



HAL
open science

HIGH FREQUENCY GRAVITATIONAL WAVES GENERATION IN LASER PLASMA INTERACTION

Xavier Ribeyre, Vladimir Tikhonchuk

► **To cite this version:**

Xavier Ribeyre, Vladimir Tikhonchuk (Dir.). HIGH FREQUENCY GRAVITATIONAL WAVES GENERATION IN LASER PLASMA INTERACTION. 2009. hal-01676599

HAL Id: hal-01676599

<https://hal.science/hal-01676599>

Submitted on 5 Jan 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

HIGH FREQUENCY GRAVITATIONAL WAVES GENERATION IN LASER PLASMA INTERACTION

Xavier RIBEYRE* and Vladimir TIKHONCHUK

Centre Lasers Intenses et Applications, UMR 5107, CNRS, Université Bordeaux 1, CEA, Université Bordeaux 1, 351, cours de la Libération, 33405 Talence, France

**Email: ribeyre@celia.u-bordeaux1.fr*

Estimates of the emitted power and the metric perturbation of the gravitational waves generated in laser plasma interaction are performed. The expected intensities are too low to be detected with the present day instruments.

Keywords: Gravitational waves; Laser plasma interaction

1. Introduction

Existence of gravitational waves is postulated in the theory of general relativity by Einstein,¹ but no direct detection of such waves has been made so far. The best evidence of their existence is due to the work of 1993 Nobel laureates Taylor and Hulse.² The search for gravitational waves (GW) radiated by extraterrestrial sources is carried out by large gravitational interferometer detectors LIGO and VIRGO.³ These detectors address the low frequency spectral band between 10 Hz and 10 kHz. Recently, astrophysical sources of high frequency gravitational waves (HFGW: $\nu > 100$ kHz) were considered and this renewed an interest for a GW Hertz experiment,⁴ which consists in generation and receiving the GW signal on Earth. One of the first considerations of the gravitational Hertz experiment in laboratory was done by Weber⁵ in a low frequency domain. In the high frequency domain the possibilities of GW generation in laboratory were considered by Rudenko⁴ and by Chapline.⁶ In particular, Rudenko proposed a GW Hertz experiment associated with high power electromagnetic waves and acoustic impulsive or shock waves travelling and interacting with a non-linear opto-acoustic medium.

2. GW generation with lasers

The GW emission is proportional to that the third time derivative of the quadrupolar mass momentum $Q(t)$ is not zero. The power emitted by a local source of GW writes: $P_{GW} \simeq G\ddot{Q}^2/5c^5$ and the metric perturbation h_{GW} is given by $h_{GW} \simeq G\dot{Q}/Rc^4$, where G , c are the gravitational and light celerity constants and R is the distance between the GW generator and the detector.

As lasers actually are the most powerful sources of electromagnetic energy on earth, we present here analytical estimates and numerical simulations of generation of the HFGW in interaction of high power laser pulse with a medium in different geometries. First, during the laser plasma interaction, a strong shock driven by the ablation pressure is generated in the bulk material. In this configuration, material is accelerated in the shock front and in the ablation zone. Because of a short laser pulse duration (ns) GW are generated in the GHz domain. During the laser interaction with a planar thick foil (more than $100\mu\text{m}$ thickness) the laser launch a shock with a velocity V_s , this shock accelerates the medium along the z axis and produces a quadrupolar mass momentum Q_{zz} . The time dependence of the quadrupolar mass momentum in shock is $Q_{zz} = S\rho_0V_s^3t^3$, where S is the surface of laser focal spot. The shock velocity $V_s \simeq \sqrt{P_s/\rho_0}$ depends on the ablation pressure P_s and the material density ρ_0 . Moreover, P_s is directly connected to the laser intensity I_L as: $P_s \simeq 112(I_L)^{2/3}$ (for the laser wavelength $0.35\mu\text{m}$), where I_L is in PW/cm^2 and P_s in Mbar.⁷ With these relations the radiated GW power reads: $P_{GW}[\text{erg/s}] \simeq 7 \times 10^{-18}P_L^2/\rho_0$ and $h_{GW} \simeq 3 \times 10^{-37}E_L/R\sqrt{\rho_0}$, where, P_L the laser power is in PW, ρ in g/cc , E_L is the laser energy in MJ and R in cm. For achievable laser parameters: $P_L = 0.5\text{PW}$, $\rho = 30\text{mg}/\text{cc}$ (foam material) and $E_L = 0.5\text{MJ}$, we have $P_{GW} \simeq 6 \times 10^{-17}\text{erg/s}$ and $h_{GW} \simeq 10^{-39}$ for the detection distance of $R = 10\text{m}$ (we believe that a distance of a few meters is needed to protect the detector from strong broadband electromagnetic perturbations created in laser interactions).

In the case of GW generation in the laser ablation zone, the rarefaction wave propagates with the sound velocity $C_s \simeq \sqrt{P_L/\rho_0}$. The expression for Q_{zz} is similar to the shock wave problem, and C_s have the same magnitude as V_s . Hence, P_{GW} and h_{GW} have the values that are similar to the shock wave GW generation problem. In the laser matter interaction, the GW in the shock wave and in the rarefaction wave are produced at the same time and in the same space region. Then we can add these two contributions having, $P_{GW} \simeq 10^{-16}\text{erg/s}$ and $h_{GW} \simeq 4 \times 10^{-40}$.

