

# Military Applications of High-Frequency Gravitational Waves (Abridged)

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*The predictions in this document of benefits of high-frequency gravitational wave-based military applications are theoretical at this time. Evidence of their success is contingent upon laboratory experiments in generation and detection. Nonetheless, given their vital strategic military and economic importance, GravWave believes these potential applications are important motivations for research and development.—Dr. Robert Baker, Jr.*

## EXECUTIVE SUMMARY

- High-Frequency Gravitational Waves (HFGWs) have excellent theoretical support and pass through all material, for example directly through the Earth, without attenuation.
- Technology developed by GravWave LLC and other institutions overseas can lead to devices, some already constructed, that can generate and detect HFGWs.
- Because of their unique characteristics, HFGWs could be utilized for uninterruptible, very low-probability-of-intercept (LPI), high-bandwidth communications.
- Other potential theoretical applications are propulsion, including “moving” space objects and missiles in flight, surveillance through buildings and the Earth itself, and remote initiation of nuclear events.
- These important potential military applications are motivations for research and development and such an R&D program is recommended for immediate initiation.
- Contrary to published misinformation, the Li-Baker HFGW detection and generation technology is not based on the Gertsenshtein effect.

**Preface:**

The following White Paper is divided into four parts: Benefits to the Military, Threats to National Security, Physics and Plan for Developing Working Prototype. It is important to recognize from the outset that, aside from communications, the military applications are theoretical. These applications can only be evaluated *after* the Proof-of-Concept Experiment, since prior to that there are many unanswerable questions. The physics, discussed in Section 3, however is sound and all applications have reasonable expectations. It should also be recognized that there have been some five decades of research concerning high-frequency gravitational waves (HFGWs)—most of them in the form of peer-reviewed publications in the open scientific literature. Three HFGW detectors have been built overseas already. Much of the prior research is described in the section concerning Physics and several dozen references are cited at the conclusion of this paper. Although most of the theoretical applications are stunning, the field of HFGW research is far from being science fiction. The plausibility of the theoretical applications cannot be adequately determined until after a proof-of-concept test is successfully completed.

### **What are high-frequency gravitational waves or HFGWs?**

Visualize the luffing of a sail as a sailboat comes about or tacks. The waves in the sail's fabric are similar in many ways to gravitational waves, but instead of sailcloth fabric, gravitational waves move through a "fabric" of space. Einstein called this fabric the "space-time continuum" in his 1916 work known as General Relativity (GR). Although his theory is very sophisticated, the concept is relatively simple. This fabric is four-dimensional: it has the three usual dimensions of space—east-west, north-south, and up-down—plus the fourth dimension of time. Here is an example: we define a location on this "fabric" as 5th Street and Third Avenue on the fourth floor at 9 AM. We can't see this "fabric," just as we can't see wind, sound, or gravity for that matter. Nevertheless, those elements are real, and so is this "fabric." If we could generate ripples in this space-time fabric, many applications would become available to us. Much like radio waves can be used to transmit information through space, we could use gravitational waves to perform analogous functions. Gravitational waves are the subject of extensive current research, which so far has focused on low frequencies. High-frequency gravitational waves, as defined by physicists Douglass and Braginsky (1979), are gravitational waves having frequencies higher than 100 kHz.

### **Military Applications**

Of the applications of high-frequency gravitational waves (HFGWs), communication appears to be the most important and most immediate. Gravitational waves have a very low cross section for absorption by normal matter, so high-frequency waves could, in principle, carry significant information content with effectively no absorption, unlike electromagnetic (EM) waves. Multi-channel HFGW communications can be both point-to-point (for example, to deeply submerged submarines) and point-to-multipoint, like cell phones. HFGWs pass through all ordinary material things without attenuation and represent the ultimate wireless system. One could communicate directly through the

Earth from Moscow in Russia to Caracas in Venezuela—without the need for fiber optic cables, microwave relays, or satellite transponders. Antennas, cables, and phone lines would be things of the past, as noted in Fig. 1.1.1. A timing standard alone, provided by HFGW stations around the globe, could result in a multi-billion dollar savings in conventional telecom systems over ten years, according to the recent analysis of Harper and Stephenson (2007). The communication and navigation needs of future magnetohydrodynamic (MHD) aerospace vehicles, such as the MHD aerodyne ([www.mhdprospects.com](http://www.mhdprospects.com)), which is high in electromagnetic interference, similar to plasma interference seen at reentry, would be another possible applications area for HFGW communications.

### 3.0 Physics

#### 3.1 Gravitational Waves

##### 3.1.1 Executive Level

What are gravitational waves or GWs? Visualize the luffing of a sail as a sailboat comes about or tacks. The waves in the sail's fabric are similar in many ways to gravitational waves, but instead of sailcloth fabric, gravitational waves move through a "fabric" of space. Einstein called this fabric the "space-time continuum" in his 1916 work known as General Relativity (or GR). Although his theory is very sophisticated, the concept is relatively simple. This fabric is four-dimensional: it has the three usual dimensions of space: (1) east-west, (2) north-south, (3) up-down, plus the dimension of (4) time. Here is an example: we define a location on this "fabric" as 5th Street and Third Avenue on the fourth floor at 9 AM. We can't see this "fabric" just as we can't see the wind, sound, or gravity for that matter. Nevertheless, those elements are real, and so is this "fabric." If we could generate ripples in this space-time fabric, then many applications become available to us. Much like radio waves can be used to transmit information through space, we could use gravitational waves to perform analogous functions.

##### 3.1.2 More Detail

The history of gravitational waves (GWs) predates Einstein's 1915 paper, where he first discussed them. In 1905, several weeks before Einstein presented his Special Theory of Relativity, Jules Henri Poincaré, the famous French mathematician and celestial mechanic, suggested that Newton's theories needed to be modified by including "Gravitational Waves" (Poincaré, 1905). Einstein (1918) derived the Quadrupole Equation, which is utilized to determine the strength of gravitational waves. A few scientists worked on methods to detect GWs, such as Joseph Weber, but at the time, it was believed by most of the scientific community that these "gravitational waves" were just artifacts of Einstein's theory and probably didn't exist in a meaningful form. Then in 1974, two astronomers, Russell Hulse and Joseph Taylor, were studying a radio star pair designated PSR1913+16 at the huge Arecibo radio observatory in Puerto Rico. They

observed that the star pair was coalescing (the pulses were received a little sooner than expected) and the energy it was losing during this coalescence was *exactly* as predicted by Einstein. They received the Nobel Prize in 1993 for this discovery, and from then on, the skepticism evaporated and scientists accepted that, due to this indirect evidence, gravitational waves did indeed exist. However, the gravitational waves generated by these star pairs are of very low frequency, only a fraction of a cycle per second to a few cycles. So if the stars orbit very tightly around each other with a period of, say, one second (for comparison, the period of our motion around the Sun is one year), the gravitational-wave frequency is 2 Hz. (The gravitational-wave frequency is twice the orbital frequency, based on theoretical analyses.) If black holes spun around each other during the final phase of their coalescence (or “death spiral”) in say, one fortieth of a second, their frequency would be  $(1/0.25) \times 2 = 80$  Hz.

### 3.2 High-Frequency Gravitational Waves (HFGWs)

#### 3.2.1 Executive Level

HFGWs are gravitational waves with frequencies greater than 100kHz, following the definition of Douglass and Braginsky (1979). The first mention of high-frequency gravitational waves or HFGWs was during a lecture by Forward and Baker (1961), based on a paper concerning the dynamics of gravity (Klemperer and Baker, 1957) and Forward’s prior work on the Weber Bar. The first publication concerning HFGWs was in 1962, Gertsenshtein’s (1962) pioneering paper, “Wave resonance of light and gravitational waves.”

