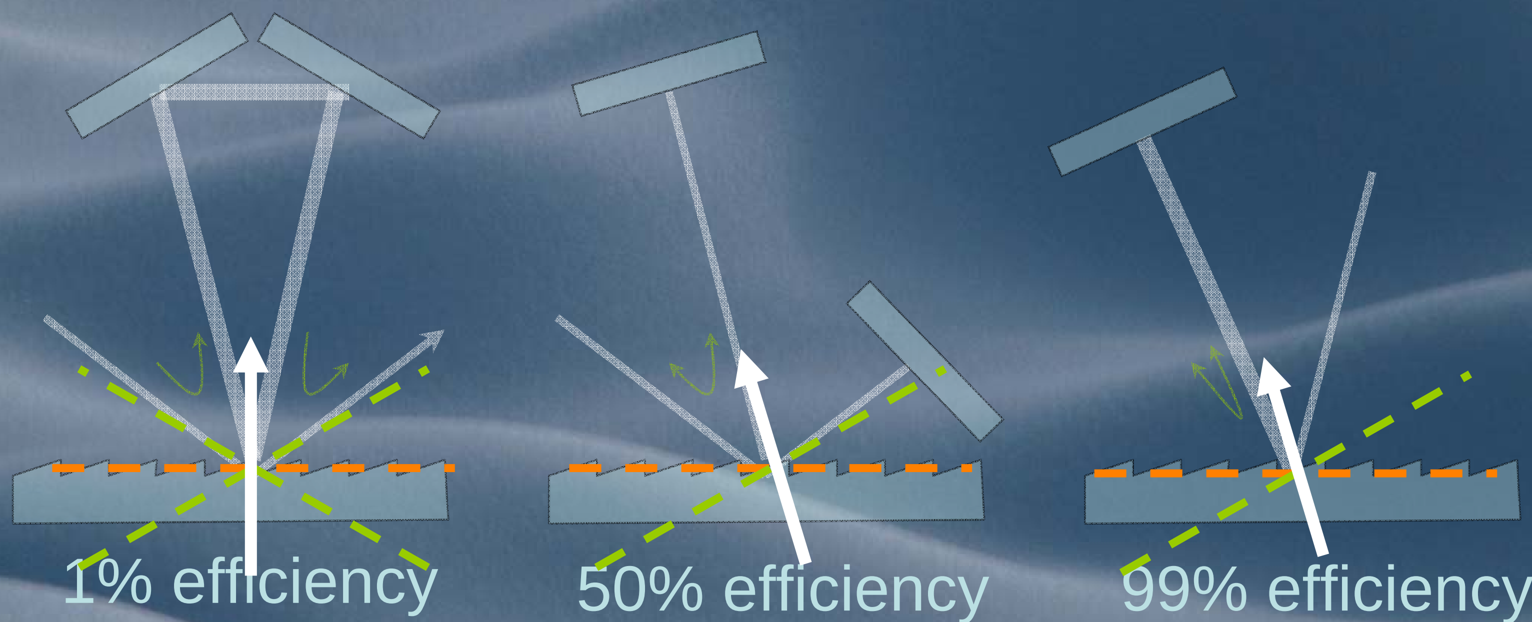
A look at key technologies: reflection gratings

Effect of the grating’s displacement noise depends on the geometry; it is different for reflected and diffracted beams



A look at key technologies: reflection gratings

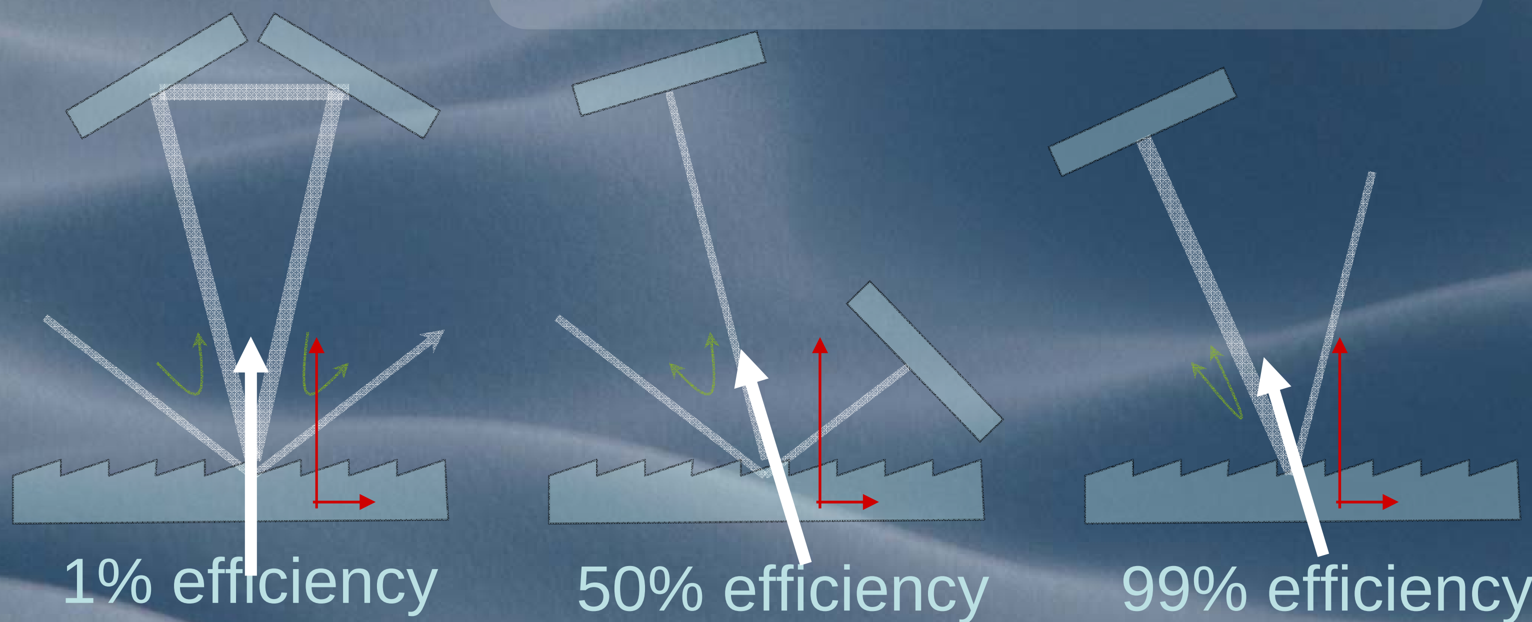
Primary isolation direction



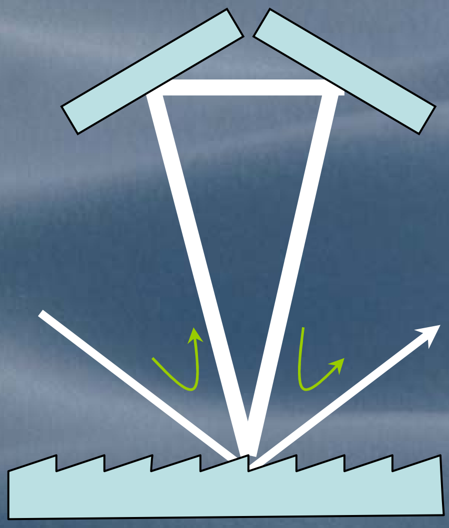
A look at key technologies: reflection gratings

Primary isolation direction

Principle axis of inertia tensor



A look at key technologies: reflection gratings



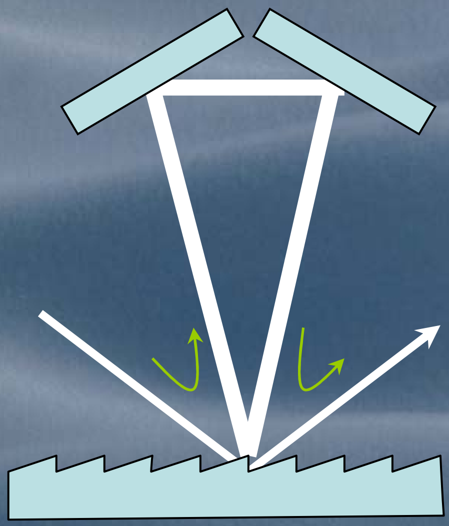
1% efficiency

Low efficiency gratings seem best suited for use in a detector:

- Phase noise due to lateral displacement of grating can be cancelled to first order
- Direction of maximum isolation requirement is aligned to principle axis of inertia tensor of the mass
- Holds promise of low-loss

A look at key technologies: reflection gratings

What can be done using low-efficiency gratings with low-loss?



