MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Proposal for the Construction of a Large Laser Interferometer for the Measurement of Gravitational Waves

Translation of Summaries of the Report M P Q 129

Vorschlag zum Bau eines großen Laser-Interferometers zur Messung von Gravitationswellen

– Erweiterte Fassung –

Gerd Leuchs, Karl Maischberger, Albrecht Rüdiger

Roland Schilling, Lise Schnupp, Walter Winkler

M P Q 131 June 1987

Max-Planck-Institut für Quantenoptik
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Preface

The existence of gravitational radiation was predicted by Albert Einstein in his theory of General Relativity already some 70 years ago. Despite major efforts, there has not yet been a direct experimental evidence for the existence of gravitational waves. According to the theory of General Relativity they are produced by accelerated masses, in close analogy to the emission of electromagnetic waves by accelerated charged particles. The effect of gravitational waves is so weak, however, that events of the magnitude of stellar catastrophes are required to allow an observation of the gravitational waves emitted.

A first aim of the planned experiment will be to prove the existence of gravitational waves; but beyond that, a successful antenna will enrich astronomy by another important observational tool: only through gravitational waves can we gain information about the millisecond processes occurring inside a star during its collapse into a supernova. These processes are of great importance, above all since this is how the heavy elements in our cosmos are created.

The first attempts to detect gravitational waves were carried out by Joseph Weber in the late sixties with antennas consisting of heavy aluminum bars. Work is going on in several laboratories to improve this detection scheme.

Meanwhile, modern measuring techniques using lasers allow the development of other methods to detect gravitational waves. One can show that a Michelson interferometer can in principle be made more sensitive than a bar antenna. In the most successful prototype of that kind so far – the 30 m interferometer at the Max-Planck-Institut für Quantenoptik – the sensitivity was brought to a first theoretical limit.

Stellar catastrophes large enough, and close enough to earth, in order to be detected with this apparatus are expected to happen on the average once per century. A rate of one event per month can be counted upon at a sensitivity 10^4 times higher than that of the existing set-up. For this purpose the armlength of the interferometer as well as the light-power have to be increased considerably. This is a challenge to optics and laser physics, and it will lead to new impulses and interesting technological developments in both areas.

The investigations performed at the Max-Planck-Institut für Quantenoptik have prepared the ground for a large scale experiment, important for the theory of General Relativity as well as for astrophysics. The final set-up is planned to be a Michelson interferometer with arms of three kilometer length each.

If one considers the efforts made to receive the information contained over the whole width of the electromagnetic spectrum, the proposal to detect gravitational waves from the universe does not seem to need any justification. Here it is not a matter of merely widening a window already successfully used, as was the case in astronomy when previously unapproachable parts of the electromagnetic spectrum have been made accessible. Rather, the step towards gravitational wave astronomy would open a totally new window. One can only speculate on the surprises waiting behind it.

In the course of the last years it became clear that further insight into the basic laws and fundamental structures of the physical world will be possible only by investigating states of extremely high energy density. Cost and size can be foreseen to put limits on the construction of ever larger accelerators, and thus presumably only astronomy and astrophysics will be able to provide new empirical approaches. Only gravity can eventually bring matter back into the state of extreme density from which it had developed at the beginning of the world. The last direct information about such a time-reversed big bang, the gravitational collapse, is precisely what is contained in gravitational waves. Perhaps the information will not be as comprehensive as one would like it to be; certainly it will bring answers to many open questions and probably it will raise new, even deeper ones.

We take this opportunity to thank Prof. Heinz Billing, *longtime former head of our group, for his unceasing efforts and his invaluable assistance in the gravitational wave project.*
Furthermore, special thanks are due to Peter Kafka *of the MPI für Astrophysik. Essentially all of Part 1 of this study was compiled and written (and later also published separately* [1]*) by him.*
We are also indebted to David Shoemaker *for his valuable help in preparing the first (1985) version* [2] *of this proposal.*

Remarks

The following collection of summaries is a translation of the summarizing sections preceding each chapter in the (German language) proposal MPQ 129

Vorschlag zum Bau eines großen Laser-Interferometers
zur Messung von Gravitationswellen
– Erweiterte Fassung –

The (updated) study MPQ 129 is organized in three main parts, just as its precursor MPQ 96 of 1985 [2]). The first part describes the origin and the physical significance of gravitational radiation as well as the mode of operation of an antenna based on a laser-interferometer. The second part points out the technical aspects of such antennas and reports on the present state of the prototypes, whereas the third part deals with the future construction of large antennas and in particular describes the proposal of the MPI für Quantenoptik.

In these three main parts a great number of very different topics are discussed. Each of the corresponding chapters is headed by a summary (Zusammenfassung) of roughly one page to give as much information about the content as is absolutely necessary for the understanding of the other chapters.

It is the translations of these Summaries (Zusammenfassungen) that is contained in this volume. For easier reference, the numbering of pages, figures, and references was made to conform with the original study. Only in very few cases have slight modifications been made with respect to the German original. The list of references in this translation contains only the publications quoted in the summaries.

The (*full*) list of publications (*in the original*) is not to be considered a complete collection of all relevant original papers. In many cases only more recent review articles are quoted; in these one will find references to earlier publications.

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1. Physics and Astrophysics of Gravitational Waves

1.1 The nature of gravitational waves

1.1.0 Summary

According to the theory of General Relativity gravitational waves are generated by the accelerated motion of masses, in analogy to the generation of electromagnetic waves by acceleration of electrical charges. Gravitational waves are believed to propagate as transversal quadrupole waves and with the speed of light. Their effect consists in the time dependent change of the spatial metric, and manifests itself in a deformation of elastic bodies or in variations of the distances between free masses in the plane perpendicular to the direction of propagation of the waves. The size $\delta\ell$ *of this distance variation is proportional to distance* ℓ *and wave amplitude* h*:* $\delta\ell = \frac{1}{2} h \cdot \ell$*. Its sign is opposite for two orthogonal directions, the orientation of which is given by the polarization of the wave.*

As sources of sufficiently high intensities of gravitational waves only astrophysical processes have to be considered. Laboratory generation of gravitational waves of detectable strength is entirely hopeless, despite the small distance between source and detector. Among the strongest conceivable emissions are the ones expected from the formation of compact astronomical objects (neutron stars or black holes), e.g. during supernova explosions. Furthermore, the final phases of the in-spiralling of binary systems with two such compact objects eventually leads to a coalescence of the two partners, in the course of which huge energies are released in the form of gravitational waves. The theoretical upper limit of the power emitted is in the order of 10^{53} *Watt.*

The exploration of such extreme collapse events will belong to the most interesting tasks of gravitational wave detectors, as the waves directly reproduce the collective mass motions in the source and also as this information presumably may not reach us by any other kind of radiation because of the high density of the surrounding matter.

