The LIGO II Interferometer Configuration

K.A. Strain
University of Glasgow

Contents

- What is an interferometer configuration?
- What are the main noise sources relevant to configurations design?
- The LIGO I configuration.
- The LIGO II configuration.
- Signal recycling.
- The R&D program in configurations.

Interferometer configurations

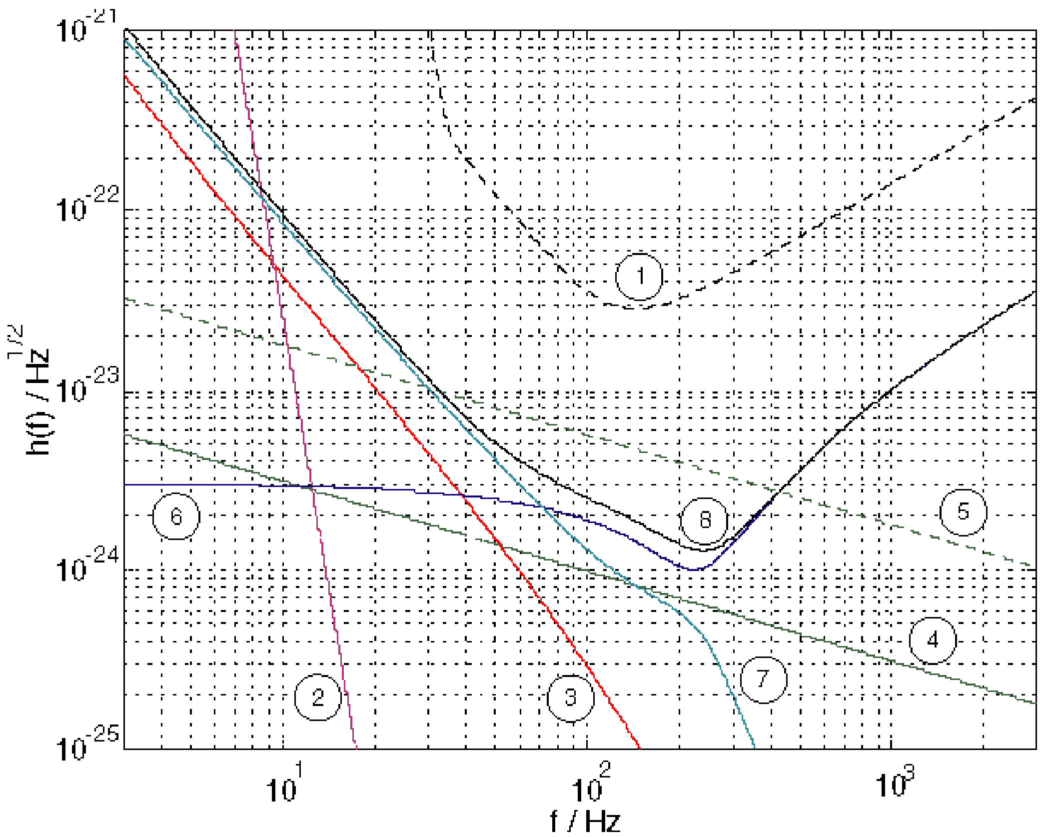
- The arrangement of the main optical components into Michelson interferometers, Fabry-Perot cavities, etc.
- The electro-optical subsystems required to readout all lengths (mirror positions) and alignments (mirror angles) that must be controlled to bring the interferometer to its correct operating condition.
- The electro-optical subsystem required to read out the main gravitational wave data stream.
- Some aspects of the feedback and control systems needed to operate the interferometer

Fundamental limits in configurations

- There are two `fundamental' limitations to the sensitivity of the optical system to gravitational waves. Both are of a 'quantum' nature.
- The `shot noise' is produced on the detected signal according to the statistics of the detected photons. It is reduced by having more light in the system.
- The `quantum radiation pressure noise' can be viewed as due to the statistics of the photon count going into the two arms at the beam-splitter. Varying momentum is applied to the test masses which move in response.

Shot noise and quantum radiation pressure noise

- Figure 2 from the LSC R&D white paper: noise contributions.