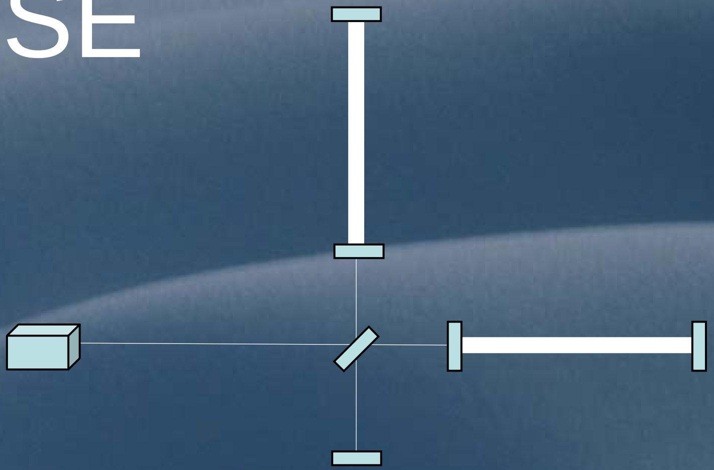
1% efficiency

Revisiting RSE

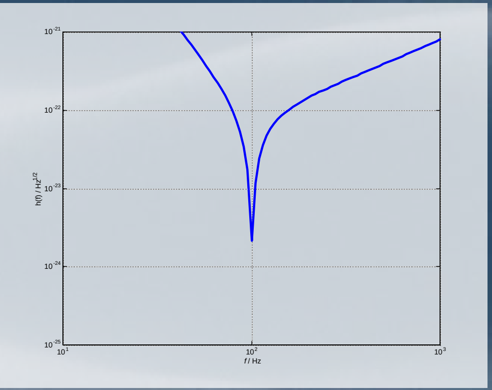
Bandwidth enhancement is limited by loss in the signal extraction cavity

$$\Delta BW = \frac{r_{ETM} t_{ITM}^{2}}{1 - r_{ITM} r_{SEM}} \left(1 - \frac{r_{ITM} r_{SEM} a}{1 - r_{ITM} r_{SEM}} \right)$$

=



RSE interferoemter



Revisiting RSE

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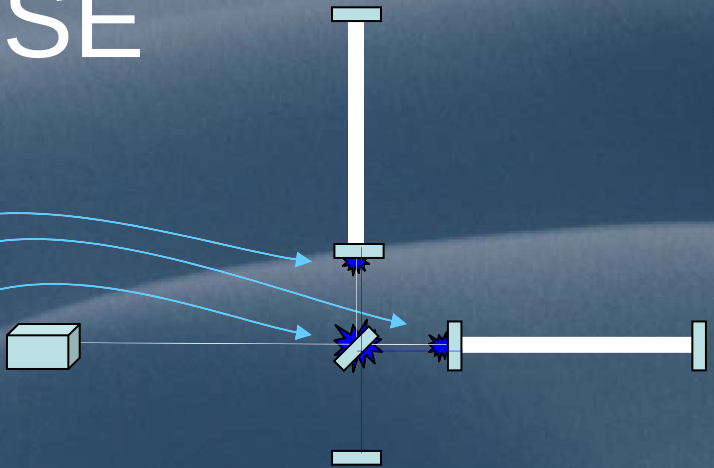
=

Loss in the signal extraction cavity is dominated by absorbtion in the optical substrates



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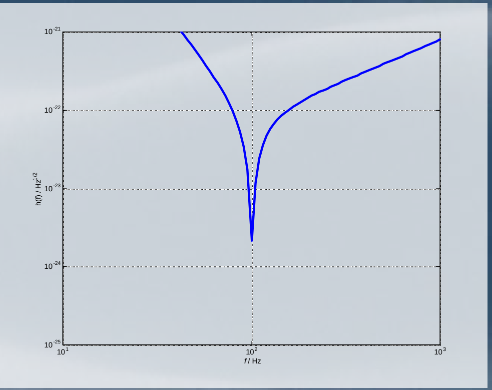
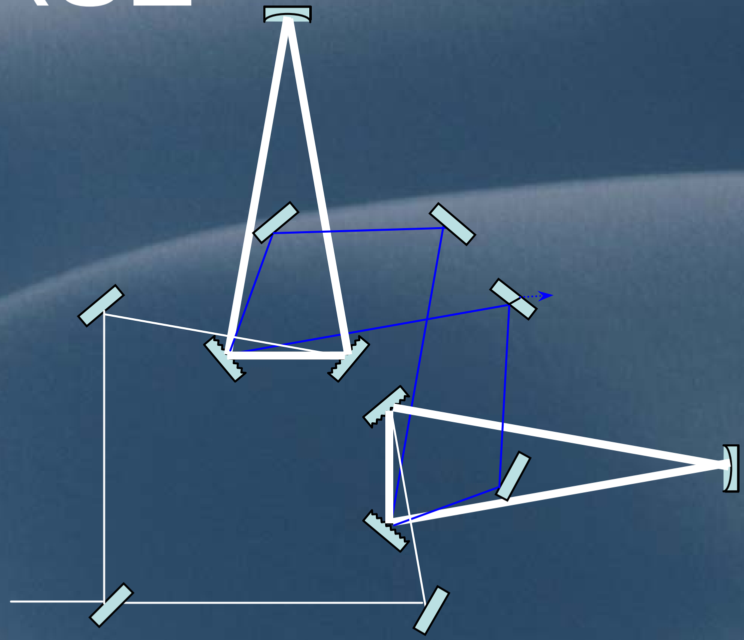


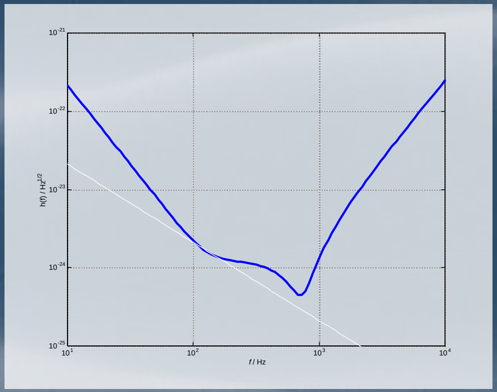
Revisiting RSE

Rather than modify design to increase the bandwidth of the arm cavities (power recycled RSE), modify it to reduce the loss in the signal extraction cavity

- Take advantage of low-loss reflection gratings to eliminate ITM substrate absorption