1.2 Observational methods developed so far

1.2.0 Summary

The first experiments for detection of gravitational waves go back to Joseph Weber, who – after preliminary efforts during the sixties – reported in 1969 [20] *on the detection of burst type gravitational wave signals, just as they are expected from astronomical collapse events. As detectors he used two heavy aluminum cylinders about a thousand kilometers apart, the oscillation of which was registered and analyzed for coincident pulses. The reported strengths and event rates exceeded, however, the theoretical concepts of the astrophysicists by orders of magnitude. Webers experiments were therefore repeated all over the world, partly with significantly improved sensitivities* [21], *but his results could not be reproduced. Nevertheless it put an experimental upper limit of* $h \approx 10^{-17}$ *on the strength of burst type gravitational wave events.*

In the course of the seventies one therefore began looking for methods that could considerably increase the sensitivity. Because the strongest gravitational wave events expected in our galaxy occur with a rate of only a few per century, one has to improve the sensitivity far enough so as to be able to reach several thousand neighboring galaxies; then at least several events per year may be detected. This requires a measurability of strains in space of the order of $h = 10^{-21}$. *To reach this goal two approaches are promising: (1) considerably improved cylinder antennas and (2) interferometric techniques.*

To realize such sensitivities with cylinder antennas one has to use materials with very high mechanical quality factor ($Q > 10^8$) *and proceed to extremely low temperatures (millikelvins). Furthermore, one faces the problem of measuring cylinder motions that are smaller than the quantum mechanical zero point fluctuations. In principle this should be possible for one of the two canonical variables, but the experimental verification is still missing. The best sensitivity obtained with cylinder antennas is about* 10^{-18} [22].

The gravitational wave detector proposed by the MPI für Quantenoptik is of the type of interferometric antennas. The effect of gravitational waves on the distance between free masses is used, comparing the time dependent variation of light paths in two different directions in space with the help of laser interferometry. Here, the quantum mechanical limit of sensitivity is some orders of magnitude better than that of cylinder antennas, but many technical problems have so far prohibited an approach to that limit. An advantage of interferometric antennas is their broadband character, which should allow to measure the time behavior of a gravitational wave event. For that purpose, the signal must set off well enough against the noise background of the antenna; here it is helpful if some of the properties of the signals to be observed are known in advance, e.g. from theoretical considerations.

1.3 Expected cosmic signals in the frequency region around 1 kHz

1.3.0 Summary

The planned antenna will be sensitive in the frequency region from a few 100 Hz up to several kHz. Here astrophysics predicts mainly two classes of strong events: first the final state of compact binary star systems (from neutron stars and/or black holes), in which under the influence of gravitational radiation both partners spiral towards each other, and second the creation of neutron stars or black holes in supernova events (or also without such striking optical activity) at the end of evolution, especially of heavy stars. In addition, also fast pulsars or other fast rotating neutron stars radiate in this frequency range, but with significant strength only if they deviate sufficiently from axial symmetry. Finally, also a stochastic background of gravitational waves from former periods of cosmic evolution might exist.

The discussion of expected or conceivable sources of gravitational radiation shows how great the uncertainties are, not only about the existence of distinct types of sources, but even more about their strength and event rate. This uncertainty partly comes from our ignorance about the creation of our galaxy, partly from the ignorance about the state of matter at densities beyond the atomic core density, and partly from the complexity of the phenomena, which does not allow reliable model calculations even if the physical foundations are well known. But all this also shows how valuable the information contained in the gravitational waves could be to close the gaps in our knowledge. (In some cases even the absence of signals may be a valuable information!)

In figure 1.3 (in section 1.3.9) some examples of sources for different distances are entered and compared with the sensitivities of existing and planned antennas. The only source type that allows a rather reliable estimate of lower boundaries for strength and event rate is the final phase of compact binary systems. By most pessimistic estimates of the event rates, the antennas have to span a distance of about 100 Mpc to detect three such events per year with a confidence limit of 90 %. But the rate could also be much higher. For supernovae the rate (at least for optically strong events) may be estimated to some extent (some per century per galaxy), but not so the signal strength. The latter depends on too many processes and parameters that are not well enough known.

A comparison of the discussed sources with the sensitivities of the antennas shows that the search for gravitational wave events with installations of the type proposed here is promising. It may well be expected that at a later time a real gravitational wave astronomy may arise from these efforts.