#### 3.2.2 More Detail

L. Halpern and B. Laurent (1964) suggested that “at some earlier stage of development of the universe (the big bang), conditions were suitable to produce strong [relic] gravitational radiation.” They then discussed “short wavelength” or HFGWs. In 1968, Richard A. Isaacson of the University of Maryland authored papers concerned with gravitational radiation in the limit of high frequency (Isaacson, 1968). L.P. Grishchuk and M.V. Sazhin (1973) published a paper on emission of gravitational waves by an electromagnetic cavity, which also involved HFGWs, and V.B. Braginsky and Valentin N. Rudenko (1978) wrote about gravitational waves and the detection of gravitational radiation. Also discussed in the literature are possible mechanisms for generating cosmological HFGWs, including relativistic oscillations of cosmic strings (Vilenkin, 1981), standard inflation (Linde, 1990), and relativistic collisions of newly expanding vacuum bubble walls during phase transitions (Kosowsky and Turner, 1993). The theme of relic or big bang-generated HFGWs (HFRGWs) and its relationship to “String Cosmology” (roughly related to the well-known contemporary string theory) was suggested by G. Veneziano (1990), and later discussed by M. Gasperini and M. Giovannini (1992). HFRGWs were discussed originally by Halpern and Jovet (1968) and later by Grishchuk (1977, 2007), and since then have emerged as having significant astrophysical and cosmological importance. This work continues today, especially the research of L.P. Grishchuk, and is the motivation for HFGW detectors developed at

INFN Genoa (Italy) and under development at Birmingham University (England), the National Astronomical Observatory of Japan (a 100MHz detector), Chongqing University (China). HFGWs are characterized by an amplitude  $A$ , which is the relative strain or fractional deformation of the space-time continuum calculated as the length change in meters (caused by the passage of a GW), divided by the original length in meters, so that  $A$  is dimensionless. Their amplitudes are, however, quite small. Typically for HFRGWs,  $A \sim 10^{-33}$  to  $10^{-30}$  (dimensionless units or m/m).

### 3.3 The Quadrupole

#### 3.3.1 Executive Level

One way we can generate wind waves is by the motion of fan blades. Likewise, gravitational waves (GWs) can theoretically be generated by the motion of masses. The Quadrupole Equation was derived by Einstein in 1918 to determine the power of a generated gravitational wave (GW) due to the motion of masses. Because of symmetry, the quadrupole moment (of Einstein's quadrupole-approximation equation) can be related to a principal moment of inertia,  $I$ , of a mass system and can be approximated by

$$P = -dE/dt \approx -G/5c^5 (d^3I/dt^3)^2 = 5.5 \times 10^{-54} (d^3I/dt^3)^2 \quad \text{watts}$$

In which  $-dE/dt$  is the generated power output of the GW source,  $P$  is in watts,  $c$  is the speed of light,  $G$  is the universal constant of gravitation, and  $d^3I/dt^3$  is the third time derivative of the moment of inertia of the mass system. The GW power is usually quite small because of the small coefficient multiplier.

#### 3.3.2 More Detail

Alternately, from Eq. (1), p. 90 of Joseph Weber (1964), one has for Einstein's formulation of the gravitational-wave (GW) radiated power of a rod spinning about an axis through its midpoint having a moment of inertia,  $I$  [ $\text{kg}\cdot\text{m}^2$ ], and an angular rate,  $\omega$  [radians/s] (please also see, for example, pp. 979 and 980 of Misner, Thorne, and Wheeler (1973), in which  $I$  in the kernel of the quadrupole equation and also takes on its classical-physics meaning of an ordinary moment of inertia):

$$P = 32GI^2 \omega^6 / 5c^5 = G(I\omega^3)^2 / 5(c/2)^5 \quad \text{watts}$$

or

$$P = 1.76 \times 10^{-52} (I\omega^3)^2 = 1.76 \times 10^{-52} (r[m\omega^2])^2 \quad \text{watts}$$

where  $[r\omega^2]^2$  can be associated with the square of the magnitude of the rod's centrifugal-force vector,  $f_{cf}$ , for a rod of mass,  $m$ , and radius of gyration,  $r$ . This vector reverses every half period at twice the angular rate of the rod (and a component's magnitude squared completes one complete period in half the rod's period). Thus the GW frequency is  $2\omega$ . Following Weber's numerical example (1964) for a one-meter long rod spun so fast as to nearly break apart due to centrifugal force, the radiated GW power is only  $10^{-37}$  watts. This result often convinces a reader that it is impossible to generate GWs in the laboratory. As will be seen, such is not the case.

### 3.4 “Jerk” or “shake”

#### 3.4.1 Executive Level

Let us consider two masses a distance  $2r$  (in meters) apart that undergo a “jerk” or a “shake,” that is, a change in force,  $\Delta f$  (in Newtons) over a short time interval,  $\Delta t$  (in seconds). In this case, the Quadrupole Equation is of the form

$$P = 1.76 \times 10^{-52} (2r \Delta f / \Delta t)^2 \text{ watts.}$$

There are two important conclusions to be drawn from this equation: first, there is a very small multiplier ( $10^{-52}$ ), so simply moving two masses will result in a very-low-power laboratory-generated gravitational wave. Second, the quantity in the parenthesis is the distance between the two masses,  $2r$ , multiplied by the jerk or shake,  $\Delta f / \Delta t$ , and it is squared, so these factors are very significant in determining the generated gravitational-wave power. This formulation of the quadrupole equation (as derived in Baker (2006)) is at the heart of many approaches to laboratory HFGW generation, since the faster the jerks (the smaller the  $\Delta t$ ), the *higher* the GW frequency and the greater the GW power. A large force change,  $\Delta f$  is also most valuable.

However, the trick is that we *don't require gravitational force* to generate gravitational waves! It's really the motion of the mass that counts, not the kind of force that produces that motion. How do we obtain a large force change? To make it practical, we need a force that is much larger than the force of gravitational attraction. Let's do a thought experiment and think of two horseshoe magnets facing each other (north poles facing south poles). They will attract each other strongly. If we reverse the magnets, put them down back-to-back with their poles facing outwards, then primarily their gravitational force acts due to their masses and we sense little or no attractive pull. As a matter of fact, magnetic, electrical, nuclear and other non-gravitational forces are about 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 ( $10^{34}$ ) times larger than the gravitational force! So, if we have our choice, we want to use “electromagnetic force” as our force, not weak little gravity (by moving objects).

#### 3.4.2 More Detail

As a validation of the forgoing form of the Quadrupole Equation, that is, a validation of the use of a jerk to estimate gravitational-wave power, let us utilize the approach for computing the gravitational-radiation power of PSR1913+16 (the neutron star pair observed by Hulse and Taylor). We computed that each of the components of change of force,  $\Delta f(f_{x,y}) = 5.77 \times 10^{32}$  [N] (multiplied by two since the centrifugal force reverses its direction each half period) and  $\Delta t = (1/2)(7.75 \text{hr} \times 60 \text{min} \times 60 \text{sec}) = 1.395 \times 10^4$  [s]. Thus, using the jerk approach:

$$P = 1.76 \times 10^{-52} \{ (2r \Delta f_c f_x / \Delta t)^2 + (2r \Delta f_c f_y / \Delta t)^2 \}$$

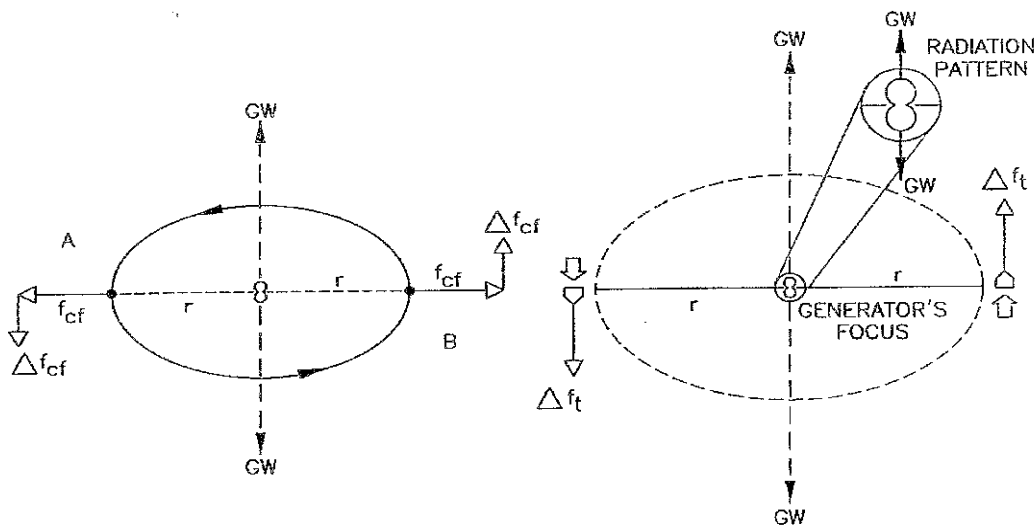
$$=1.76 \times 10^{-52} (2 \times 2.05 \times 10^9 \times 5.77 \times 10^{32} / 1.395 \times 10^4)^2 \times 2 = 10.1 \times 10^{24} \text{ watts} \quad (3.4.2a)$$

compared to the result of  $9.296 \times 10^{24}$  watts using Landau and Lifshitz's (1975) more exact two-body-orbit formulation. The most stunning closeness of the agreement is of course fortuitous, since due to orbital eccentricity, there is not complete symmetry among the  $\Delta f_{cf,x,y}$  components around the orbit and there are variations inherent in the approximations.