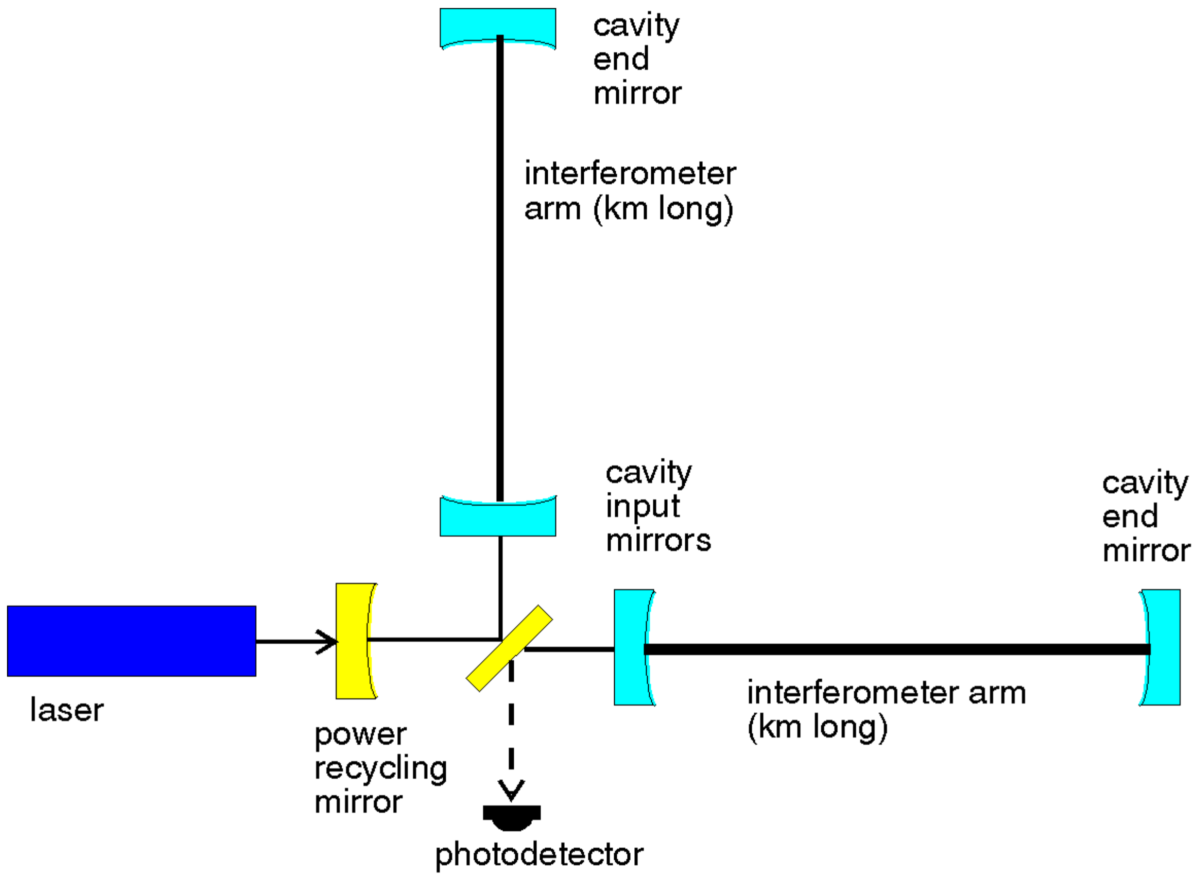
1 LIGO I total
2 Filtered seismic noise
3 Suspension thermal noise
4 Internal thermal noise - sapphire
5 Internal thermal noise - fused silica (fallback)
6 Shot noise
7 Radiation pressure noise
8 LIGO II total

The LIGO I configuration

- A Power Recycled, Fabry-Perot, Michelson interferometer.
- The basic differential length sensing of the Michelson interferometer is enhanced by multiple overlapping reflections along the arms in Fabry-Perot cavities.
- This enhances both the number of photons stored in the arms and the interaction time of the light with gravitational radiation. Both improve the sensitivity.
- Ultra-low-loss optics are used so most of the light (> 97%) is reflected and can be recycled using the partially transmitting *power-recycling* mirror.

The LIGO I configuration

- A simplified diagram of the main optical components of the LIGO I configuration.