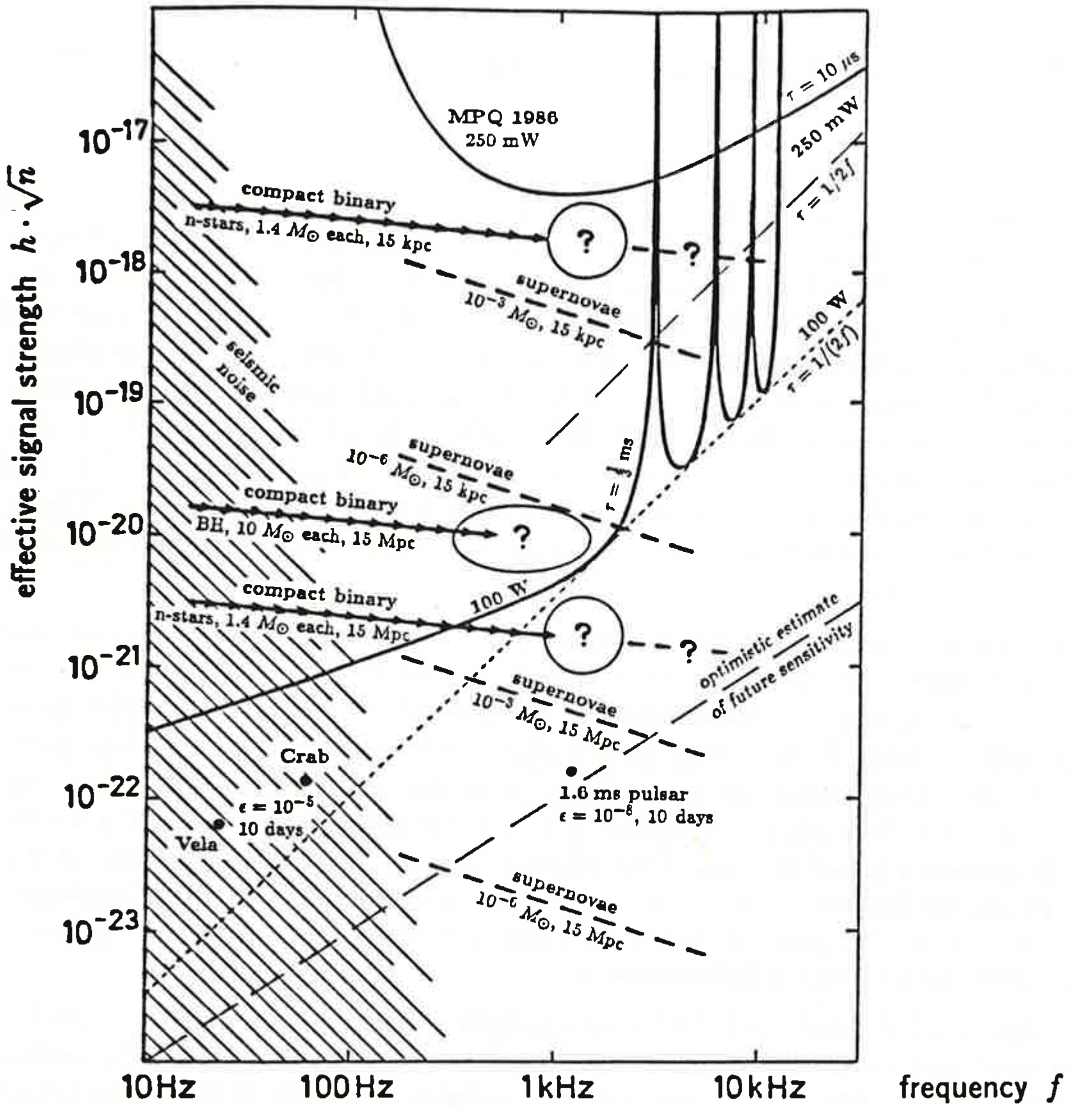

Fig. 1.3 : Signal strength expected from some more likely sources, expressed as product $h\sqrt{n}$ versus frequency f, where h is the gravitational wave strain and n is a quality factor specifying the number of oscillations near the frequency f. Examples given are supernova events with emitted g.w. energies of 10^{-3} or 10^{-6} $M_\odot$, and the evolution of compact binaries; in both cases they are given for distances inside our galaxy (15 kpc) and to the Virgo cluster (15 Mpc). As examples of periodic sources, some pulsars are indicated. The curve for supernovae in our galaxy also indicates an upper bound to the signals that could have been expected from the supernova SN 1987 A.

For comparison, the fundamental limit due to shot noise is shown, for an effective light power of 100 W. The dotted line indicates the sensitivity limit if for each frequency the storage time τ were optimized: $\tau = 1/(2f)$. The solid curve touching this line describes the proposed delay-line antenna (at $P = 100$ W), optimized for $f_m = 1.5$ kHz. In the vicinity of the even harmonics of f_m, the antenna becomes particularly insensitive.

A corresponding limit for 250 mW is given by the upper dashed line, and the top curve (MPQ 1986) indicates the best experimental results so far, achieved in the 30 m prototype operated with $\tau = 10\mu s$.

The lower dashed line indicates a sensitivity limit conceivable under very optimistic assumptions of "recycling" of light at an input power of 100 W (and on suppressing all other noise sources sufficiently) [42,43].

2. Laser Interferometry for the Detection of Gravitational Waves

2.1 Laser interferometry using long optical paths

2.1.0 Summary

For broadband measurements of the extremely small strains $h/2 = \delta L/L$ caused by gravitational waves, interferometric methods are well suited. As was shown in Part 1, a sensitivity of the order of $h \approx 10^{-21}$ is required to be able to measure events at a scientifically useful rate.

Of particular advantage is a Michelson interferometer[1] (as indicated in figure 2.1), since the symmetry between the two arms will lead to a cancellation of a large number of noise effects [37,38]. From considerations of light power and stability, laser light seems the only feasible source of illumination [39]. Aside from the currently used argon ion lasers (wavelength $\lambda = 0.5145\,\mu m$), also Nd:YAG lasers $\lambda = 1.06\,\mu m$ are being considered.

Short term deviations $\delta L(t)$ from an appropriate operating point (e.g. the minimum of interference) are compensated by a feedback system. The compensating voltage $V_P(t)$ that the feedback applies to an electro-optical crystal, a Pockels cell, thus represents the output signal to be analyzed for gravitational waves. The path difference $\delta L(t) = h(t) \cdot L$ caused by a gravitational wave of strength $h(t)$ is the larger, the longer the optical path L is chosen. The phase difference in the interferometer will, however, increase with increasing path L only until an optimum path $L_{opt} = c/(2f_m)$ is reached, half the wavelength of the gravitational wave. For a typical mean frequency f_m of 1.5 kHz, this results in $L_{opt} = 100$ km. A good vacuum is required to avoid fluctuations of the refractive index in the light path due to fluctuations in the residual gas.

Optical paths of the required length L can be realized, e.g., with so-called optical delay lines [36]; in these, the light is bounced back and forth between two mirrors separated by a distance ℓ, and it exits, after an even number N of passes, via the same hole in the front mirror by which it had entered (for simplicity, $N = 4$ is chosen in figure 2.1). Thus, the total path is $L = N \cdot \ell$. With currently available mirror reflectivities (99.99 % and better, at least for small mirrors), a number of reflections of up to $N = 10^3$ would pose no problems. For sufficient separation of the beams, however, a mirror diameter of $D \approx 2.5 \cdot \sqrt{L\lambda}$ is required: $D = 0.6$ m for $L = 100$ km and $\lambda = 0.5145\,\mu m$.

In a different scheme [93] to realize long optical paths L, each arm consists of a Fabry-Perot cavity, again made up of two (concave) mirrors at distance ℓ.

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[1] In this report, the term *Michelson interferometer* denotes an arrangement in which the paths in two symmetric arms are compared interferometrically, and where the long optical paths can be realized either with multiple reflections in delay lines or with Fabry-Perot resonators. This differs from a more restrictive usage where a "Michelson" signifies an interferometer using delay lines.

This method will allow much smaller mirrors ($D \approx 2 \cdot \sqrt{\ell\lambda}$), but at the price of a number of operational disadvantages.

The Gravitational Wave Group at the MPI für Quantenoptik will – at least for the moment – continue to pursue the delay line approach that has so far proved advantageous. It is planned, also, to study a variant in which the two large mirrors are replaced by $N-1$ separately suspended smaller ones. Advantages and disadvantages of this yet untested mirror set-up will be discussed.

Even if a total optical path L of 100 km is realized, the strain in space to be measured, $h \approx 10^{-21}$ (as expected from stellar collapse events in the Virgo cluster), would cause path changes δL of as little as 10^{-16} m, i.e. only $2 \cdot 10^{-10}$ optical wavelengths. With a number of, say, 15 reflections at each mirror ($N = 30$, $\ell = 3$ km), this would represent a mirror displacement of only $3 \cdot 10^{-18}$ m, to be detected in the presence of a large number of noise sources. The experimental difficulties and the fundamental limits will be further discussed in the ensuing chapters (2.2 to 2.5).