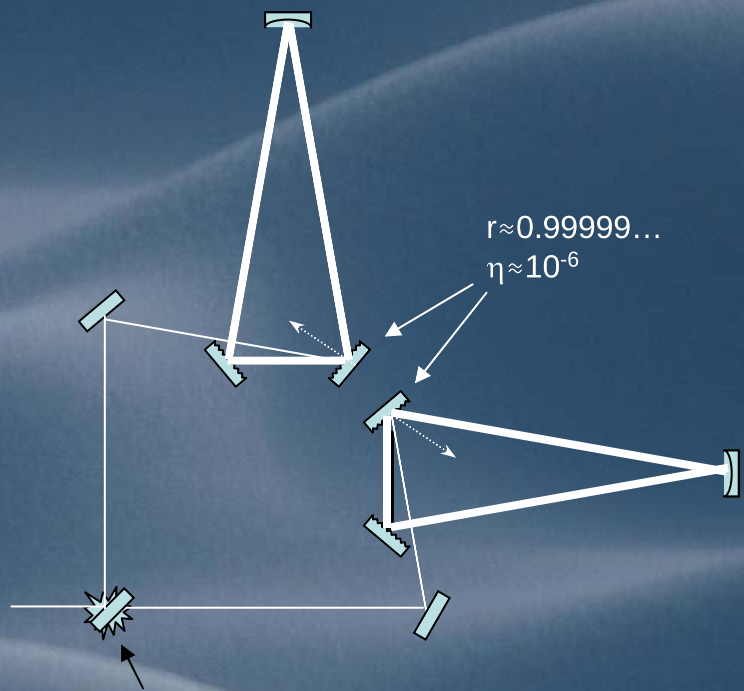
- Reconfigure geometry to separate signal extraction cavity from the beamsplitter





RSE with reflection gratings

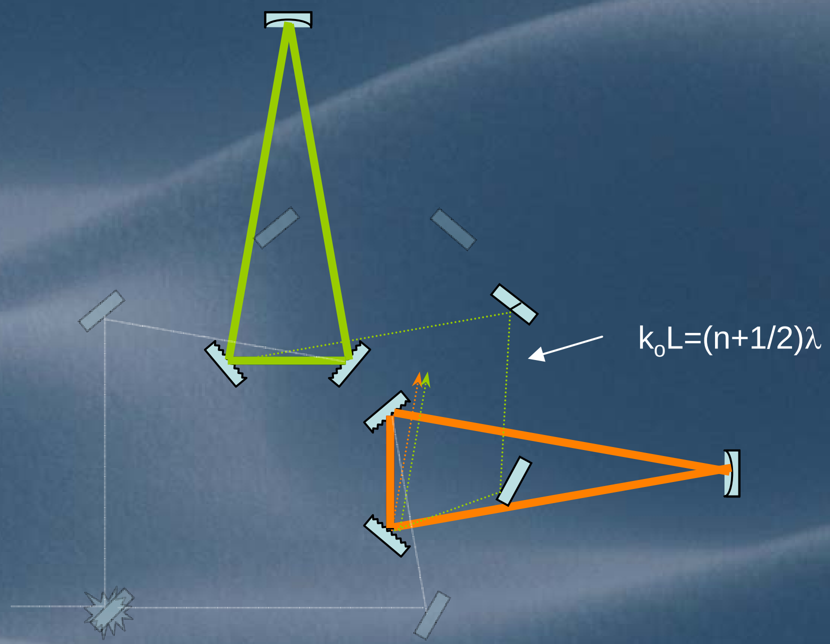
- Input power is split and critically coupled into arm cavities



Lossy beamsplitter is not inside a cavity

RSE with reflection gratings

- Input power is split and critically coupled into arm cavities
- Carrier exiting arm at output coupler is cancelled by carrier from other arm



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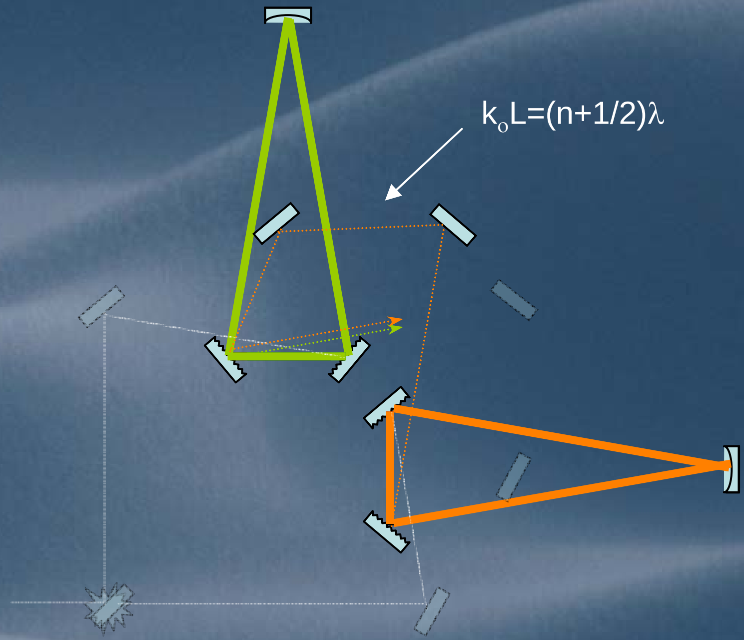

RSE with reflection gratings

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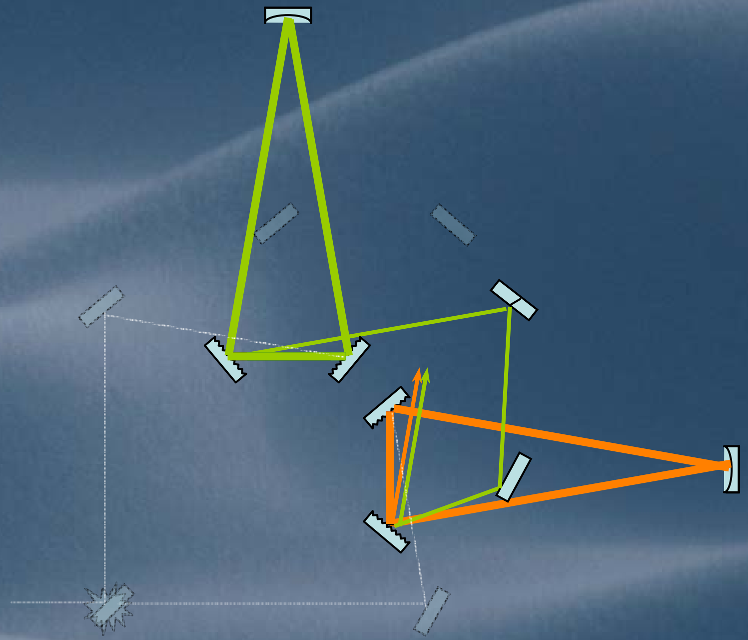

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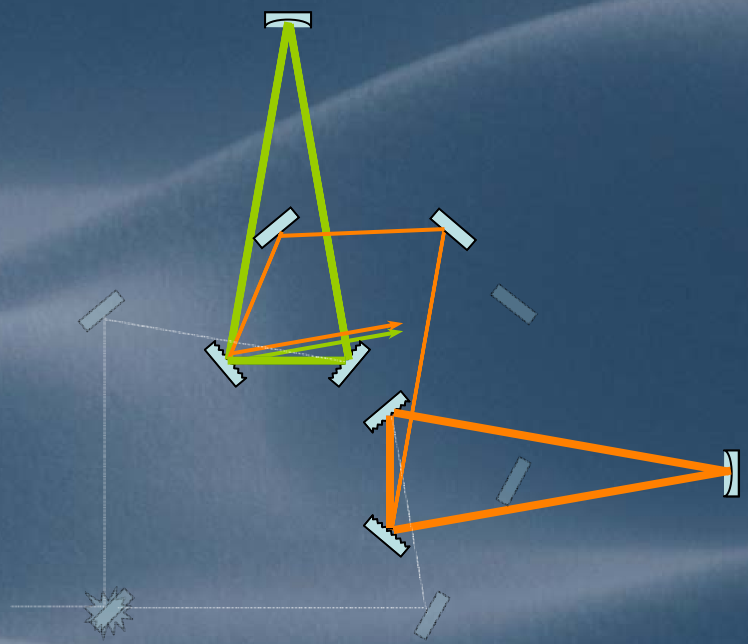