### 3.5 Laboratory HFGW Generation

#### 3.5.1 Executive Level

How could we make use of this analysis and generate GWs in the laboratory? Instead of the change in “centrifugal force” of the two orbiting black holes, let us replace that force change with a change of non-gravitational force: the much more powerful one of electromagnetism. Please see Fig. 3.5.1. One way to do this is to strike two laser targets with two oppositely directed laser pulses (a laser pulse is an electromagnetic wave). The two targets could be small masses, possibly highly polished tungsten. Each laser-pulse strike imparts a force on the target mass acting over a very brief time, commonly defined as a “jerk” or shake or impulse. Einstein says, according to his broad concept of “quadrupole formalism,” that each time a mass undergoes a change or buildup in force over a very brief time, gravitational waves are generated—in the laboratory!



**Figure 3.5.1. Change in Centrifugal Force of Orbiting Masses,  $\Delta f_{cf}$ , Replaced by Change in Tangential Force,  $\Delta f_t$ , to Achieve HFGW Generator's Radiation**

The duration of these pulses is very short—a very small fraction of a second, perhaps only one thousand billionth—but that short duration leads to an extremely high

frequency, on the order of billions cycles per second (say, 1,000,000,000,000 Hz or a Terahertz, or THz) for this pulse duration,  $\Delta t$ , which essentially is the inverse of the frequency, that is  $1/1,000,000,000,000 \text{ s}^{-1} = 0.000,000,000,000,1$  second. There are several theories for potential laboratory HFGW generators. For example, piezoelectric crystals (Romero and Dehnen, 1981, similar to acoustic resonators, and Woods and Baker, 2005), microscopic systems (Halpern and Laurent, 1964), infrared-excited stacks of gas-filled rings (Woods and Baker, 2009), electromagnetic cavities (Grishchuk and Sazhin, 1973), a nuclear-energy source (Fontana, 2004), high-intensity lasers (Baker, Li and Li, 2006), and several others. All of these candidate HFGW generators should be analyzed for possible military applications.

### 3.5.2 More Detail

Another embodiment of the laboratory HFGW generation concept is to replace the laser targets by two parallel tracks of millions of very inexpensive little piezoelectric crystals, which are found in cell phones, and energize them by thousands of inexpensive magnetrons found in microwave ovens. Please see Fig. 3.5.2. The little crystals each produce a small force change, but millions or billions of them operating in concert can produce a huge force change and generate significant HFGWs. This generator concept has been analyzed in Romero and Dehnen (1981) and Woods and Baker (2005). A large number of elements for a given HFGW-generator length can be best realized by reducing the size of the individual elements to submicroscopic size, as discussed in U. S. Patent Number 6,784,591 (Baker 2000).

Let us consider a proof-of-concept HFGW generator, using  $1.8 \times 10^8$  cell-phone film bulk acoustic resonators or FBARs and 10,000 microwave-magnetrons for a proof-of-concept laboratory HFGW generator. Assuming a 10  $\mu\text{m}$  distance or margin between the FBARs (100  $\mu\text{m}$  on a side with conventional FBARs), the overall length of the laboratory generator will be  $110 \times 10^{-6} \text{m} \times 1.8 \times 10^8 \text{ elements} = 19.8 \text{ km}$ , which is the same result as that found by Baker, Stephenson and Li (2008). It will have a total HFGW power of 0.066 W and for a distance out from the last in-line, in-phase FBAR element of one HFGW wavelength (6.1 cm at 4.9 GHz), it will have a flux of  $3.53 \text{ Wm}^{-2}$ , yielding a HFGW amplitude,  $A = 4.9 \times 10^{-28} \text{ m/m}$ . This result differs slightly from the result of Baker, Stephenson and Li (2008), since they took the distance out as 1.5 HFGW wavelengths (9 cm) not one wavelength, or 6.1 cm. Other ideas could involve molecular-size resonators or even off-axis spinning atomic nuclei. More recently, Woods and Baker (2009) have proposed a ring of near-infrared (IR)-excited molecules. The use of the IR ring concept of Woods may even further reduce the power and size requirements of the device to  $\ll 20$  watts and millimeters in length and width.

# HFGW Generator

Using Magnetron-FBAR (Piezoelectric Crystals)

Similar to Romero and Dehnen (1981)



**Figure 3.5.2 Magnetron FBAR (Piezoelectric Crystal) HFGW Generator.**

## 3.6 Laboratory HFGW Detection

### 3.6.1 The Gertsenshtein Effect

#### 3.6.1.1 Executive Level

If high-frequency gravitational waves (HFGWs) propagate in a static magnetic field, then the interaction of the HFGWs with the static magnetic field can generate a perturbative electromagnetic (EM) waves (photon flux), which propagates only in the same and in the opposite propagating directions of the HFGW. This is the inverse Gertsenshtein Effect (G-effect). The perturbative EM wave (or in quantum language, perturbative photon flux (PPF), is a second-order perturbation. This second-order PPF exhibits a very small value. Whether from the framework of classical or quantum theories, the conversion of the HFGW to the EM wave will be extremely low. Thus the PPF in the pure inverse G-effect cannot cause a detectable signal (Eardley, et al., 2008) so it is **not** utilized by us in HFGW detection.

#### 3.6.1.2 More Detail

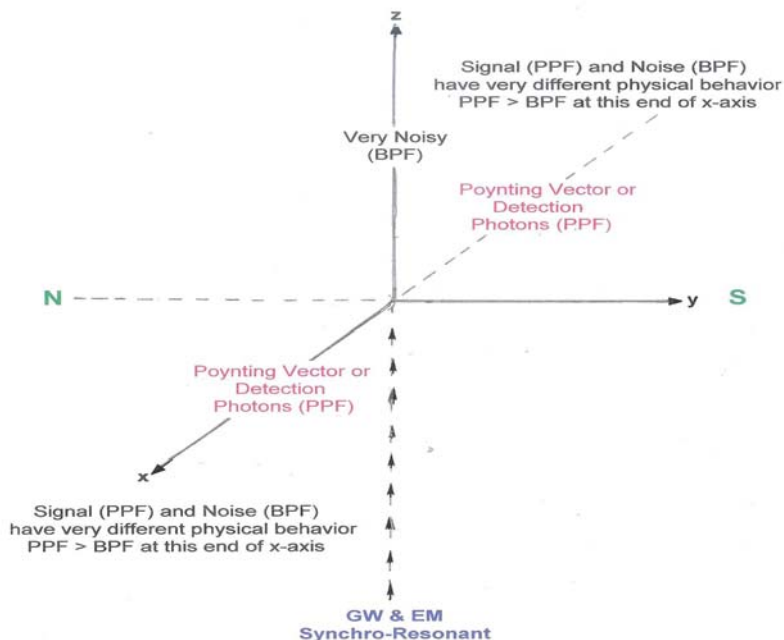
At the outset, it should be emphasized that neither the HFGW detector nor the HFGW generators discussed in this paper utilize the Gertsenshtein Effect. The purpose in mentioning it is to show that gravitational waves and electromagnetic (EM) waves actually interact. Gertsenshtein (1962) analyzed the energy of gravitational waves that is excited during the propagation of electromagnetic (EM) radiation (e.g., light) in a constant magnetic or electric field. He found it is possible to excite gravitational waves by light (or other EM energy). He also states at the conclusion of his two-page article that it is possible to do the inverse: generate EM radiation *from* GWs.