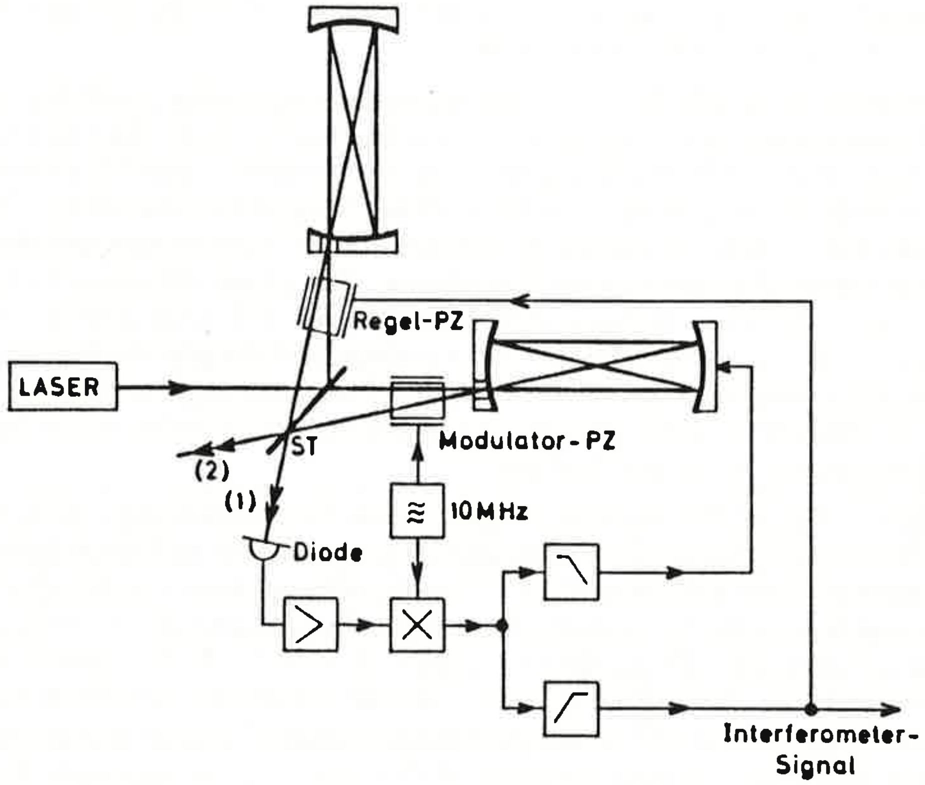

Fig. 2.1 : Schematic diagram of a Michelson interferometer with optical delay lines ($N = 4$). Feedback control of the operating point is accomplished via electro-optical crystals (modulator and control Pockels cells) and via mechanical mirror control. The high frequency part of the feedback signal represents the output signal of the interferometer.

2.2 A first fundamental limit: shot noise

2.2.0 Summary

A first fundamental limitation of the antenna sensitivity stems from the statistical power fluctuations due to the quantum nature of light. This so-called shot noise fakes a fluctuating path difference in the interferometer, with equal contributions of the mean squared fluctuations $<(\delta L)^2>$ per unit bandwidth over the whole frequency band ("white noise"). These contributions can be described by a (linear) spectral density

$$\widetilde{\delta L}_{\mathrm{SR}}(f) = \sqrt{\frac{\hbar c}{\pi} \cdot \frac{\lambda}{\eta P}} \; . \tag{2.1}$$

This white noise decreases – due to more efficient averaging – as the available converted light power ηP is increased ($2\pi\hbar$ is Planck's constant, c the velocity of light, λ the wavelength of the light, and η the quantum efficiency of the photo diode, a value close to unity).

For the argon ion lasers chiefly considered at present ($\lambda = 0.5145\ \mu$m), with a (single mode) power $P = 5$ W now commercially available, this leads to $\widetilde{\delta L}_{\mathrm{SR}} = 0.3 \cdot 10^{-16}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$. With $L = 100$ km and a measuring bandwidth of 1 kHz, one arrives at a limit for the strain sensitivity h of 10^{-20}, still about one power of ten away from the goal of $h = 10^{-21}$.

To reduce the shot noise limit by this factor of 10, according to equation (2.1) the light power P circulating in the interferometer would have to be raised by two powers of ten. Two approaches seem promising, and presumably both will have to be employed simultaneously.

Operation of argon ion lasers at powers up to 300 W has been reported; so far, however, only for durations of a few hours (mirror burn-out). With Nd:YAG lasers, even higher powers (time averaged) have been reported, but various problems (single mode and noise behavior) will yet have to be investigated. Operation at the original light frequency ($\lambda = 1.06\ \mu$m) or at double frequency ($0.53\ \mu$m) appear possible.

Higher light powers can, however, also be achieved by coherent superposition of the light from a number of medium power lasers (commercial types with high reliability). This scheme requires phase-locking several "slave" lasers to a well stabilized "master" laser. Preliminary experiments [94] have been promising. In case of failure of one laser, the antenna's operation could be continued (at slightly reduced power).

The other scheme for reducing shot noise exploits the fact that in the usual operation of the interferometer the interference at the measuring port is kept near minimum; thus, practically all light leaves via the other output port unused. With an additional beam splitter (or coupling mirror) this light can be returned to the interferometer, leading to a substantial enhancement of the power inside the interferometer ("recycling"). This method requires a very efficient stabilization of the laser frequency, for a fixed phase relation must be maintained between the light

just emitted from the laser and the light that has circulated in the interferometer for as long as several milliseconds.

The "second control circuit" incorporated in the prototype at the MPI für Quantenoptik for a more efficient frequency control represents an important step towards this "recycling". Meanwhile, preliminary tests with recyling have been performed at the MPI für Quantenoptik; in these experiments (in a simplified interferometer, but with separately suspended and controlled mirrors) a considerable enhancement over the laser power applied has been achieved, accompanied by an appropriate reduction of the shot noise level.

A further method for reducing shot noise could be the utilization of optical fields with non-classical photon statistics. For freely suspended mirors, this possibility has so far been investigated only theoretically; however, the existence of the required non-classical light fields ("squeezed states"), and their use in rigid interferometers, has recently been demonstrated by several investigators.

2.3 Mechanical noise sources

2.3.0 Summary

To obtain the required sensitivity, a thorough isolation of the interferometer from mechanical vibrations is essential. Particular care must be spent on the isolation of the mirrors, the displacements of which appear multiplied with N, the number of passes in the optical delay line.