Another GW source is a thin foil accelerated by a high ablation pressure produced by the laser heating and ablation.⁷ In this case, the quadrupolar mass momentum writes: $Q_{zz}(t) \simeq Mz^2$, where M is the initial mass foil. We can assume that the mass ablated during the laser interaction is negligible, then the GW emitted power writes: $P_{GW} \simeq GM^2(\dot{z}\ddot{z})^2/5c^5$ and $h_{GW} \simeq GM\dot{z}^2/c^4R$. With a high energy laser of a MJ class a velocity $\dot{z} \simeq 300\text{km/s}$ is achievable in 2 ns for a foil mass about 2 mg. Then, $P_{GW} \simeq 5 \times 10^{-19}\text{erg/s}$ and $h_{GW} \simeq 1.5 \times 10^{-40}$ with $R = 10\text{m}$.

HFGW could be produced with high power laser facilities dedicated to the inertial confinement fusion like the National Ignition Facility (NIF, USA), the Laser Megajoule (LMJ, France), or the European project for the inertial fusion energy HiPER.⁸ The laser driven implosion fusion can radiate HFGWs if the implosion of cryogenic deuterium-tritium (DT) micro-sphere would be asymmetric and produce a quadrupolar momentum Q_{zz} . In the case, $Q_{zz} \simeq \epsilon Mz^2$, where ϵ represents the non-symmetric part of the explosion. Such an asymmetric DT can be created by launching a bipolar shock.⁸ With this ignition scheme the asymmetry $\epsilon \simeq 0.2$ is

achievable. The laser Megajoule can implode a mass around 0.2 mg, with a velocity \dot{z} around 3×10^8 cm/s. The time scale of the explosion is around 20 ps. With these parameters, we have $P_{GW} \simeq 2 \times 10^{-14}$ erg/s and $h_{GW} \simeq 3 \times 10^{-39}$ with $R = 10$ m. The fusion reactions produce in the central DT core high velocity jets, which radiate HFGW in 50 GHz domain during the plasma expansion of less than 100 ps.

Another possibility to generate GWs in the THz domain would be to use a high intensity picosecond laser pulse.⁹ A circular polarized pulse with intensity $I_L \gtrsim 10^{21}$ W/cm² pushes a matter via the ponderomotive force it accelerates to the velocity $V_p = \sqrt{I_L/c\rho_0}$, which could be of the order of 10^9 cm/s or more. The radiated power reads: $P_{GW} \simeq 5 \times 10^{-25} P_L^3/\rho_0 \Phi^2$ [erg/s], where Φ is the laser focal spot diameter (in cm) and P_L in PW. Moreover, the metric perturbation writes: $h_{GW} \simeq 8 \times 10^{-40} P_L \tau_L/R$, where P_L is in PW and τ_L in ps. A power about 7 PW during 1 ps, with a focal spot about 30 μ m on a plastic target ($\rho_0 = 1$ g/cc), will be achievable on PetaWatt Class laser facilities (PETAL, NIF-ARC). With these parameters: $P_{GW} \simeq 2 \times 10^{-17}$ erg/s and $h_{GW} \simeq 6 \times 10^{-42}$ for a detection at the distance of 10 m.

3. Conclusion

Although all considered schemes have quite different geometries sizes and time scales, the generated GW powers and metric perturbations are not much different. This follows created by the observation that h_{GW} from a point-like source can be estimated as $G\mathcal{E}/Rc^4$, where \mathcal{E} is the available energy. With the maximum laser energy available today of 1 MJ, h_{GW} cannot be larger at the distance of few meters than 10^{-39} . The noise detection level $(h_{GW})_{min} \simeq 10^{-30}$ given in Ref. 4 is many order of magnitude higher. We conclude that available today laser sources are insufficient to generate HFGW on a detectable level. The limitation that we found for the point-like sources (with the size of the order of the emission wavelength) apply also to the sources of a larger size that might use interference effects to collimate emission in a certain solid angle. Although this may increase the intensity at the detector by one or two orders of magnitude, this do not affect the total emission power, which is still far away from the detection threshold.

References

1. A. Einstein, Preuss. Akad. Wiss. Berlin, Sitzber. p.154, (1916), p.688, (1918).
2. R. A. Hulse and J. H. Taylor, Astro. Phys. J. **L51** p.195 (1975).
3. V. B. Braginskii, Physics-Uspekhi, **43** 691, (2000).
4. V. N. Rudenko, Gravitation & Cosmology **10** pp. 41-49 (2004).
5. J. Weber, Phys. Rev. **117** 306, (1960).
6. J. F. Chapline *et al.*, Phys. Rev. D **10** 1064, (1974).
7. S. Atzeni and J. Meyer-ter-Vehn, Physics of the Inertial Fusion, Clarendon Press-Oxford (2004).
8. X. Ribeyre *et al.*, Plasmas Phys. and Control. Fusion, **51** 015013 (2009).
9. N. Naumova *et al.*, Phys. Rev. **102** 025002, (2009).