Limitations of the LIGO I configuration

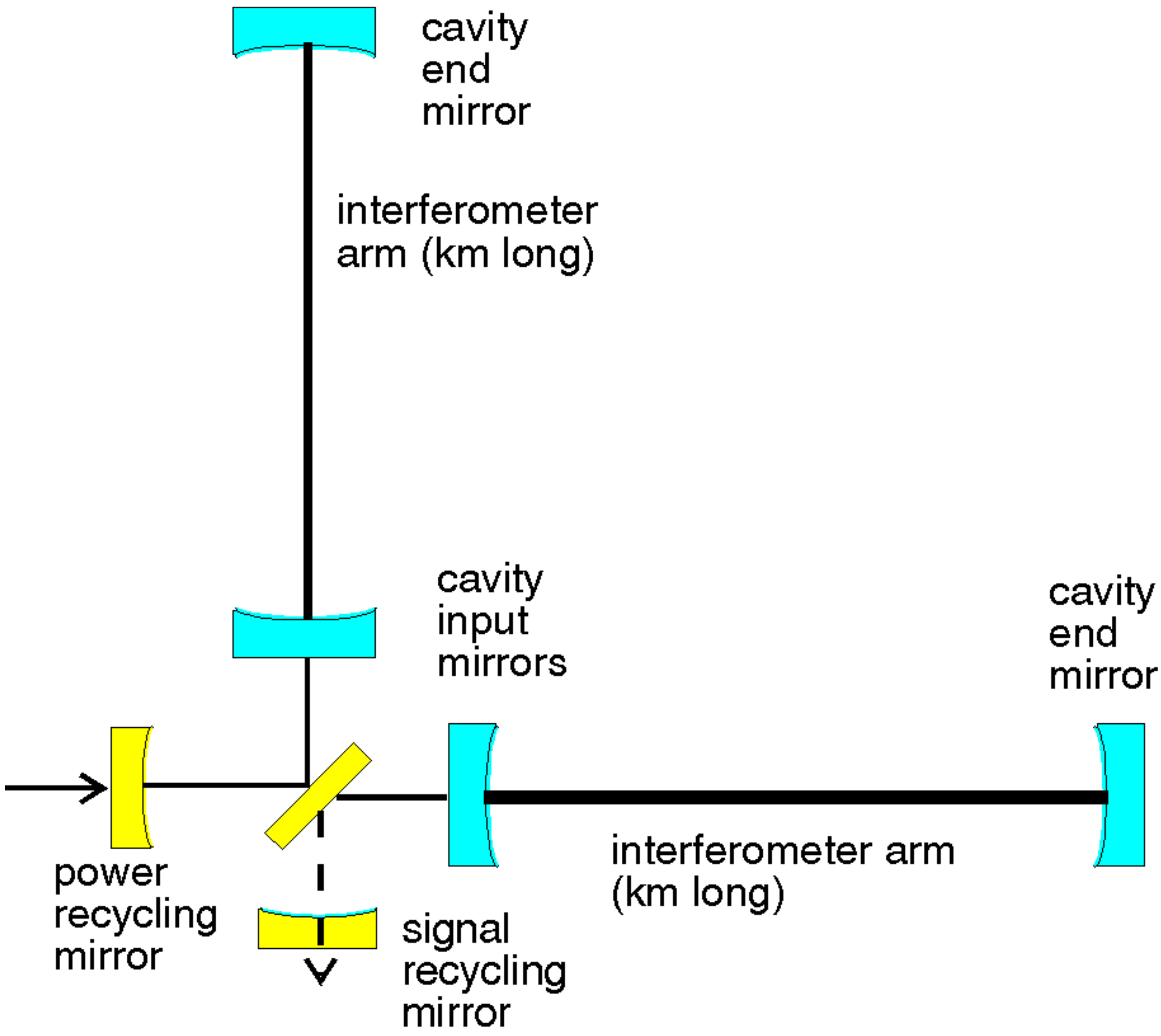
- The shape of the frequency response is defined by the response of the Fabry-Perot arm cavities. It cannot easily be optimised for a particular observation. The minimum of shot noise is always at low frequency (where other noise may be large).
- The `open' output port makes the system intolerant of certain types of imperfection of the optics in the power recycling/beam-splitter region.

The LIGO II configuration

- This is an incremental change from the LIGO I configuration
- *Signal recycling* is added to the power recycled, Fabry-Perot Michelson interferometer.
- Just one extra mirror, and appropriate revision of the read out and control systems are required.
- Additional performance enhancements are achieved through improvements in the Laser and Optical components (as described in a subsequent presentation).