RSE with reflection gratings

- Input power is split and critically coupled into arm cavities
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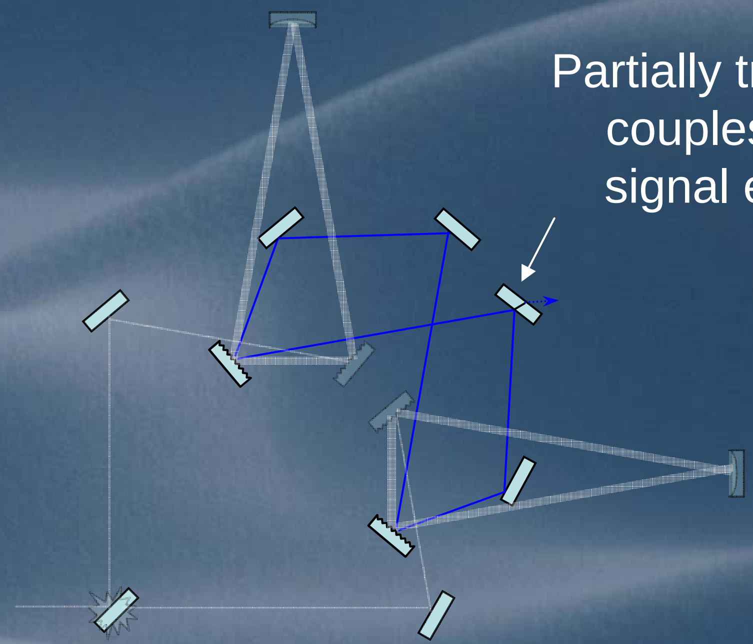
- Signal extraction cavity has no lossy elements inside of it



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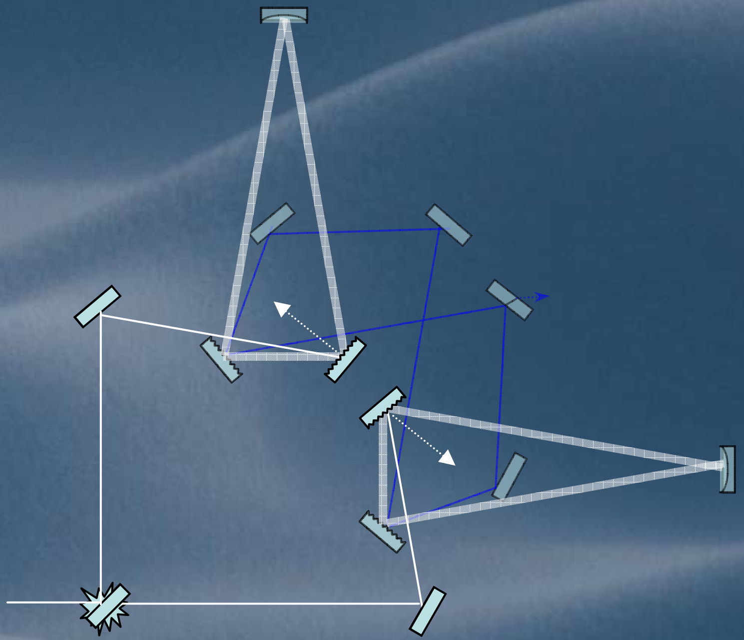
- Laser noise is filtered by arm cavities



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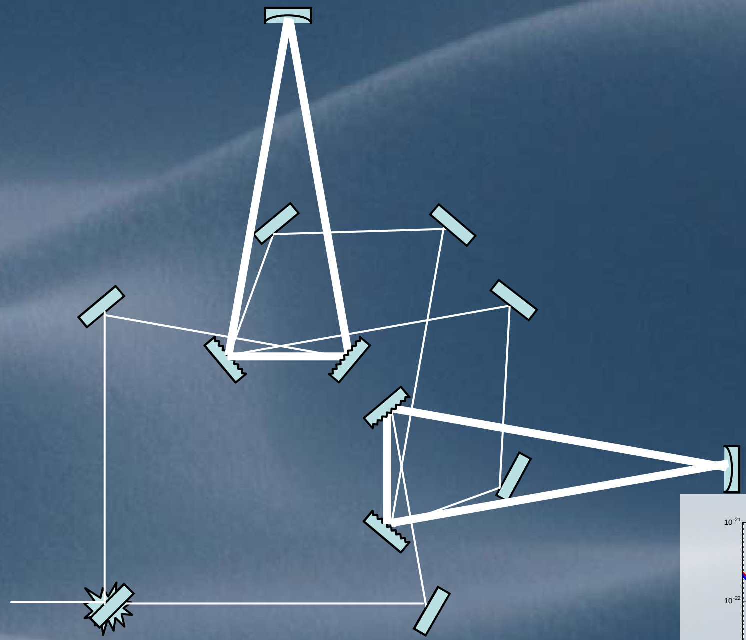
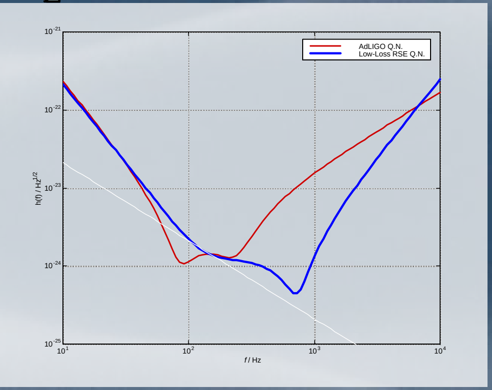
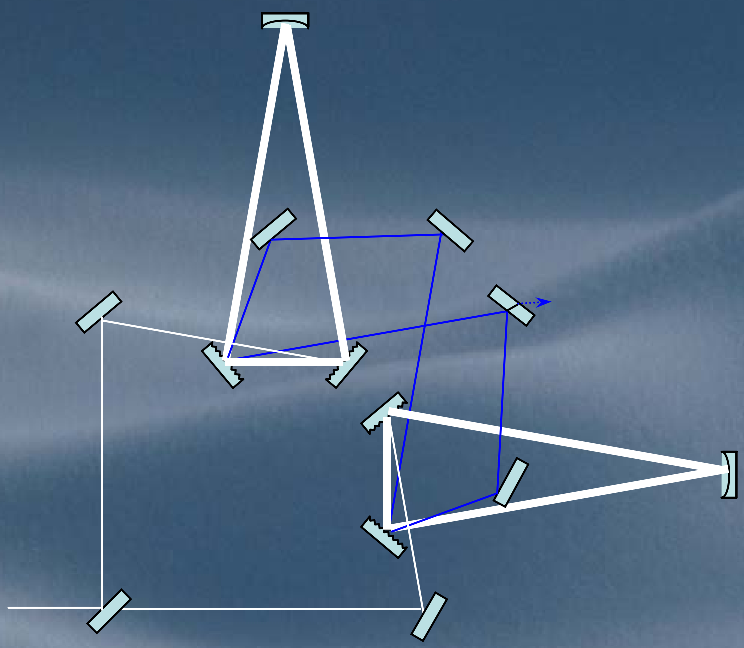