The first measures taken are passive ones: the mirrors are suspended by relatively long, very thin, wires. For frequencies f well above the pendulum frequency f_P (of the order of 1 Hz), the mirror displacements are reduced below the displacements of the suspension points by a factor $(f_P/f)^2$, i.e. by 5 powers of ten at $f = 300\,\mathrm{Hz}$.

For a further reduction, the suspension points are, in turn, isolated from ground vibrations by mechanical filters. This is achieved in some laboratories with alternating layers of elastic and of heavy materials (rubber and lead). At Garching an additional pendulum stage is used, formed by suspending the common platform from which the individual optical components are hung.

Above frequencies of 100 Hz, these measures lead to a suppression of the mechanical vibrations that is sufficient for present prototype sensitivities. With increasing sensitivity, the demands will rise, but even then purely passive measures are expected to suffice.

Towards lower frequencies, the seismic excitation increases approximately with a $1/f^2$ law. Furthermore, the pendulum suspension of the (four) mirrors and of other components leads to a strong enhancement over the external excitation near the pendulum frequencies (near 1 Hz). Although these oscillations are well below the frequency range of interest, the nonlinear dependence of the interferometer signal on the mirror displacement leads to apparent mirror motions even at these higher frequencies. It is essential, therefore, to keep – even at the pendulum frequencies – the path differences δL well below a light wavelength. Active control circuits are used for this purpose. A first step consists of a frequency-selective damping of the motions of each individual mirror, in the frequency range around the pendulum resonance [120].

*For stabilizing the **distances** between the mirrors, low frequency control systems with much higher demands are used. One such control system serves to keep the **absolute** lengths of the optical paths (L_1, L_2) in the two arms constant. At low frequencies, a stability of about 10^{-8} m is sufficient, and this can be met with interferometric methods [94].*

*Much higher yet are the demands on the stabilization of the path **difference** $\Delta L = L_1 - L_2$ between the arms; in the experiments at the MPI für Quantenoptik, this difference is held to less than 1/100 of a wavelength, or only 5 nm. With $N \approx 100$ passes in the optical delay line, this corresponds to a residual mirror motion of 0.05 nm (= 0.5 Å). The particularly large displacements caused by mechanical excitation at low frequencies were thus suppressed to sufficiently low levels.*

To avoid acoustic excitation of the mirrors, and noise due to local fluctuations of the residual gas pressure, the whole interferometer must be operated in high vacuum (better than 10^{-6} mbar).

A further noise source is scattered light that returns via the (vibrating) tube walls to the main beam; it can lead to spurious signals even if the mirrors were at complete rest.

2.4 Second fundamental limit: thermally excited motions

2.4.0 Summary

A second fundamental limitation of the sensitivity is due to the thermally driven vibrations of the test masses (mirrors). Even if all excitation by ground motions, acoustics, and residual gas were eliminated (see preceding chapter), the thermal excitation would remain, leading to a kinetic energy of $kT/2$ in each of the numerous flexural and compressive modes of the end masses (k = Boltzmann constant, T = absolute temperature).

Near their resonant frequencies, these mirror oscillations have amplitudes that are several orders of magnitude above the signals expected from gravitational waves. The proper remedy is to keep all mirror resonances involved sufficiently far outside the frequency range of interest, preferably at frequencies above 5 kHz. For this, it is important to keep the design of the suspended masses as simple as possible.

In the scheme with optical delay lines, the very large mirrors required are sufficiently heavy to be used as the test masses. To avoid additional resonances, it proved advantageous to suspend these mirrors directly – without any mounting mechanisms – in a wire sling [94], quite similar to the suspension used with Weber bars.

This departure from the earlier scheme of a compact central block containing beam splitter, Pockels cells, and near mirrors provided the additional advantage that the inevitable thermally driven motions of beam splitter and Pockels cell mounts will not couple onto the mirrors, the motions of which appear multiplied with N. In later improvements, also the beam splitter and the Pockels cell mounts were suspended separately in the same wire sling scheme. In this set-up, no resonances were visible in the frequency region below 6 kHz.

Resonances above 6 kHz will, however, due to their low-frequency tails, also contribute noise in the measuring range, with a statistical motion $\delta\ell$ of the mirror surfaces featuring a "white" (frequency-independent) spectrum. This fluctuation will be the smaller, the larger the mirror mass M and the mechanical quality factor Q are, and the higher the resonant frequency f_0 is. For the mirrors envisioned (fused silica, 0.6 m in diameter), the noise contributions in a frequency range of 1 kHz bandwidth will reach $4 \cdot 10^{-19}$ m.

The essential conclusion from these considerations is that one has to choose the geometrical arm length ℓ in the order of a few kilometers in order to arrive at the desired sensitivity h ($= 2\,\delta\ell/\ell$) of about 10^{-21}.

In a possible (but not yet tested) variant of delay lines with many separate mirrors (N instead of 2), the thermal fluctuations may be lower by a factor $\sqrt{2/N}$ which might facilitate achieving the required sensitivity.

2.5 Optical noise sources

2.5.0 Summary

Aside from the fundamental limitation due to the quantum nature of light (shot noise, see Chapter 2.2), there are a number of further optical noise sources, all of a more technical nature.

The laser light used for the illumination of the interferometer is subject to three major types of fluctuations (intensity, beam geometry, frequency) that give rise to noise signals competing with the signal due to gravitational waves. These laser fluctuations have in common that they manifest themselves as noise signals only to the extent that the interferometer deviates from ideal symmetry.

The mode of operation chosen, near a minimum of interference, makes the interferometer quite insensitive to power fluctuations of the laser. With the sensitivities reached in the prototypes so far, a reduction of these power fluctuations was not yet required, but various methods would be available should the need arise.

Fluctuations in beam geometry (with respect to position, orientation, diameter, divergence) constitute a severe noise source, the effect of which depends on how far the wave fronts of the two interfering beams deviate from an exact match [120]. Very accurate matching of the optical components in the two arms, and very precise adjustment of the beam splitter can alleviate the problem, but nevertheless additional measures have to be taken to reduce the beam fluctuations. Passive methods are the "mode selector" developed at the MPI für Quantenoptik [135] and mono-mode glass fibers [136, 137]. An active control of beam position and orientation was developed at Glasgow [138].

Fluctuations of the laser frequency ν (and thus of the wave length $\lambda = c/\nu$) are transformed into noise signals via an inequality ΔL between the optical paths L_1 and L_2. Differences in the radii of curvature of the mirrors appear unavoidable, and in order to match the wave fronts, one will have to put up with a certain inequality ΔL. This necessitates an extremely good stabilization of the laser frequency.

At the MPI für Quantenoptik, the frequency jitter was reduced to about $10^{-1}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ (linear spectral density) with the aid of a primary control loop. An additional stabilization down to the order of $10^{-3}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ was achieved with a secondary control loop, and further improvements appear possible.