The LIGO II configuration

- The main components of the LIGO II interferometer

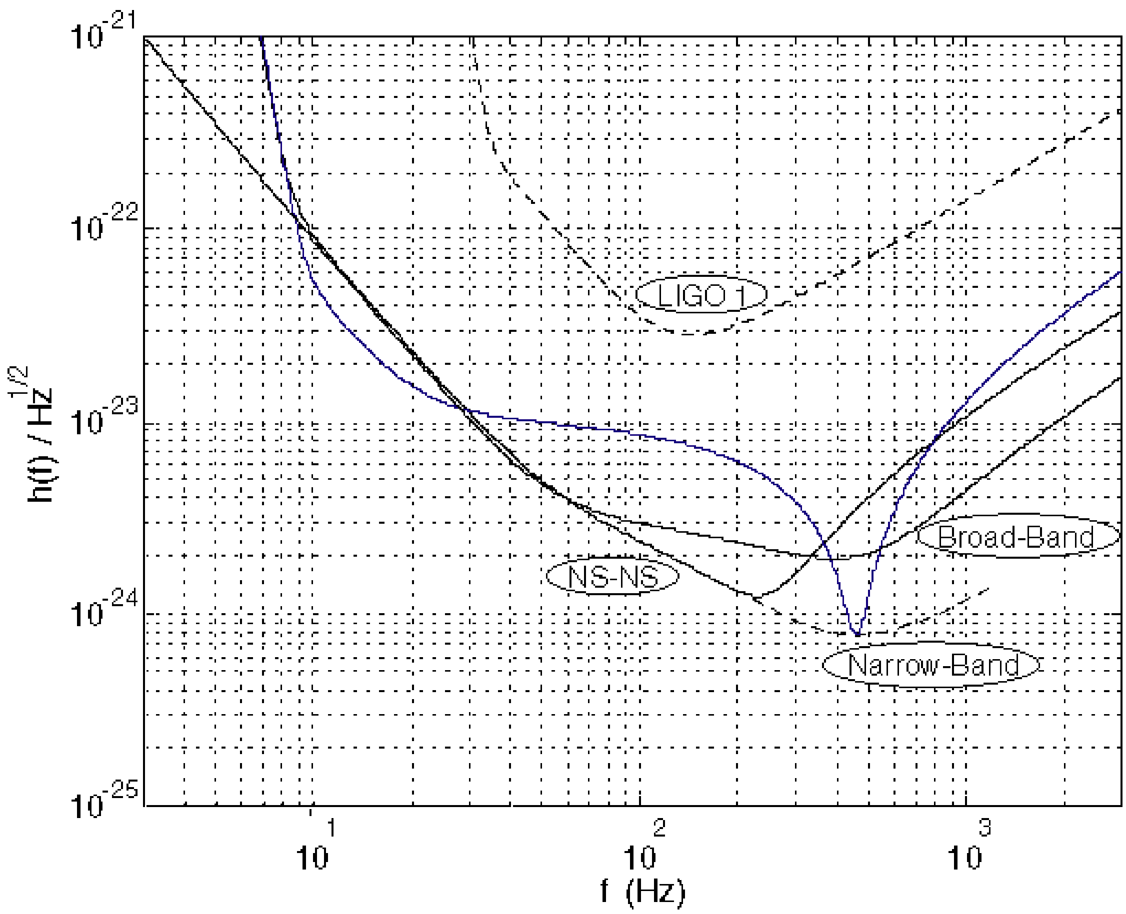


Signal recycling

- Placing a *signal recycling mirror* at the output port of the interferometer forms the signal recycling cavity in which signal components are resonant.
- The frequency response of the system is modified from the response of the arm cavities
- If the signal recycling mirror is chosen so that the response is narrowed the configuration is called *dual recycling*.
- If the response is broadened the technique is called *resonant sideband extraction.*
- In each case the peak of the response can be tuned to a desired observation frequency.