### 3.6.2 The Fangyu Li Effect

#### 3.6.2.1 Executive Level

The **Fangyu Li Effect**, a recent breakthrough in HFGW detection, was first published in 1992 and subsequently, some ten peer-reviewed papers have been published concerning it. The Fangyu Li Effect is *very different* from the classical (*inverse*) Gertsenshtein Effect. With the Fangyu Li Effect, a gravitational wave transfers energy to a separately generated electromagnetic (EM) wave in the presence of a static magnetic field. That EM wave has the same frequency as the GW (ripple in the spacetime continuum) and moves in the same direction. This is the “*synchro-resonance condition*,” in which the EM and GW waves are synchronized (move in the same direction and have the same frequency).

The result of the intersection of the parallel and superimposed EM and GW beams, according to the Fangyu Effect, is *new EM photons moving off in a direction perpendicular to the beams and the magnetic field direction*. Thus, these new photons occupy a separate region of space (see Fig. 3.6.2a) that can be made essentially noise-free and the synchro-resonance EM beam itself (in this case a Gaussian beam) is not sensed there, so it does not interfere with detection of the photons. This Fangyu Li Effect was utilized by Baker (2001) in the design of and patent of (<http://www.gravwave.com/docs/Chinese%20Detector%20Patent%2020081027.pdf>) a device to detect HFGWs, the innovative Li-Baker HFGW Detector.



**Figure 3.6.2a. Detection Photons Sent to Locations that are Less Affected by Noise**

The synchro-resonance solution of Einstein’s field equations (Li, Baker, Fang, Stephenson and Chen, 2008 pp. 411 to 413) is radically different from the Gertsenshtein

(1962) effect. The newer Fangyu Li Effect solution also uses coupling between EM and gravitational waves (Li, Tang and Zhao, 1992) that arises according to the theory of relativity. And a strong static magnetic field in the  $y$ -direction,  $B$ , is superimposed upon a GW propagating in the  $z$ -direction, as in the inverse Gertsenshtein effect. However, with the Fangyu Li Effect, there is an *additional* focused microwave beam (“Gaussian beam”) at the expected frequency, phase and bandwidth of the HFGWs in the same direction ( $z$ ) as the GW (as shown in Fig. 3.6.2a).

*Unlike the Gertsenshtein effect, a first-order perturbative photon flux (PPF), comprising the detection photons, will be generated in the  $x$ -direction. Since there is a 90 degree shift in direction, there is little crosstalk between the PPF and the superimposed EM wave (Gaussian beam), so the PPF signal can be isolated and distinguished from the effects of the Gaussian beam, enabling detection of the GW.*

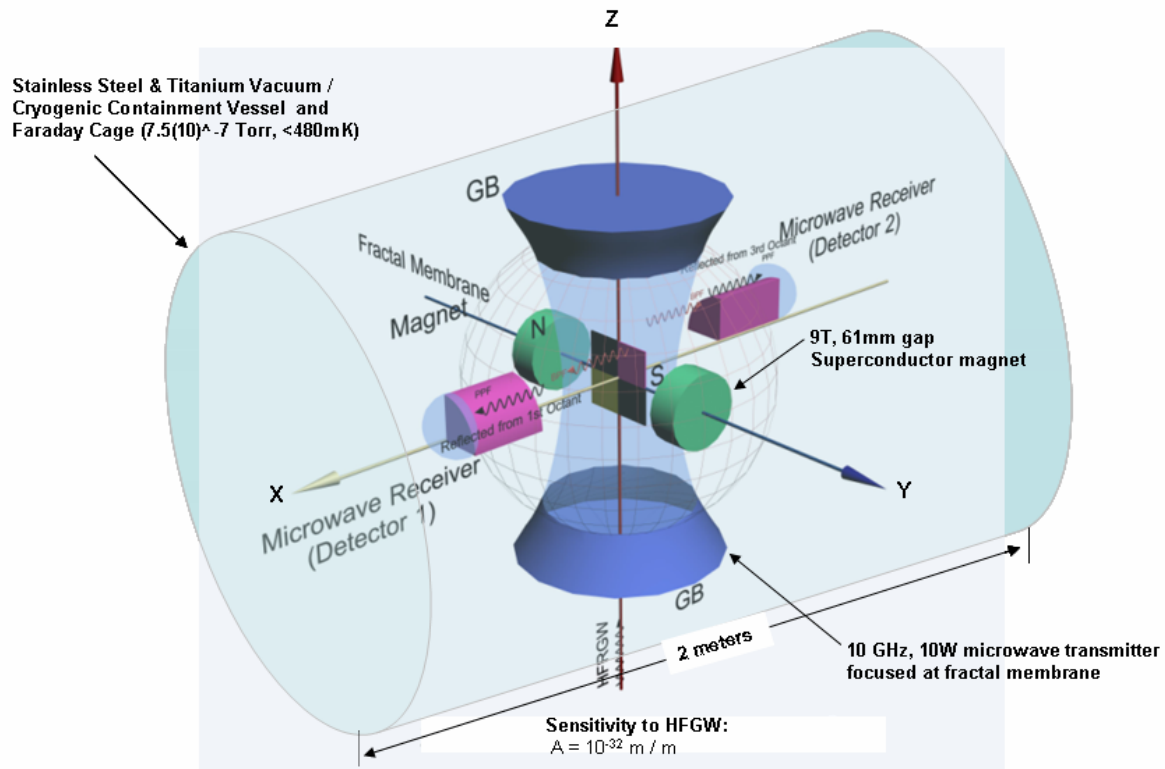
Here’s how it works:

1. The perturbative photon flux (PPF), which signals the detection of a passing gravitational wave (GW), is generated when the two waves (EM and GW) have the same frequency, direction and phase. This situation is termed “synchro-resonance.” These PPF detection photons are generated as the EM wave propagates along its  $z$ -axis path, which is also the path of the GWs, as shown in Fig. 3.6.2a.
2. The magnetic field is in the  $y$ -direction. According to the FangYu Li Effect, the PPF detection photon flux (also called the “Poynting Vector”) moves out along the  $x$ -axis in both directions.
3. The signal (the PPF) and the noise, or background photon flux (BPF) from the Gaussian beam have very different physical behaviors. The BPF (background noise photons) are from the synchro-resonant EM Gaussian beam and move in the  $z$ -direction, whereas the PPF (signal photons) move out in the  $x$ -direction along the  $x$ -axis.
4. The PPF signal can be intercepted by electromagnetic-interference-shielded microwave receivers located on the  $x$ -axis (isolated from the synchro-resonance Gaussian EM field, which is along the  $z$ -axis). In addition, isolation is further improved by cooling the microwave receiver apparatus to reduce thermal noise background.

The resultant efficiency of detection of HFGWs is very much greater than from the inverse Gertsenshtein effect, which has been exploited in some previously proposed HFGW detectors. The proposed novel Li-Baker detection system is shown in Fig. 3.6.2b. The detector is sensitive to HFGWs directed along the  $+z$ -axis, and the precise geometrical arrangement of the major components around this axis is the key to its operation.