The second control loop also provides an efficient reduction of the noise signals due to light scattered in the interferometer. Such scattered light components can have extremely large path differences ΔL with respect to the main beam with which it interferes. Thus, despite the smallness of its intensity (only 10^{-8} of the main beam, e.g.), the scattered light effect can transform frequency fluctuations into intolerably large noise signals. It is hoped that even in more sensitive interferometers this scattered light problem can be solved with frequency stabilization alone.

There is, however, the additional possibility of using an appropriate modulation of the laser frequency in order to render the scattered light contributions

ineffective. The idea is to break the coherence between the scattered light components and the main beam, thus "washing out" their time-averaged influence, whereas the main beams returning from the two arms retain their full coherence. Such a modulation can consist of sinusoidal components, of switched phase steps, or of "white noise", and it finds its most extreme realization in the use of ultrashort light pulses in the mode coupled operation of a laser. With such schemes, a major part of the noise signals due to scattered light can be suppressed.

2.6 Status of the different laboratories

2.6.0 Summary

During the last few years five laboratories have been involved in developing laser interferometers for gravitational wave detection. In chronological order these are: MIT (Massachusetts Institute of Technology, since about 1971), MPI für Quantenoptik (Garching, initially at the MPI für Astrophysik in München, 1975), Glasgow (University of Glasgow, 1976), Caltech (California Institute of Technology, 1980) and finally Orsay (Université de Paris-Sud, 1983). The activities in these laboratories and the results of the corresponding prototypes are described here. Also discussed are the techniques that have led to significant improvements in sensitivity.

A presentation of the prototype sensitivities of four more senior laboratories was prepared by Kip Thorne for the NSF-Workshop [145], *and it is reproduced here with his kind permission. In its upper part this figure 2.15 shows the evolution of the sensitivities expressed as the (linear) spectral density $\tilde{\mathfrak{X}}(f)$ of the noise amplitude at a frequency of $f = 2$ kHz. The lower part sketches the corresponding strains $h_{\rm rms}$ for a broad band signal, to facilitate comparison with resonant bar antennas. The most recent measurements of the noise spectra are reported in Sections 2.6.1. to 2.6.5.*

The construction of a prototype with $\ell = 1.5$ m arm length was started quite early at MIT, under the supervision of R. Weiss [36]. *This prototype uses the delay line technique, at present with $N = 56$ folded beams. Some decisions made in this early stage later on have prevented this prototype from reaching a high sensitivity. Today its noise level is still very high, partly because the light path $L = N \cdot \ell$ has only the moderate length of 82 m. The group at MIT contributed significantly to questions of optical delay lines, of beam steering and mode cleaning with monomode fibres and of "whitening" the laser light to suppress stray light effects. The broad band phase modulation of the laser light necessary to achieve the "whitening" can, however, only with difficulty be combined with the technique of light recycling. Considerable sensitivity improvement is expected from the 5 m prototype currently under construction at MIT.*

The prototypes developed at Glasgow (first under R.W.P. Drever and then under J. Hough) and later on at Caltech (under R.W.P. Drever) [146, 125] *use the Fabry-Perot technique, with values of finesse $\mathcal{F}$ initially around 100 to 200 and now of 2000 to 5000. One of the two Fabry-Perot resonators is used for frequency stabilizing the laser and the signal is obtained by comparison with the resonator in the other arm. However, the final goal is a more symmetric arrangement where the light coming back from the two resonators is combined and interferes destructively. It is only in this mode of operation that light recycling could be employed. The best results (some yet unpublished) for the prototype at Glasgow ($\ell = 10$ m) and at Caltech ($\ell = 40$ m) which were obtained by December 1986 are included in figure 2.15.*

Quite early, with the 3m-prototype interferometer of the Max-Planck-Institut (labeled "Munich 3m" in figure 2.15) very good results were achieved, but only

after the elimination of several noise sources that have been recognized here for the first time. In the final form of operation (August 1982), with a total optical path of $L = 138 \times 3.05$ m $= 420$ m, its measured noise level in the frequency range from 0.5 to 3 kHz was only slightly above the fundamental shot noise limit [38].

An additional order of magnitude in strain sensitivity $h_{\rm rms}$ was gained with the larger 30m-prototype which initially (June 1984) was operated with $N = 50$ beams ($L = 50 \times 30$ m $= 1.5$ km) [94]. *There, again, the fundamental shot noise limit was essentially reached at frequencies around 1 kHz. Later on a correspondingly better performance was obtained also for a laser power of about 0.3 W* [97].

The "second feedback loop" used for an improved frequency stabilization of the laser in the 30m-prototype was an important intermediate step towards the recycling of light, which in the meantime has been demonstrated at Garching [97]. *Experiments with light recycling have also been carried out at Orsay. Instrumentally their approach was quite different, but the results obtained were comparable.*

So far no measurements have been reported from two very young groups: one in Tokyo (Institute of Space and Astronautical Science), where the construction of a 10 m-prototype was just started (January 1987), the other one in Pisa (Istituto Nazionale di Fisica Nucleare), where an extremely efficient seismic isolation system is being developed. No detailed information is available about the work on the 3 m-prototype in the People's Republic of China (Institute for Gravitational Physics, Quanzhou).