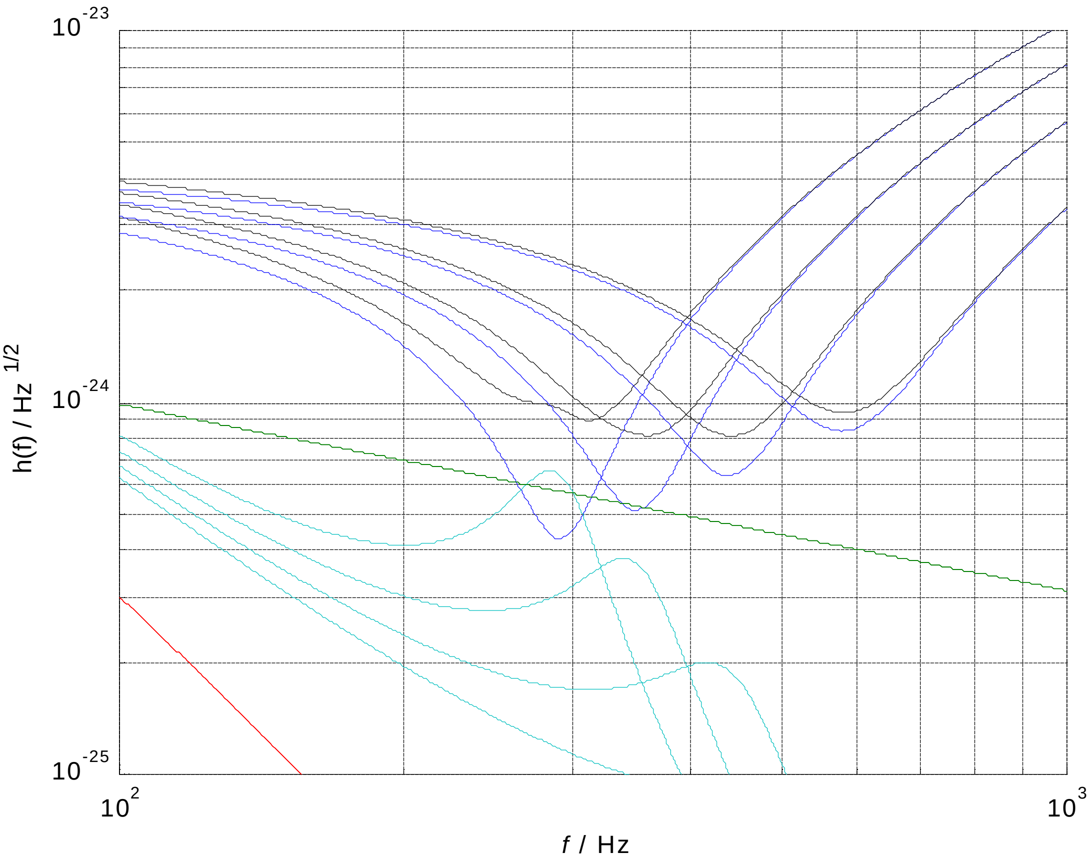
Signal recycling responses

- Figure 1 from the LSC R&D white paper: signal recycling responses.



Signal recycling responses

- Illustrative example responses that can be achieved by tuning one particular reflectivity of signal recycling mirror.



Signal recycling: additional benefits

- The balance between the shot noise and quantum radiation pressure noise can be optimised for a given potential signal (whenever one is improved by signal recycling the other is made worse). In this case we have a *quantum limited interferometer* - it is working at the uncertainty limit.
- The output port of the interferometer is `closed’. This reduces the significance of certain types of optical imperfection in the interferometer

Signal recycling: observation modes

- Variable frequency response allows different *observing modes*.
- It would be possible to work just with one signal recycling mirror and vary the tuning, but this is not optimum over the whole frequency range
- We allow the signal recycling mirror to be changed to provide better performance at the extremes of the range of observation frequencies.
- Thus we accomplish specific goals such as pulsar searches or other targeted observations.

Signal recycling: new requirements

- The position of the signal recycling mirror must be controlled. This needs an additional read out and control systems (for longitudinal position and angular alignment).
- The presence of the signal recycling mirror radically alters the operation of the existing read out schemes. These must be re-optimised to work with signal recycling.
- As more degrees of freedom of control are added the complexity of bringing the system quickly to full operation increases. Studies of optimisation of lock-acquisition are needed.

The structure of the Advanced Configurations Group

- ANU: bench-top experiments in RSE.
- CalTech: LIGO I, the 40m interferometer and bench-top experiments in RSE.
- GEO: signal recycling on GEO 600 and the Garching 30m interferometer. The Glasgow 10m system as a test bed for RSE. Initial inventors of signal recycling and RSE, first demonstration of both techniques.
- MIT: sensing and control for LIGO I.
- TAMA: TAMA 300 and small scale RSE prototype.
- University of Florida: LIGO I input optics experience and bench-top experiments.

R&D Program

- Bench-top experiments (CalTech, University of Florida and Australian National University) to identify all necessary sensing methods.
- a Science prototype (GEO:Glasgow, 10m interferometer). Two year program from Oct 2000 to Oct 2002.
- an Engineering prototype (CalTech: 40m interferometer). The main focus shifting here from Oct 2002 until Oct 2004.
- Continued co-operative efforts on modelling throughout the LSC groups at LSC/AIC and STAIC meetings.