The detector, shown in Fig. 3.6.2b, has five major components.:

1. A Gaussian (focused, with minimal side lobes) microwave beam (GB) is aimed along the  $+z$ -axis at the same frequency as the intended HFGW signal to be detected (Yariv, 1975), typically in the GHz band, and also aligned in the same direction as the HFGW to be detected. The microwave transmitter's horn antenna is not shown, but would be located on the  $-z$  axis.
2. A static magnetic field  $\mathbf{B}$ , generated by two powerful magnets (typically using powerful superconductor magnets such as those found in a conventional MRI medical body scanner), is directed along the  $y$ -axis.
3. Two paraboloid-shaped reflectors, which are formed from "fractal membranes" (Wen *et al.*, 2002; Zhou *et al.*, 2003; Hou *et al.*, 2005), are located in the  $y$ - $z$  plane at the origin of the coordinate system to aim and focus the detection photons at diffraction-limited spot antennas connected to two microwave receivers. These reflectors, shown in planer form in Fig. 3.6.2c, are segmented (similar to a Fresnel lens) and located back-to-back in the  $y$ - $z$  plane. They are thin enough (less than a centimeter thick in the  $x$ -direction) to not block the  $z$ -directed Gaussian beam. These microwave reflectors reflect the  $x$ -directed detection photons (PPF) and reject the  $z$ -directed Gaussian-beam photons, which move parallel to the surface of the reflectors in the  $y$ - $z$  plane.
4. High-sensitivity shielded microwave receivers are located at each end of the  $x$ -axis.
5. Interior noise from thermal photon generation is eliminated by cooling the Li-Baker detection apparatus to below  $\sim 48$  mK (0.048 Kelvin). There are effectively no thermal photons at 10 GHz. Noise from the interior background photon flux (BPF) from the EM Gaussian beam is reduced to a negligible level by moving the receivers out to the side about a meter away from the EM beam and by a series of superconductor or microwave absorbent baffles to "shade" the receivers. Stray EM resulting from scattering of particulate matter near the apparatus and possible dielectric dissipation can be effectively suppressed by evacuating the apparatus to about  $7.5 \times 10^{-7}$  Torr (a rather high vacuum). External noise is eliminated by the use of a steel and titanium cryogenic containment vessel surrounding the low-temperature Li-Baker detection apparatus.



**Figure 3.6.2b Schematic of Ultra-Sensitive HFGW Detector**



**Figure 3.6.2c Fractal membrane component of Li-Baker detector exhibited in planar form**

It should be noted that the identification of this synchro-resonance, which the Li-Baker HFGW detector is based on, has been extensively covered in the literature. At least ten peer-reviewed research publications concerning its theory of operation have appeared

following Li, Tang and Zhao (1992), including those by Li and Tang (1997), Li *et al.* (2000), Li and Yang (2004), Baker and Li (2005), Baker, Li and Li (2006), Baker, Woods and Li (2006), Li and Baker (2007), Li, Baker and Fang (2007), Baker, Stephenson and Li (2008), and Li *et al.* (2008).

Unlike the existing British, Italian and Japanese detectors, the proposed ultra-high-sensitivity Li-Baker Chinese detector depends on a different principle: it does not use the resonance of the British and Italian detectors or the interferometers of the Japanese detectors (the LIGO, Advanced LIGO, GEO600, TAMA and Virgo low-frequency GW detectors also utilize interferometers). As previously discussed, the theory the Li-Baker detector is based on is similar to but different from Gertsenshtein's GW theory.

### 3.6.3 Other HFGW Detectors

#### 3.6.1 Executive Level

In the past few years, HFGW detectors have been fabricated at Birmingham University, England, INFN Genoa, Italy and in Japan. These types of detectors may be promising for the detection of the HFGWs in the GHz band (MHz band for the Japanese) in the future, but currently, their sensitivities are orders of magnitude less than what is required for the detection of high-frequency relic gravitational waves (HFRGWs) from the big bang. Such a detection capability is to be expected, utilizing the Li-Baker detector. Nevertheless, all four candidate detectors (plus, possibly, the use of superconductors (Li and Baker, 2007)) should be analyzed for possible military applications.

#### 3.6.2 More Detail

The Birmingham HFGW detector measures changes in the polarization state of a microwave beam (indicating the presence of a GW) moving in a waveguide about one meter across. Please see Fig.3.6.2a. It is expected to be sensitive to HFGWs having spacetime strains of  $A \sim 2 \times 10^{-13} / \sqrt{\text{Hz}}$ , where Hz is the GW frequency, and  $A$  is a measure of the strain or fractional deformation in the spacetime continuum (dimensionless m/m).



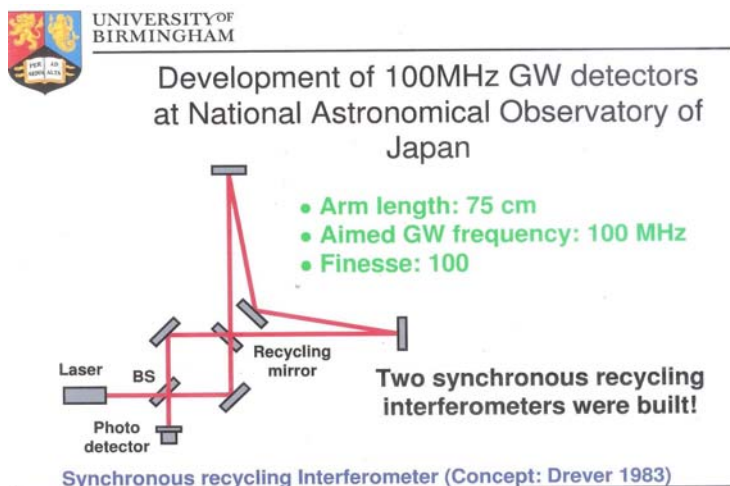
**Figure 3.6.2a. Birmingham University HFGW Detector**

The *INFN Genoa* HFGW resonant antenna consists of two coupled, superconducting, spherical, harmonic oscillators a few centimeters in diameter. Please see Fig. 3.6.2b. The oscillators are designed to have (when uncoupled) almost equal resonant frequencies. In theory, the system is expected to have a sensitivity to HFGWs with size (fractional deformations) of about  $\sim 2 \times 10^{-17} / \sqrt{\text{Hz}}$  with an expectation to reach a sensitivity of  $\sim 2 \times 10^{-20} / \sqrt{\text{Hz}}$ . As of this date, however, there is no further development of the *INFN Genoa* HFGW detector.



**Figure 3.6.2b. INFN Genoa HFGW Detector**

The Kawamura 100 MHz HFGW detector has been built by the Astronomical Observatory of Japan. It consists of two synchronous interferometers exhibiting an arms length of 75 cm. Please see Fig. 3.6.2c. Its sensitivity is now about  $10^{-16} / \sqrt{\text{Hz}}$ . According to Mike Cruise of Birmingham University its frequency is limited to 100 MHz and at higher frequencies its sensitivity diminishes.



**Figure 3.6.2c. The National Astronomical Observatory of Japan 100MHz Detector.**

#### 4.0 Plans for Developing Working Prototype

4.1 Plans & Specifications for Li-Baker Detector (Please see Appendix A: Proposal submitted to the National Sciences Foundation)

4.2 Fabrication of Prototype from Off-the-Shelf Components

The details of this 4.2 effort must, necessarily depend upon the plans and specification developed in the initial 4.1 effort.

4.3 Proof-of-Concept Test: Detection of Relic HFGWs by Li-Baker Detector

Testing of the Li-Baker detector will commence after final assembly, cool-down, and confirmation of high vacuum.. First, noise rejection will be estimated by turning on and off the static magnetic field and measuring the output of the two microwave detectors. The field will then be turned on and the Gaussian beam turned off and again, and the output of the microwave detectors measured. After analyzing the results of these noise tests, the detector will search for relic HFGW signals in 5 to 10 GHz region, based on Grishchuk (2008). Successful detection, and replication by other researchers will then provide proof of the efficacy of the detector.

4.4 Plans & Specifications for Magnetron/FBAR HFGW Generator

A large jerk or shake is required to generate a significant HFGW signal. GravWave proposes to use an extremely large number of piezoelectric elements lined up and in phase, as proposed by Romero and Dehnen (1981), to generate HFGWs for detection and study in the laboratory. This will employ Film Bulk Acoustic Resonators (FBARs), found in cell phones, energized by inexpensive magnetrons, found in microwave ovens. The concept (Woods and Baker 2005) is to create two lines or tracks, each composed of about 180 million FBARS (about 6,000 can be on a four-inch diameter silicon wafer), energized by 10,000 magnetrons (each FBAR, when energized, produces an internal jerk or shake of about 2 N).