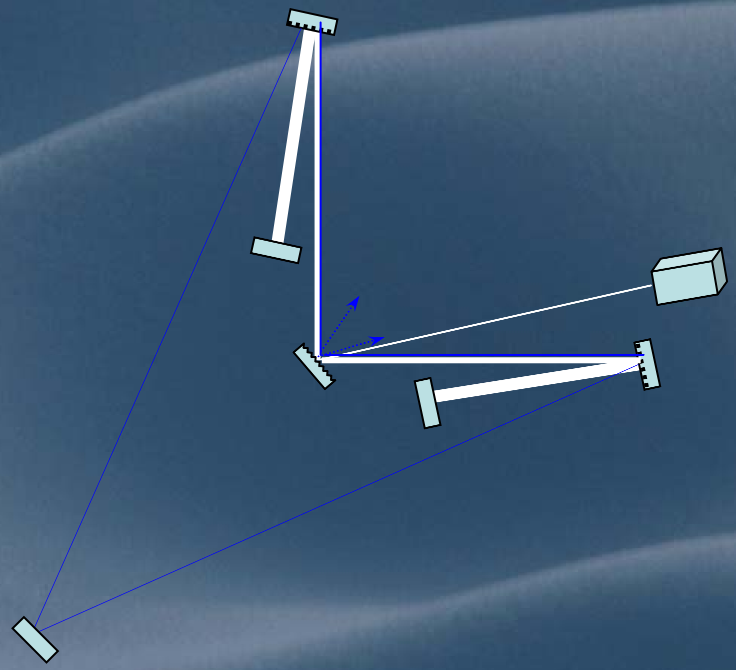
NS-NS inspiral range
187->236 MPc



Other configurations with reflection gratings



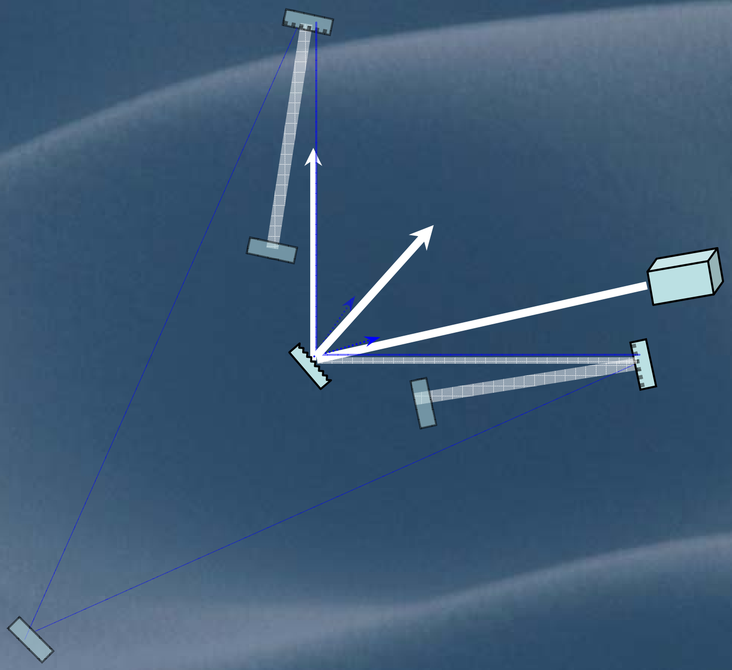
reflective RSE



reflective power recycled RSE
(Drever 1995)

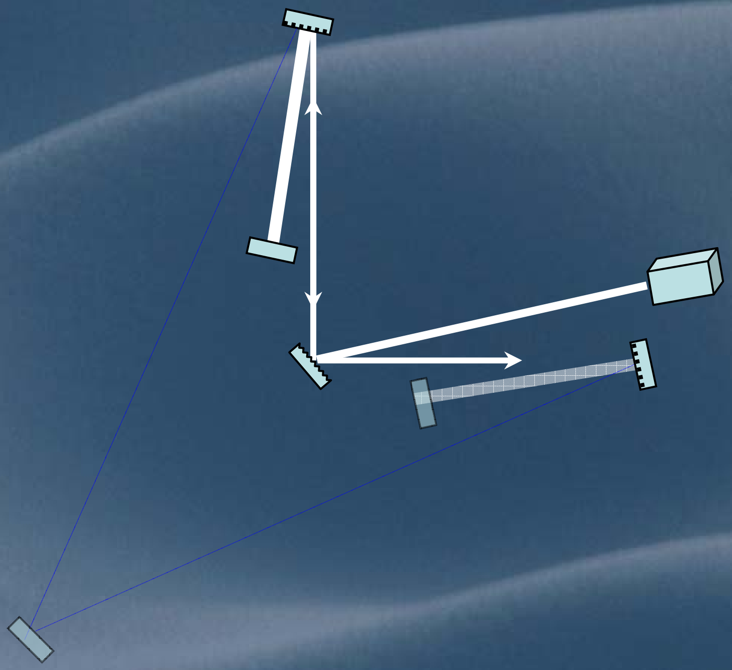
Power recycled RSE with reflection gratings

- Input power is diffractively coupled into the middle of the power recycling cavity



Power recycled RSE with reflection gratings

- Input power is diffractively coupled into the middle of the power recycling cavity
- Each grating arm cavity forms one end of the recycling cavity



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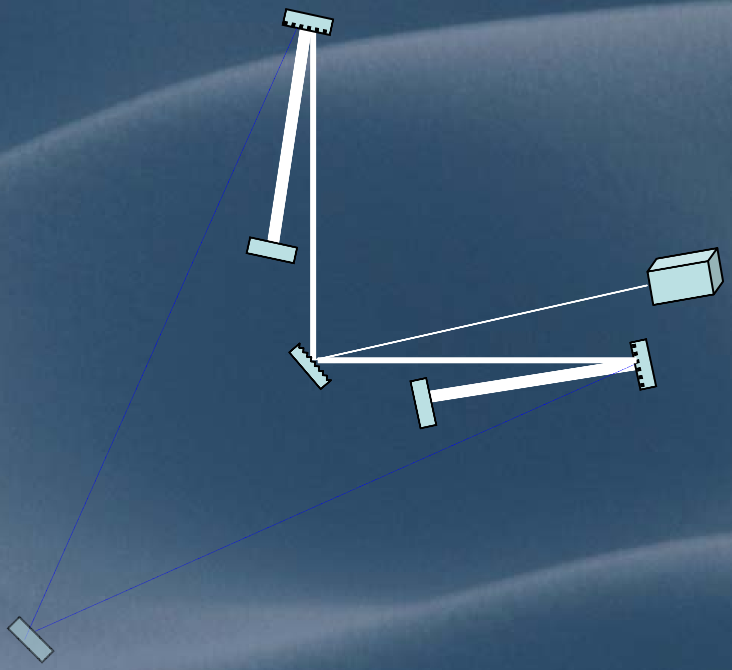
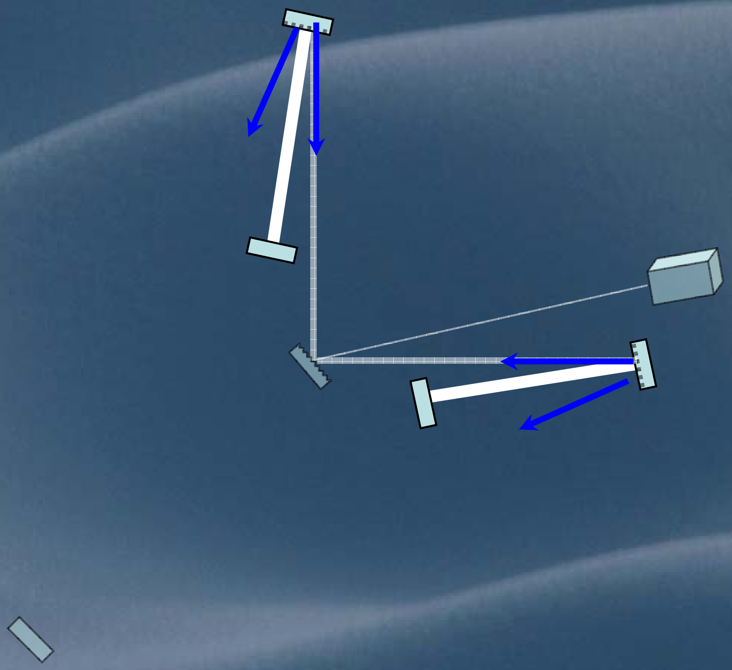


Power recycled RSE with reflection gratings

- Input power is diffractively coupled into the middle of the power recycling cavity
- Each grating arm cavity forms one end of the recycling cavity
- Signal sidebands from arm cavities exit the arms in two directions