The science prototype R&D program (2 years)

- To add signal recycling to the 10m Fabry-Perot Michelson interferometer at Glasgow.
- To test basic operation of a suspended-mass, resonant sideband extraction interferometer. (Sensing and control, frequency response, effect of closing the output port.)
- To further validate the modelling code that is being used to design the LIGO II configuration.
- To add power recycling to complete the LIGO II configuration. Repeating the above tests.
- To begin studies of lock acquisition.

The engineering prototype R&D program

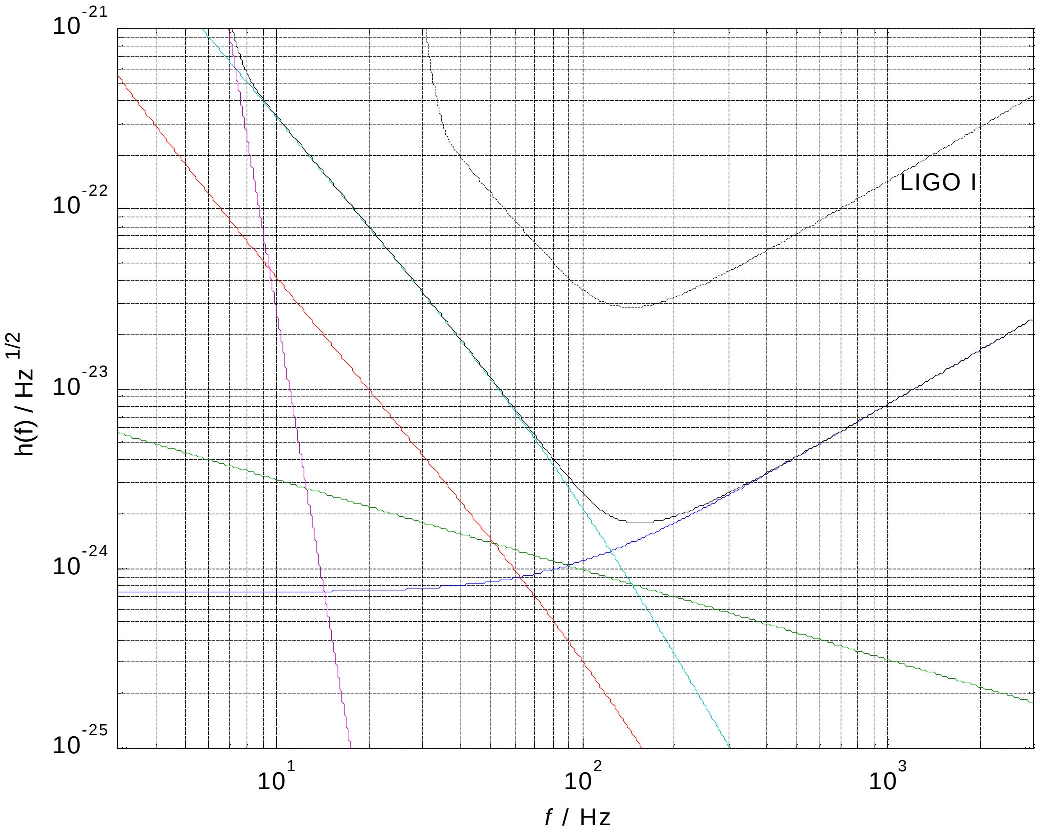
- To further investigate the sensing system tested in the science prototype and selected for LIGO II.
- To integrate the sensing and control systems using the `style' of digital control required for LIGO (and used in LIGO I).
- To optimise lock-acquisition to ensure that the start-up time of the system is a very small fraction of the typical time in lock (to be of order one week).
- To liase with the Suspensions group to ensure that the suspensions and control aspects are compatible.

Is there an alternative configuration?

- At recent LSC meetings the AIC Working Group has considered the possibility of alternative configurations for LIGO II.
- NO other configuration approaches the one selected in terms of the combination of technical readiness and performance.
- Systems with no arm cavities are technically ready, but do not offer the desired performance.
- Systems based on Sagnac interferometers or employing advanced quantum detection techniques offer improved performance but are not technically ready.

Fallback option: no signal recycling

- With no signal recycling the response is fixed. This reduces broadband performance by a factor of ~2, and reduces (narrowband) high frequency performance by a factor of ~8 (at 1kHz).



Conclusion

- The addition of signal recycling to the LIGO I configuration to produce the LIGO II configuration can enhance the science reach of the detector with a modest increase in complexity.
- This solution is technically feasible and will be fully ready after a short R&D program.