The radiation pattern at the focus of the HFGW generator, exactly midway between the two tracks, is computed in Landau and Lifshitz (1975, p. 349). It is in the shape of two symmetrical lobes of radiation directed in both directions (a figure “8”) normal to the plane defined by the line connecting the two tracks and direction of the FBARS’ impulsive force vector or jerk.

There is a design parameter relationship or “figure of merit” for a high-frequency gravitational wave laboratory generator comprising a number of vibrating masses or elements (e.g., piezoelectric crystals or FBAR pairs), which are lined up and in phase, that states: The amplitude of the generated gravitational radiation is proportional to the distance between the individual vibrating masses (e.g., the width of the in-line, in-phase piezoelectric crystals, or the distance between in-line, in-phase oppositely directed FBAR

pairs), the frequency of the generated gravitational radiation, the change in force of the vibrating masses during each cycle, and the square of the number of in-line, in-phase vibrating masses or elements (piezoelectric crystals or FBAR pairs).

Let us consider a proof-of-concept laboratory HFGW generator, using  $1.8 \times 10^8$  cell-phone film bulk acoustic resonators or FBARs and 10,000 microwave magnetrons, as discussed. Assuming a  $10 \mu\text{m}$  distance or margin between the  $100 \mu\text{m}$  on a side for conventional FBARs, the overall length of the laboratory generator will be  $110 \times 10^{-6} \text{ m} \times 1.8 \times 10^8$  elements = 19.8 km. It will have a total radiated HFGW power of 0.066 W and for a distance out from the last in-line, in-phase FBAR element of one HFGW wavelength (6.1 cm), it will have a flux of  $3.53 \text{ W m}^{-2}$ , yielding an HFGW amplitude there of  $A = 4.9 \times 10^{-28} \text{ m/m}$ . This amplitude can be easily detected at a distance of 1 meter by the Li-Baker HFGW Detector. The length of the parallel-track array of magnetron/FBARs can be reduced to 198 m by staggering the rows of FBARs.

The inline set of FBAR elements also produces a more needlelike radiation pattern of HFGWs, so the flux and resulting *signal amplitude* may even be larger. Although the frequencies may be different, one can extrapolate approximately from the results of Dehnen and Romero-Borja's analyses, in which the angle of the needle-like radiation pattern is inversely proportional to the square root of the product of the distance between the radiators (the width between FBAR bands or tracks) and N. The distance for the system discussed here is 6.1 cm and for Dehnen's system, 0.00001 m, for a factor of 6,100 and N differs by  $1.8 \times 10^8 / 5 \times 10^7 = 3.6$  for a product of  $2.2 \times 10^4$  and the inverse of the square root is  $6.7 \times 10^{-3}$ . Using the result from Dehnen's paper (Eq. (4.51), page 12) of a needle half angle of 1.7 degrees, we would extrapolate to 0.0115 degrees or approximately  $2 \times 10^{-4}$  radians.

#### 4.5 Proof-of-Concept Test of Generator, using Li-Baker Detector

The magnetron-FBAR HFGW generator will be tested with the Li-Baker HFGW Detector. The Magnetrons will be energized (requiring about 20 MW) and the detector will be employed to receive the signal –like the “Bell-Watson” experiment.

## APPENDIX A

### **Proposal submitted to the National Sciences Foundation by Louisiana State University, September, 2008 entitled “Development of design of ultra-high sensitivity high-frequency gravitational wave detector.”**

This is a joint academia/industry project to design the ultra-high sensitivity Li-Baker detector for high-frequency gravitational waves (HFGWs). The partnership consists of Louisiana State University (LSU) and Transportation Sciences Corporation (TSC) in California. The Li-Baker HFGW detector exploits a solution of field equations that couples photons and GW in first order, and the sensitivity of the detector will be much better than previously-proposed HFGW detectors. The outcome of this study will be an engineering-ready design for the HFGW detection system, to be developed under continued funding. Future construction of this detector will broaden the search spectrum of the existing LIGO low frequency GW detection system; it will be used to detect and characterize the relic HFGW cosmological background radiation, contributing to clarifying the origins of the universe. This offers the first and best hope of GW detection in a completely new GW frequency régime around 10GHz, near the cutoff of what is cosmically generated and a proof of the capability of the detector to sense the HFGW emissions of the HFGW generator discussed in Sections 4.4, 4.5 and 4.6.

This first activity is to develop designs, plans and specifications for the Li-Baker configuration for ultra-high sensitivity detection of relic high-frequency gravitational waves (HFRGWs) in the laboratory. The first goal will be to develop the design to a stage where the likely performance can be evaluated in detail. Following a future proposal, the Li-Baker detector will subsequently be built and used for the basic-science purposes of sensing HFRGWs having their origin related to the “big bang”, as well as for detecting laboratory-generated HFGWs (Romero and Dehnen, 1981; Baker, 1999, 2000; Woods and Baker, 2005, 2009). As discussed in Sections 4.4, 4.5 and 4.6. Use will primarily be made of “off-the-shelf” components, and components described in the open scientific literature and in the various patents issued to Project Scientist **Robert M L Baker, Jr.** (Baker, 1999, 2000, 2001, and Patents Pending) who is the inventor of the Li-Baker HFGW Detector (Baker, 2001). Other components will be designed by the project participants during the Detector Design (DD) process. The project plan and timing are described below under separate headings for each component of the work.

#### ***DD1.1 Containment Vessel***

Design of the cryogenic containment vessel and vacuum system: **Dr. R.C. Woods (LSU) + graduate student, G.V. Stephenson (TSC), Dr. R. M L Baker (TSC)**. This will be divided into four subtasks

:

**DD1.1.1 Selection of material for the containment vessel:** this choice will be made in light of the vessel's approximate size and shape, initially anticipated to be cylindrical, overall approximately 2m diameter and 3m length. Manufacturing ultra-high vacuum chambers requires fabrication that ensures leak-free performance. For example, Meyer Tool & Manufacturing, Inc. (Oak Lawn, Illinois) supplies custom chambers for ultra-high vacuum (UHV) applications. Companies such as Meyer will be consulted and/or visited to evaluate their manufacturing capability. The final selection from the expected short-list of titanium, stainless steel and/or aluminum containment vessels will be made based upon manufacturer recommendation and evaluation of test data.

**DD1.1.2 Detailed design of brackets and fixtures for the internal equipment, wiring, piping and through-wall connections:** the general principles demonstrated by existing Magnetic Resonance Imaging (MRI) system designs (e.g. from Siemens MRI, GE Healthcare, and others) will be followed to determine the most compatible design of the internal equipment, wiring, piping and through-wall connections for the HFGW detector. A cryostat or cryogenic containment vessel supported inside the vacuum vessel will house the superconducting magnet assembly necessary for the Li-Baker detector. Through-wall fittings and seals for copper leads supplying the magnet and other internal apparatus will be needed. Design of brackets, wiring, and piping of detector equipment will also be based upon input from the other tasks.

**DD1.1.3 Design of vacuum system:** there are a large number of "off-the shelf" Ultra-High Vacuum (UHV) equipment providers such as: Varian, Inc. (Lexington, Massachusetts), Kimball Physics, Inc. (Wilton, New Hampshire), and Edwards High Vacuum Ltd. (UK), amongst others. Those with capability for producing a system able to evacuate the chamber to about  $10^{-7}$ Torr for the HFRGW detector will be approached to undertake a detailed specification.

**DD1.1.4 Detailed design of size and shape of containment vessel:** determination of the containment vessel's precise dimensions will be based upon the final designs of the equipment determined by the other tasks and will integrate all the specific sub-task designs, resolving any conflicts between units.