Power recycled RSE with reflection gratings

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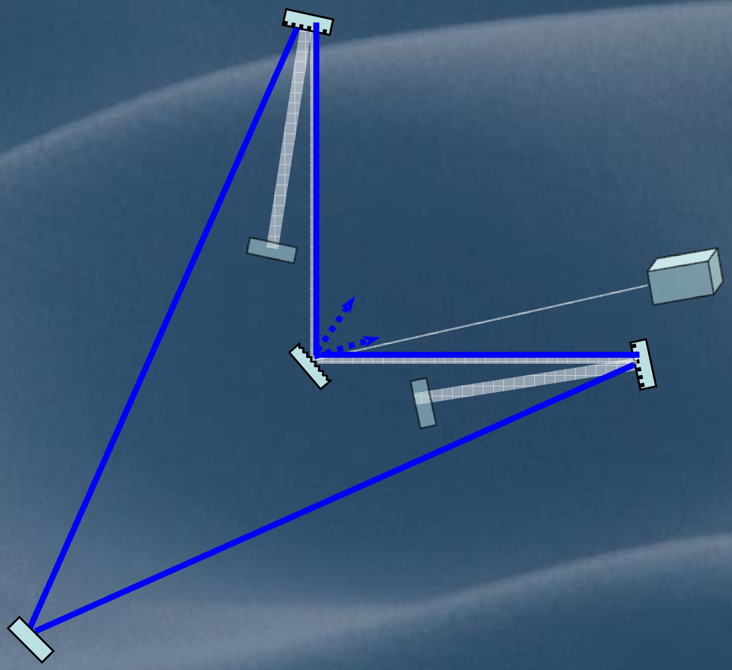
- Signal extraction mirror closes the signal extraction cavity path



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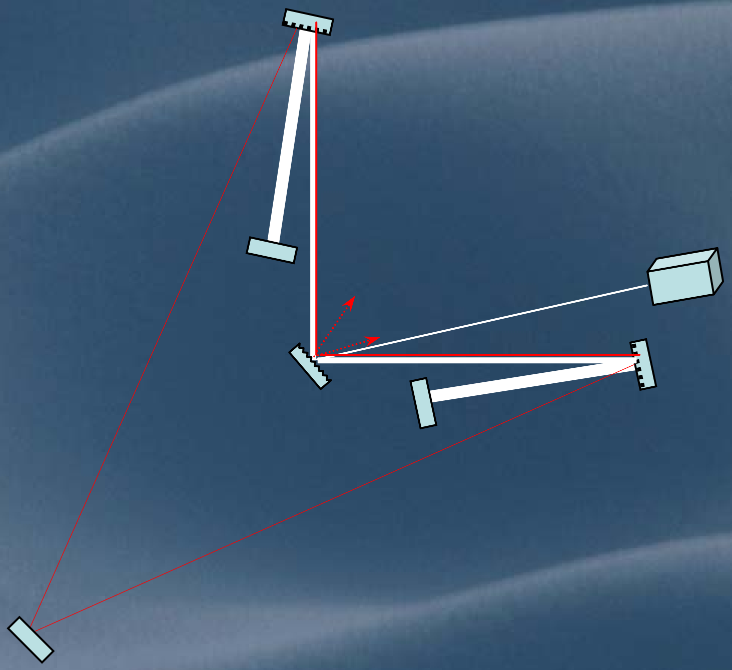
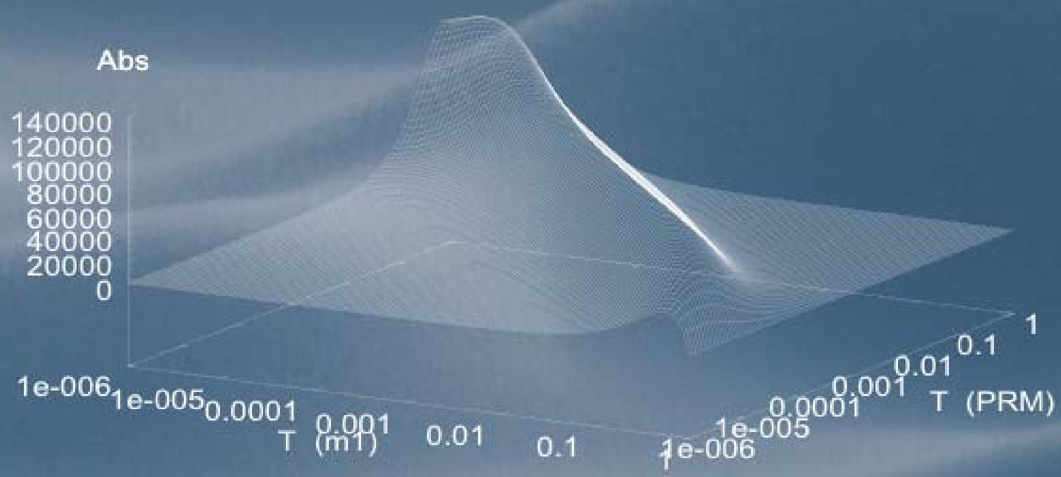
- Laser technical noise follows the signal everywhere



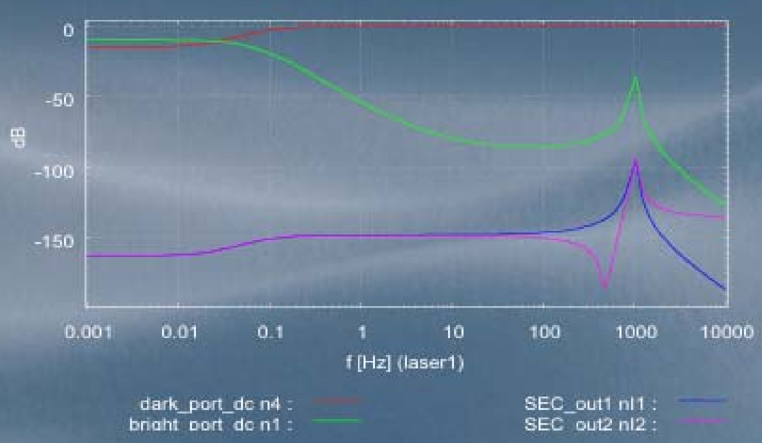
Power gain dependence on diffraction efficiency

the total power gain in the arms of the grating ring RSE
(loss of 1ppm per mirror and a signal tuning of 20 degrees)



The left-most axis is the diffraction efficiency of the arm cavity gratings, the right-most axis is that of the recycling cavity grating.