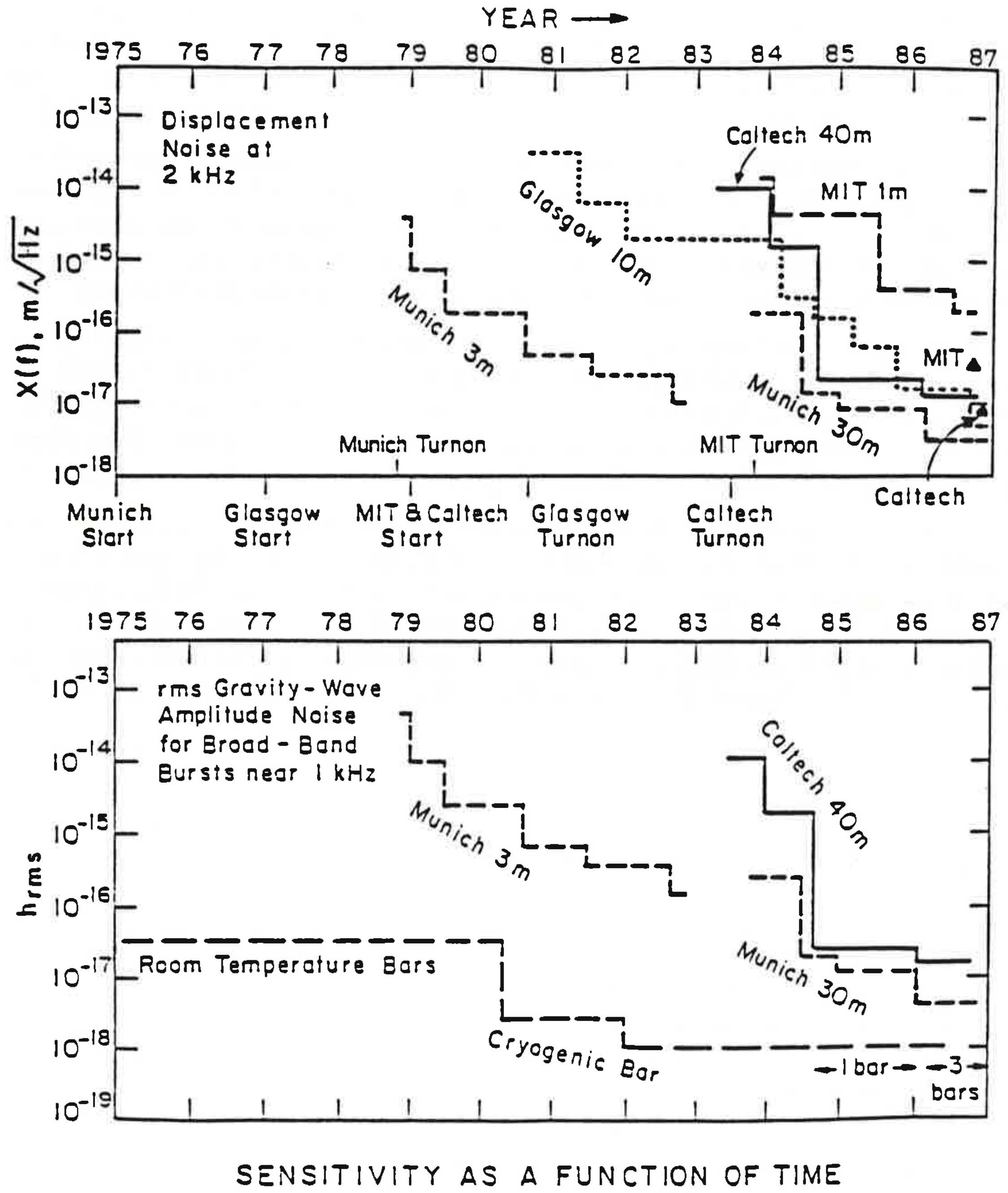

Fig. 2.15 : Evolution of the sensitivities of various interferometer antennas, compiled by Kip Thorne [145].

Upper part (2.15 a): Noise spectrum expressed by the apparent mirror motion $X(f) = \tilde{\delta\ell}(f)$ *at a frequency* $f = 2$ *kHz.*

Lower part (2.15 b): For comparison with bar antennas: strain h_{rms} *of a broad band gravitational wave pulse that equals the rms noise.*

Some more recent improvements are discussed in the text of the full report MPQ 129 (in German).

3. Proposals for the Construction of Large Scale Gravitational Wave Antennas

3.1 Proposal of the MPI für Quantenoptik for a large scale gravitational wave antenna

3.1.0 Summary

The discussion in Part 2 has shown that the construction of gravitational wave antennas with a sensitivity around $h = 10^{-21}$ *required for Virgo cluster events is feasible. Although based on known technologies much development is yet to be done, and the quoted sensitivity may be reached only with considerable financial and technological effort. In particular, the effects of noise sources like thermal mirror excitation, seismic and vacuum pressure fluctuations can be kept low enough only if the mirror separation* ℓ *is increased up to a few kilometers.*

The proposal of the MPI für Quantenoptik is to build a large antenna with an arm length of about 3 km. The diameter of the vacuum tubes should be about 1 m in order to accomodate the successfully tested method of optical delay lines. Moreover, this leaves open several options: change to a YAG-laser (wave length $\lambda = 1.06\,\mu m$*), incorporation of additional interferometers, and increase of the total optical path L in connection with using several smaller mirrors. In addition the larger tube diameter reduces the scattered light problem due to tube wall motion.*

It is reasonable to request that the vacuum tubes be easily accessible, and that they are protected from environmental influences (temperature changes, wind, precipitation, acoustic noise and ground vibration). The best design seems to be a (possibly sliding) suspension with supports having well separated foundations, sheltered by a soil covered tunnel which is accessible to service personel. Other possibilities are discussed.

Ultimately, for the operation of an antenna station there should be at least two differently oriented interferometers, each with arms 3 km in length. This ensures a sensitivity with respect to the two different states of polarization of the gravitational wave. A configuration with altogether three interferometers would be even better because of the redundancy of the measurement, and of continued operation even in case of maintenance on one of the interferometers. It is proposed to achieve this by adopting a triangular design consisting of three interferometers the arms of which have mutual angles of 60° (figure 3.4). The small decrease of sensitivity (the signal is 13% smaller than for 90° arms) is compensated for by the reduced size of the required estate and by the better usage of tunnels and buildings.

The site should be fairly plane, i.e. have constant tilt, to keep the ground preparation inexpensive. For experimental reasons an exactly horizontal site would have advantages but is not absolutely necessary. The antenna should be separated by at least 1 km from sources of noise and ground vibration and from traffic routes.

Farming on the site area can be allowed if this perturbs the antenna only during a few days per year. For several reasons it is desirable to have the site within less than two hours by car from the supervising institute (MPQ Garching).

3.2 Definition phase

3.2.0 Summary

Before constructing a facility as large as the proposed antenna, some studies on details of the buildings, the vacuum and the optical system have to be done. Such studies were started soon after the first version of this proposal has been presented by the MPI für Quantenoptik in 1985, and some of them have already been completed.

These investigations are performed jointly by the gravitational wave detection group at the MPI für Quantenoptik, by the construction department of the general administration of the Max Planck Society, and by commercial companies. The distribution of the work among these groups depends largely on the subject.

With regard to the planning of the facility there are three main aspects: site selection, design of the buildings and of the vacuum system. A survey of possible sites in Bavaria was carried out with respect to topography, distances to inhabited areas and heavy traffic, seismic ground motions and finally, depth of the watertable. This preselection was done in collaboration with the construction department, and was based on computer stored topographic data of the Industrieanlagen-Betriebsgesellschaft mbH (IABG). For several of these sites the seismic behaviour was measured by the Geophysikalisches Institut der Universität München, and a report concerning the construction costs has been prepared by the engineering company Dorsch Consult. Preliminary design studies for the buildings and the vacuum system have lately been worked out by commercial companies.

Further investigations are still necessary, particularly for the optical system. It is important to note that the actual design of the optics influences neither the building nor the vacuum system. Therefore, the two subjects can be dealt with seperately at least until the end of the phase of detailed planning.