## *DD1.2 Signal Processing*

Design of the recording apparatus hardware and software development that will be needed to handle merging the two receiver inputs over an averaging period of up to 1,000s: **Dr. R. M L Baker (TSC), G.V. Stephenson (TSC)**. This will require the conceptual design of digitizing hardware and software to handle the data gathered, including the combination of multiple receiver signals, the use of delay histograms, statistical filtering techniques, and the study of false alarm pitfalls in non-linear signal processing. There is much overlap with this area and DD1.5, the design of the detection receivers. The expected GW signal structure must be characterized to optimize the matched filtering needed. The definition of a detection event is the foremost consideration, and will be studied both in terms of the threshold level and in terms of the

statistics of exceeding that level. Expected signal to noise enhancements (“processing gain”) will be investigated for various filtering and processing options, and the effect of the  $Q$ -factor inherent in the detection apparatus will be included in this area of the investigation. Linear processing techniques such as multiple receiver combination and delay histogram searches will be studied, and nonlinear signal processing will also be considered, including its effect on detectability, as well as its effect on false alarm generation. This task includes the selection of the best computing and digitizing recorder platforms for the signal-processing needed. Also under this task is an investigation of whether magnetic field modulation can be used to advantage in this detector. Any scattered BPF does not depend upon the applied magnetic field or on the GW. Therefore, the wanted PPF can be “labeled” by varying the applied (nominally static) magnetic field in some way. A common technique in magnetic resonance experiments is to use field modulation coils that superimpose upon the constant applied magnetic field a time-varying component at low frequency (e.g., around 50Hz but asynchronous with the commercial power supply frequency). As a result, the PPF is “labeled” as whatever is recovered from the receivers at the same frequency as (and indeed phase-locked to) the modulation, so therefore the PPF can be distinguished from scattered BPF very easily. Typically a lock-in amplifier (referenced to the field modulation) is used to recover the signal in such an arrangement, which provides significant noise rejection by effectively reducing the detection bandwidth.

### ***DDI.3 Microwave Transmitter (Gaussian beam)***

Design of the microwave transmitter for the Gaussian beam, directed towards the central fractal membranes: **Dr. R.C. Woods (LSU) + graduate student, Dr. R. M L Baker (TSC), G.V. Stephenson (TSC)**. This is expected to require 10 to possibly 10,000W (1,000W nominal) at around 10GHz, with an associated power supply and appropriate safety interlocks. Possible technologies include solid-state, magnetron, traveling-wave tube (TWT), or high-power klystron, and specifications will be developed under this component of the work. These are all mature technologies and commercial units will suffice. Possible suppliers include: Microwave Power Inc. (Santa Clara, California; solid-state, up to 500W); ETM Electromatic Inc. (Newark, California; TWT or klystron, up to 10kW); and Toshiba Electron Tube and Devices Co., Ltd. (Japan; TWT or klystron, over 10kW). Generally speaking, wideband solidstate amplifiers produce less output power than medium bandwidth models or narrow-band tube designs, so that the compromise here will be to decide whether to accept lower power in favor of wide tunability. Also required is a suitably matched transmit antenna. Again, commercial designs will suffice, such as those from Rozendal Associates Inc. (Santee, California), ETS-Lindgren (Cedar Park, Texas), or Orban Microwave Products (El Paso, Texas). The compromise that must be worked out in the antenna design is that a high-gain antenna is needed to constrain the GB to be within the resonance cavity or interaction volume (so that microwave input power is not wasted), but a high-gain antenna is less tunable than a broadband low-gain antenna. As in other work areas of this proposal, the complete design will need to establish the cost-performance tradeoff issues surrounding the various approaches.

#### **DD1.4 Fractal Membranes and Microwave Absorbers**

Design of the fractal membranes as microwave reflectors/absorbers at select frequencies (Wen *et al.*, 2002; Zhou *et al.*, 2003) and other high-performance microwave absorbers: **Dr. R. M L Baker (TSC), G.V. Stephenson (TSC).**

**DD1.4.1** Design of the **fractal membrane (FM) reflectors** at the waist of the Gaussian beam including their paraboloidal form. An analysis will be completed to determine the optimal material of the FMs (copper, stainless steel, or aluminum are the obvious leading candidates). A paraboloidal surface will be designed that can be fabricated from the FM to focus the PPF at the planned locations of the microwave receivers. Hong Kong University of Science and Technology can fabricate the fractal membranes out of these metals in almost any form.

**DD1.4.2** The **interior** of the containment vessel (except for an opening at the Gaussian-beam transmitter end) must be treated to eliminate exterior sources of noise. Either a Faraday Cage (using a mosaic of HTSC tiles, e.g., YBCO) or fractal membranes are possibilities. Both will be examined in detail to determine the optimal approach. A design compatible with the containment vessel shape (DD1.1.4) and placement of interior detector elements will be developed.

**DD1.4.3** Selection of appropriate microwave **absorbing material** at around 10GHz; design of the interior baffles around the Gaussian beam, and a “tunnel” between fractal-membrane reflectors and receivers (Baker, Stephenson and Li, 2008). A computer program for ray tracing of the PPF and the BFF will be developed and utilized for the baffle design. An analysis will be made of the latest technology reported by Chan *et al.* (2006), Landy *et al.* (2008), and Yang *et al.* (2008), and these will be compared with those available from established suppliers of current technology high performance microwave absorbing materials including ARC Technologies, Inc. (San Diego, California), Millimeter Wave Technology Inc. (Passaic, New Jersey), Cuming Microwave (Avon, Massachusetts), and many others.

#### **DD1.5 Detection Receivers**

Design of the microwave receivers (for the PPF) at each end of the detector containment vessel, tunable around 10GHz: **G.V. Stephenson (TSC), Dr. R.C. Woods (LSU) + graduate student, Dr. R. M L Baker (TSC).** Three possibilities have already been identified for the technology to be used here, and specifications will be developed for each option found suitable for use in the final design so as to enable a final choice to be made.

**DD1.5.1 Off-the-shelf microwave horn plus HEMT receiver:** if tens to hundreds of photons per sample are available then standard microwave horns may be used, coupled to high electron mobility transistor (HEMT) amplifiers. This task will include a sensitivity analysis of this receiver type to determine the suitability of this approach, and a

conceptual design will be developed using off-the-shelf components. Now highly developed, HEMT technology has previously been found reliable enough to use in the receivers for differential microwave radiometers (DMRs) flown in the NASA COsmic Background Explorer (COBE) satellite mission.

**DD1.5.2 Rydberg-Cavity Receiver** as developed at Kyoto University (Yamamoto *et al.*, 2000): Rydberg atoms are excited atoms with one or more electrons that have a much higher principal quantum number than ground state, usually conditioned *via* laser pumping. The low binding energy of the excited electrons leads to very low photoionization energy; therefore, Rydberg atoms are sensitive to low-energy microwave photons, and allow a microwave device somewhat analogous to a conventional photomultiplier tube to be constructed. When a microwave photon strikes a high cross-section Rydberg atom, it causes the electron to be ejected and the atom is ionized. If a large electric field is established within the container, the electron is accelerated, causing cascading impact ionization. The advantage of this receiver is that it is sensitive to low-energy single-photon events, and has very good time resolution. The disadvantage is its cost and complexity. This task will include a conceptual design of an alternative Rydberg atom receiver apparatus suitable for the PPF arising from HFRGW, and will also include a sensitivity calculation of the proposed apparatus.

**DD1.5.3 Circuit QED microwave receiver** as developed at Yale University (Schuster *et al.*, 2007): a third option will also be explored, the Circuit QED microwave photon receiver. A resonant co-planar waveguide, containing a Cooper Pair Box (CPB) in the center and delineated by Josephson junctions, define a photo-sensitive area in the center of the cavity. The cavity qubit energy levels shift when the cavity encounters a microwave photon. The advantage of this type of receiver is that it is very sensitive to individual photons and can integrate multiple photons over time. It has the disadvantage that this device is of a unique design that is currently available only from Yale University, and is likely not to be exportable. This task will include developing a conceptual design using this alternative type of receiver for the PPF arising from HFRGW.

### **DD1.6 Cryogenic System**

Specification and design of the cryogenic system refrigeration unit, required for low-temperature operation to obtain the best possible reduction in intrinsic thermal noise: **Dr. R.C. Woods (LSU) + graduate student, Dr. R. M L Baker (TSC), G.V. Stephenson (TSC)**. The required criterion is that the temperature  $T$  satisfies  $kBT \ll \hbar\omega$  (where  $kB$  is Boltzmann's constant), i.e.  $T \ll \hbar\omega/kB \approx 480\text{mK}$  for detection at 10GHz. This condition is satisfied by the target temperature for the interaction volume  $T < 48\text{mK}$ , which can be obtained using a common helium-dilution refrigerator. Then, the signal PPF will be significantly greater than the thermal photon flux. Cost/performance tradeoffs may also be important in this design, so that other possible economic solutions to receiver cooling will also be considered before finalizing the design.