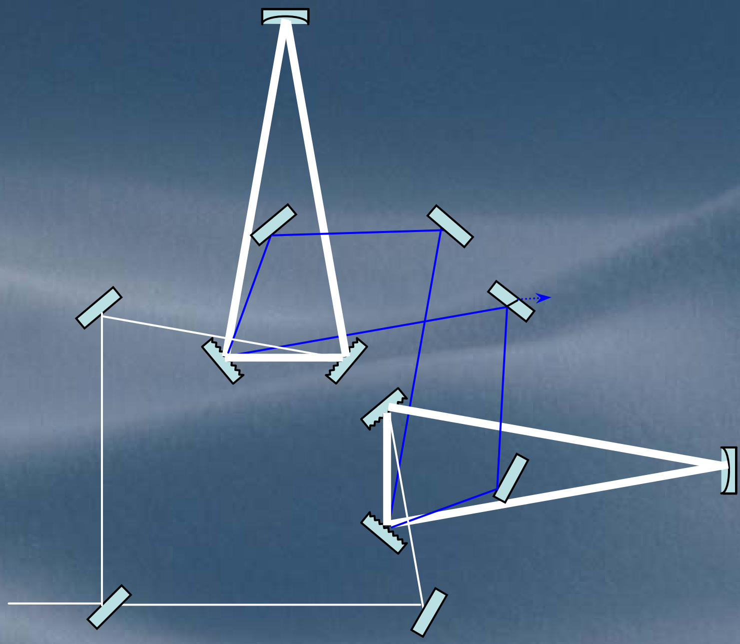
Laser noise coupling to output



Laser noise coupling

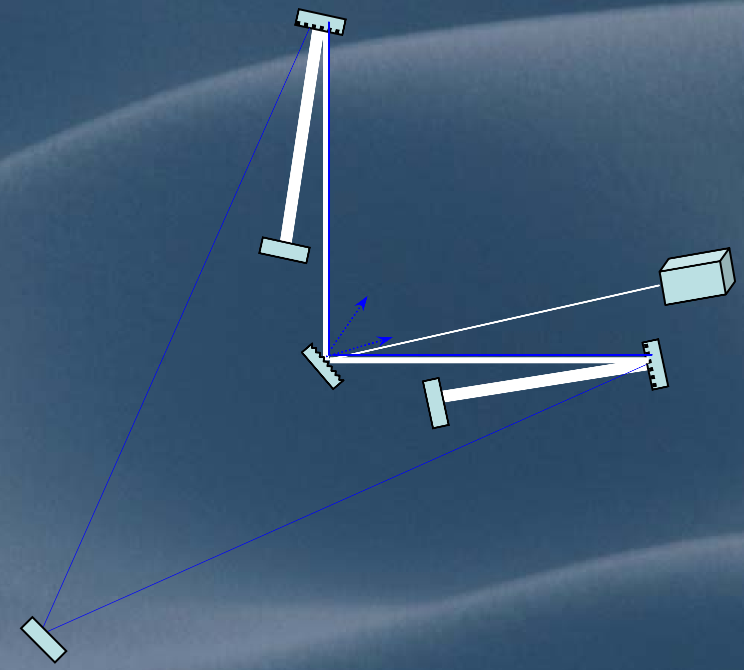
Signal transfer function

Reflection grating interferometer comparison



reflective RSE

- Grating efficiency 10ppm
- Laser power 50W
- Good separation of signal and laser noise



reflective power recycled RSE

- Grating efficiency 0.001
- Laser power 25W
- Poor separation of signal and laser noise

Summary

With reflection gratings on core optics comes:

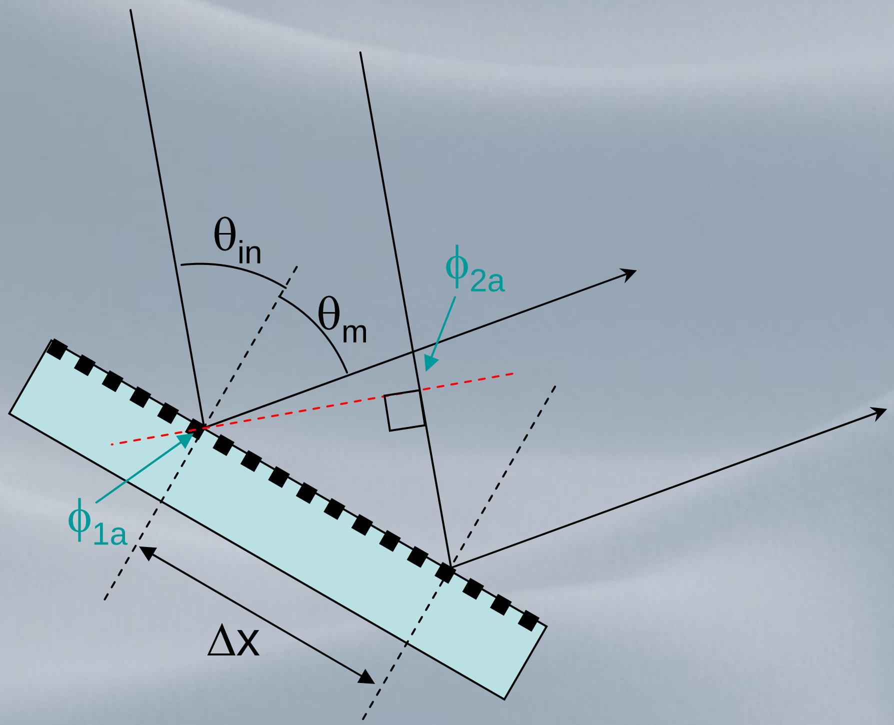
- New suspension design requirements
- Promise of low loss
- Capability of very high power storage
- Decreased bandwidths of arm cavities
- Need for higher finesse signal extraction cavity
- Need for lower loss in the signal extraction cavity

Current configurations are not optimized for minimizing loss - but rather managing thermal loads

Conclusion

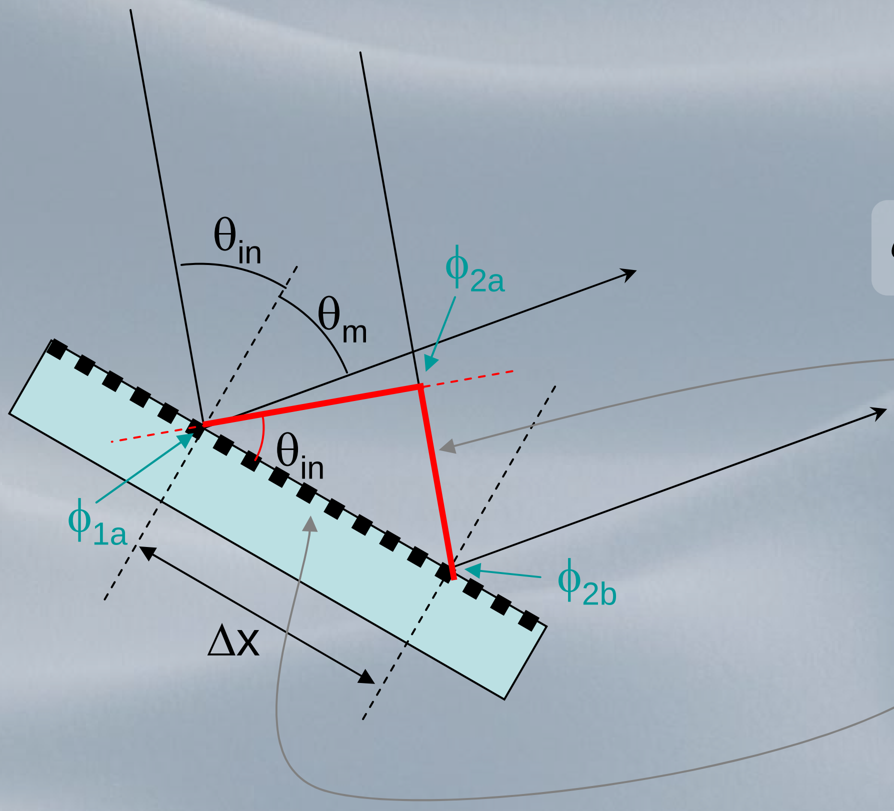
It is exciting that there is still opportunity for improvements in interferometer design