With respect to the optical system close collaboration with the producer will be essential. Some of the extreme requirements can be fulfilled only by leaders in the respective technologies. For almost all these tasks there are appropriate companies in West Germany which simplifies the collaboration. It is expected that this research and development will be helpful also for other applications.

For the production of the very large mirrors for the optical delay line extreme care has to be taken in all three production steps (substrate, polishing and coating). A set of mirrors having the quality necessary for the large facility should be produced as soon as possible so that it can be tested in the 30 m prototype interferometer. (At present the quality aimed at cannot be checked with any other device.)

Also important are production and studies of optical fibres, where single mode performance and a high threshold for light power damage are essential. Pockels cells for a large beam diameter having high optical quality and damage threshold have to be ordered and tested. Photodiodes have to be tested with respect to quantum yield and upper limits for photo-current and frequency response. It may be that minor modifications will be necessary.

Some of the optical methods to be used have still to be studied and refined further. Among them are:

- *phase locked combination of several argon-ion-laser beams (at first two)*
- *better stabilization of the laser (mainly with respect to frequency)*
- *reduction of scattered light perturbations with various types of light modulation at the interferometer*
- *recycling of the light*
- *improved seismic isolation (possibly active feedback).*

Many of these techniques when developed to their limits will be interesting also for other applications. In addition and of more fundamental interest, experiments generating non-classical light fields (squeezed states) are performed.

During the course of the definition phase it should be discussed whether the use of the large facility for other projects is possible and desirable. Some meteorological and geophysical data must be logged in any case when operating the large facility. However, other applications would require a modification of the set-up or even a temporary shut down of the gravitational wave detector.

The idea of using the Sagnac-effect to measure fluctuations of the earth rotation and possibly the (relativistic) gravitomagnetic effect has been much discussed in the literature. A separate section deals with this question.

The definition phase was started in 1986. Preliminary studies for the planning of the optical system may yet take another year. It would be desirable if during this time the detailed planning could already be started in order not to delay the completion of the large facility.

3.3 Preliminary design considerations

3.3.0 Summary

In order to estimate the total cost of a large gravitational wave antenna preliminary design studies on tunnel construction, vacuum system and auxiliary systems have been prepared by the companies Dorsch Consult and Interatom. The construction department of the MPG estimated the space required inside the end houses. Thus the major part of the costs is accounted for. The final numbers are comparable to the cost estimates in the MIT [139] and the British proposal [106]. Details which still have to be fixed in the definition phase will have only minor impact on the total costs.

The cost estimates have shown that for an arm length of 3 km the fixed costs are smaller than the length dependent costs which consist of two roughly equal parts, the tunnel construction and the vacuum tubes. The costs for the tunnel construction include moving of the soil, laying the foundation and constructing the tunnel itself. For a single interferometer the total length of the tunnel will be 6 km, increasing by only 3 km to a total of 9 km for a "redundant" triangular configuration. Other costs also depending on the length of the tunnel like power, signal, water and control lines make up only a small portion of the total length dependent costs.

The amount of money needed for the vacuum system is the other large position of the length dependent cost. The three items, raw material, production, and installation of the cleaned tubes, contribute about equally. In comparison, the costs for the pumps required for a vacuum of 10^{-6} *mbar are not very significant. The tube length for a single interferometer is 6 km, for a "redundant" facility consisting of three interferometers it is 18 km.*

The buildings at the ends of the interferometer arms have to house the test-mass vacuum tanks (diameter 2 to 3 m and height 3 m). The laboratory space required is at least 400 m^2 *(20 m × 20 m) and its height should be about 5 m. It has to be ensured that the laboratory can be run under clean room conditions.*

With some auxiliary space for office, computing and a small workshop the volume of the buildings will be about 2500 m^3*. In addition to one of these houses (and preferably somewhat separated spatially) there has to be a supply station with electrical transformer, direct current generator, processing of cooling water etc. The costs for these buildings can be estimated reliably based on total volume and special requirements. The costs for infrastructure (access, supply of electricity, water and telephone) may play some role when chosing a site, although it will not be very significant.*

In comparison to the costs discussed so far the expense for optics and laboratory equipment are less important. This holds even if eventually the facility is upgraded to the full triangular configuration.

The total costs for a 3 km interferometer are estimated to consist of three more or less equal parts for tunnel, tubes, and fixed costs. For a "redundant" triangular facility with three interferometers of 3 km arm length each, the tunnel costs will

increase by a factor of 1.5, and the fixed costs likewise. In contrast the costs for the vacuum system will nearly triple. Therefore, a full triangular configuration with three interferometers will be about twice as expensive as a single interferometer.

The largest portion of the running costs will be the one for electrical power. However, the full electrical power will be needed only when the lasers are run at full power, which presumably will happen about five years after starting construction. With the advent of alternative laser systems the electrical power requirements may be reduced substantially. Even if all the measured data are to bestored on magnetic tape the running costs for date storage will only be a small portion of that for electricity.

3.4 Plans of other laboratories and international collaboration

3.4.0 Summary

The construction of large antennas is planned by all the groups currently engaged in interferometric detection of gravitational waves (MIT, MPQ, Glasgow, Caltech, Orsay/Pisa). Fairly advanced are the preliminary studies in the USA, where the two groups at MIT and Caltech jointly push the construction of two antennas each of 4 km arm length, and in Great Britain, where the University of Glasgow, assisted by the Rutherford Laboratories and the University of Cardiff, is planning an interferometer that ultimately shall have a length of 3 km. In both countries, USA and Great Britain, proposals for the construction of large interferometers have been submitted to the national funding agencies. Also in Italy the funding of an interferometer with 3 km arm length has been applied for.

In addition to the five groups in the USA, Great Britain, France/Italy and West Germany there is substantial interest in the construction of large scale laser interferometric gravitational wave detectors in Japan, the USSR and the People's Republic of China.

Owing to the good relations between the laboratories involved, results and information are frequently exchanged between these groups. At the workshop on "Gravitational Wave Physics and Astronomy", especially organized by the MIT-group in November 1986 for the US-refereeing panel, representatives from the European groups also participated.

The collaboration among the groups in Europe has existed already for several years, and since two years with financial support through the EC twinning program. Once a year all members of the European groups meet for several days. Exchange of scientists has already started.

A signal detected by a gravitational wave antenna can be considered significant only if it is supported by a coincidence measured with at least one other antenna spatially well separated from the first one. Following this reasoning two equivalent antennas are projected in the US, one located in California and the other one in New England. Presumably, no country in Europe will support two spatially well separated antennas so that international collaboration is obligatory. In a common statement the European and the US groups have agreed to an exchange of information and data.

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