**DD1.6.1 Off-the-shelf cryogenic systems:** a number of companies have developed ultra-low temperature systems (mK range) for a variety of applications. A common application is refrigeration of receivers as needed in the Li-Baker HFRGW detector. One possibility is the Oxford Instruments' KelvinoxMX range (see summary data attached) that appears to suit the present requirements subject to further evaluation of each model in the range. Other manufacturers to be investigated include Scientific Magnetics (UK), and Cryofab Inc. (Kenilworth, New Jersey).

**DD1.6.2 Specifications for system best suited to the detector:** specifications will be established for the selected cryogenic system. This will include cryogen level monitoring devices (e.g., Oxford Instruments Intelligent Level Meter ILM200) for warning if the cooling fails.

### ***DD1.7 Electromagnet***

Development of the electromagnet specification needed to produce the required static magnetic field (up to 35T, ~3T nominal): **Dr. R.C. Woods (LSU) + graduate student, Dr. R. M L Baker (TSC), G.V. Stephenson (TSC)**. It is expected that a commercial design can be identified for this task. The chosen design will be capable of providing the requisite magnetic field at least over the interaction cavity volume in the containment vessel. Exceptional field-uniformity is not a particularly important issue in this application, though the GW interaction volume or cavity (roughly cylindrical, 6cm diameter and 30cm long) plus extra volume for the surrounding apparatus is somewhat larger than many other experimental applications require, and the required field is perpendicular to the cylindrical axis. Hence, one solution is that the final solenoid design must completely surround the cylindrical axis of the interaction volume perpendicular to the applied field. An alternative approach is to use two solenoids, one each side of the interaction volume, similar to the popular Helmholtz coil configuration. In a development of this, a number of small (~6cm diameter) solenoids could be stacked along the length of the interaction volume, with their Helmholtz-like opposite paired solenoids the other side of the interaction volume. In the latter cases, since the paired solenoids are not perfect ring coils, the resultant field would be non-uniform. A quantitative estimate would be needed to ensure that the non-uniformity is not serious in the present application, but this is not expected to be a problem since field non-uniformity just produces non-uniform PPF generation in the interaction volume. The fractal membrane reflectors would still focus all the PPF at the receivers. The design tradeoff will be whether one or two large magnets are more cost-effective than a larger number of smaller magnets. The design effort will be divided into two major sub-tasks: off-the-shelf electromagnets currently available, and emerging-technology proposed magnets that may become available during the construction phase of the HFGW detector.

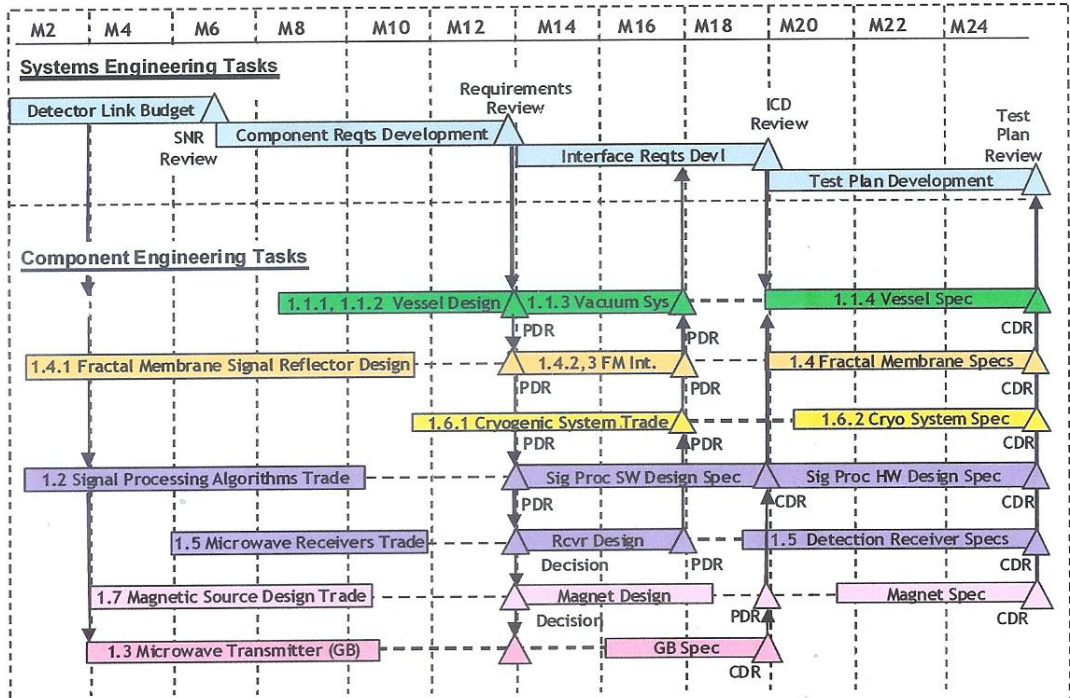
**DD1.7.1 Off-the-shelf hardware:** Excepting major installations, iron-core magnets are limited to around 2T over small volumes so that superconducting magnets are expected to be used here. Cryogen-free (more accurately, the cryogen is completely enclosed and recycled each time the magnet is cooled for use) superconducting magnets producing fields

up to 16T are available commercially from a number of manufacturers including Scientific Magnetics, Oxford Instruments, and Cryogenic Ltd. (all UK). As examples, Oxford Instruments can supply magnets producing 9T in a 20cm bore, and 5T in a 1m bore. Typically, cooling is provided by an integral Gifford-McMahon cryo-cooler at 4.2K. Use of a cryogen-free “dry” magnet means that there are no cold seals to be a source of leaks.

**DD1.7.2 Emerging technology:** Since the detection PPF signal is directly proportional to the static magnetic field value, the detector sensitivity will be increased by using larger fields than currently-available commercial designs permit. To this end we will investigate the feasibility of codeveloping with a third-party (e.g., National High Magnetic Field Laboratory, Tallahassee, Florida) a custom-made high-field design capable of up to 35T (Bird, 2004), which may be realizable during the construction phase of the Li-Baker detector. If successful, achieving this value of magnetic field would improve the sensitivity of the Li-Baker detector by an order of magnitude. In this case, if a separate refrigeration system is required, the specification would include cryogen level-monitoring to ensure safe auto-rundown of the superconducting magnet if the helium level falls below a pre-set value, to reduce the danger associated with cryogenic-system related magnet failure.

### *Systems Engineering Tasks*

Following the completion of the Li-Baker detector development tasks, plans and specifications will be drawn up by LSU in collaboration with TSC. Since overlap of tasks is possible, approximately 18 months will be allowed for the detector design, and approximately 8 months for the preparation of plans and specifications. With approximately two months overlap of the major tasks, a total of two years will be scheduled for the detector’s design and development of the plans and specifications. Fig. 4.1a shows a Gantt chart for scheduling the project. For any large engineering project, coordination among investigators is important for the development of a coherent, unified design. This is the role of systems engineering tasks, depicted at the top of Fig. 4.1a. In the present case, the development of the detector will demand the close coordination of the detection link budget very early on, in order to carefully guide the component design for each of the component areas, and to ensure that the sensitivity goals can be met. This task culminates in a review of the predicted signal-to-noise ratio. A follow-on to this task is the development of key component requirements Interface requirements development is the next level of detail in systems engineering task area, resulting in interface control documentation/drawing review prior to the critical design reviews of the component equipment areas. Finally, the systems engineering activity concludes with the development of test plans that will detail integration activities and reduce integration risk in subsequent phases. These activities are standard level-of-effort tasks that are rolled into other task bids as a background activity.



ICD = Interface Control Documentation/Drawing  
 PDR = Preliminary Design Review = design approval  
 CDR = Critical Design Review = design complete

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