Consider phase shift on diffracted beam due to input beam displacement



$$\phi_1 \equiv \phi_{2a} = \phi_a$$

Consider phase shift on diffracted beam due to input beam displacement



$$\phi_1 \equiv \phi_{2a} = \phi_a$$

$$\phi_{2b} = \phi_{2a} + mk_g \Delta x + k_0 \Delta x \sin\theta_{in}$$

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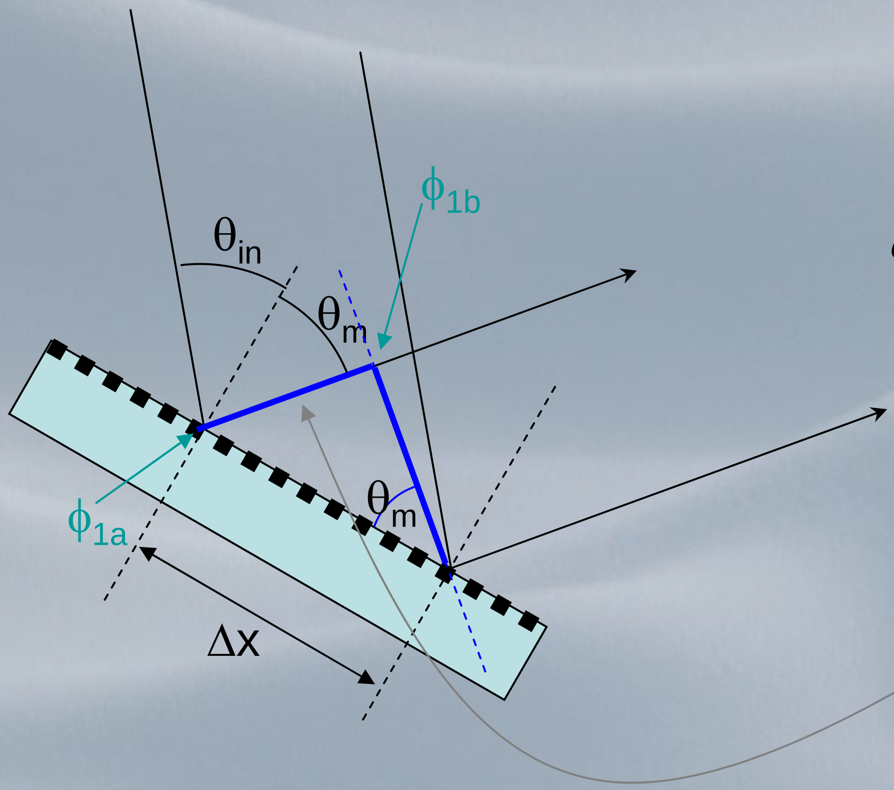

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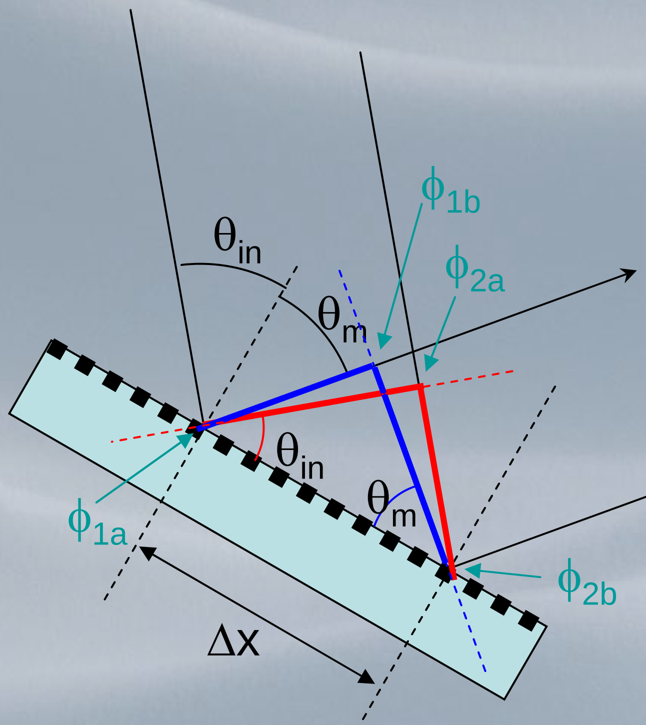

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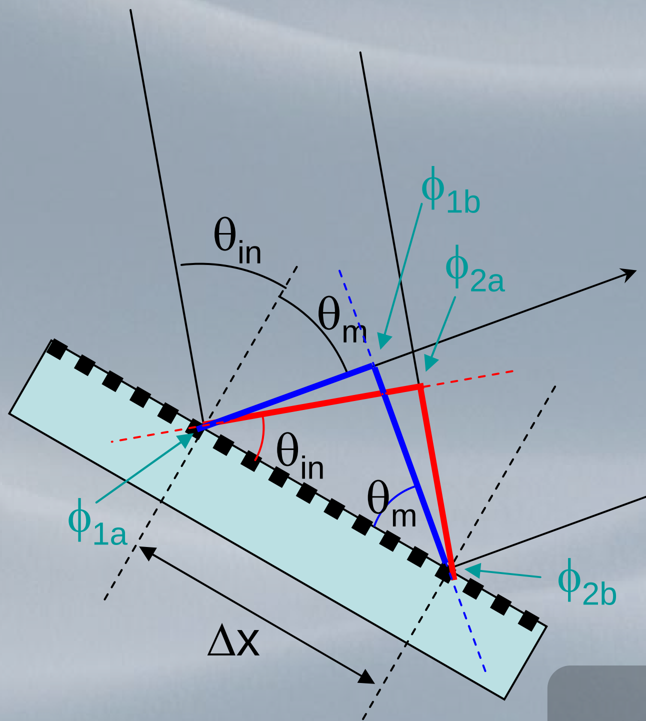
$$\phi_{1b} = \phi_{1a} + k_0 \Delta x \sin\theta_m$$

$$\Delta\phi = \phi_{1b} - \phi_{2b} = mk_g \Delta x + k_0 \Delta x \left(\sin\theta_{in} - \sin\theta_m\right)$$

Consider phase shift on diffracted beam due to input beam displacement



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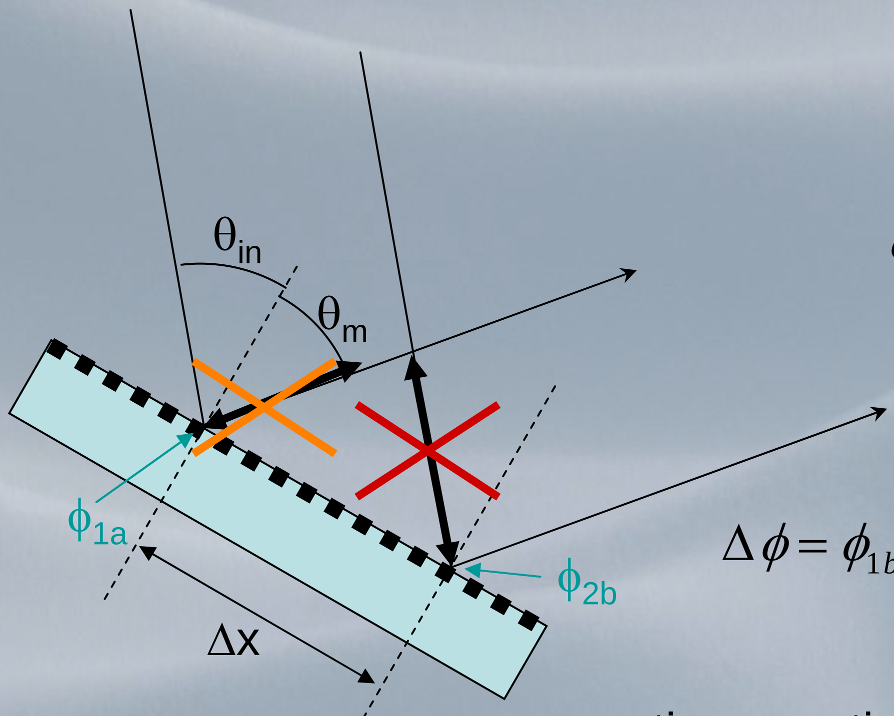
$$\Delta\phi = \phi_{1b} - \phi_{2b} = mk_g \Delta x + k_0 \Delta x \left(\sin\theta_{in} - \sin\theta_m\right)$$

grating equation: $\sin\theta_m - \sin\theta_{in} = m\frac{k_g}{k_0}$

$$\Delta\phi = 0$$

If you just consider lateral translation of grating



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grating equation: $\sin\theta_m - \sin\theta_{in} = m\dfrac{k_g}{k_0}$

$$\Delta\phi = mk_g \Delta x = mk_g \Delta\theta L$$

$$\Delta\theta \approx 10^{-22}\left[\frac{\Delta\phi}{10^{-12}}\right]\left[\frac{10^7}{k_g}\right]\left[\frac{10^3}{L}\right]$$