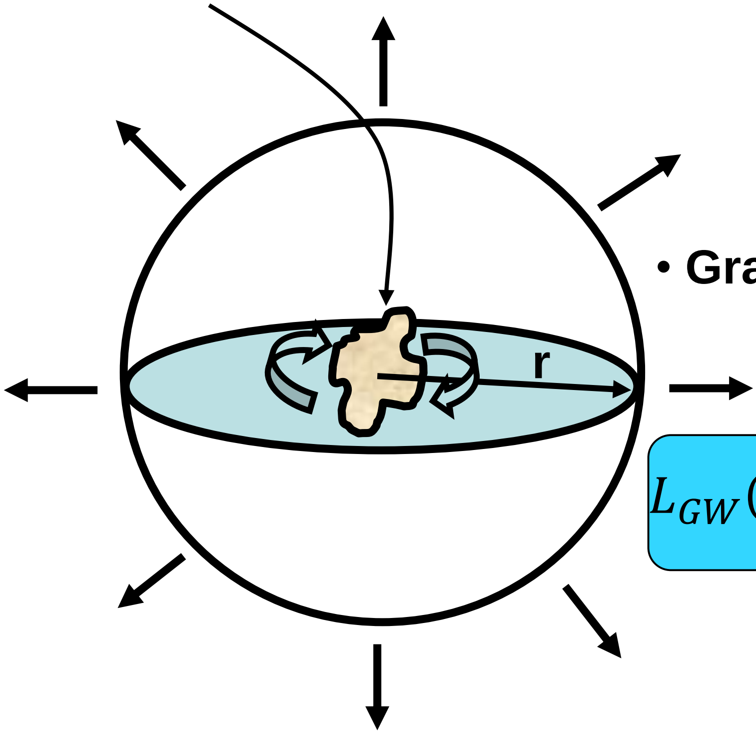
Possible Experimental Tests of General Relativity and Gravity on LMJ-PETAL

Ribeyre X. and Tikhonchuk V. T.
Centre Lasers Intenses et Applications (CELIA)
Université Bordeaux 1-CNRS-CEA
France

IZEST – ELI-NP Conference
17-19 Septembre 2014 PARIS

Emission of gravitational waves (GW)

Source : Mass acceleration



• **Linearized Einstein's equations***

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad h_{\mu\nu} \ll 1$$

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h$$

• **Gravitational waves luminosity L and perturbation h**

• **slow motion v << c and far from sources**

$$L_{GW}(t) = \frac{G}{5c^5}\left(\dddot{I}^{jk}\,\dddot{I}_{jk}\right)_{(t-\frac{r}{c})} \qquad h_{jk}(t) = \frac{2G}{rc^4}\left(\ddot{I}_{jk}\right)_{(t-\frac{r}{c})}$$

• **Quadrupolar moment of mass:**

$$I^{jk}(t) \equiv \iiint \rho(\vec{r},t)\left[r^j r^k - \frac{1}{3}\vec{r}^{\,2}\delta^{jk}\right] d^3r$$

Due to very small factor G/c^5 (~10^{-60} CGS): $\dddot{I}^{jk}$ **and** $\ddot{I}_{jk}$ **MUST BE VERY LARGE TO PRODUCE A HIGH LUMINOSITY**

* Tourrenc Ph. Relativité et gravitation, Armand Colin (1992)
Maggiore M. Gravitational waves, Vol. 1 Oxford (2008)

Gravitational waves spectral domain

High Frequency Gravitational Waves (HFGW)
Radio and optical band

Previous GW generator studies

- **Weber* (1960) Bar vibration** $\nu_g > \mathrm{kHz}$
- **Chapline et al.** (1974) GW produce by nuclear explosion** $\nu_g > \mathrm{GHz}$
- **Rudenko et al.*** (2003) GW generation with Ferromagnetic electromechanical transducer, micro explosion …** $\nu_g > \mathrm{GHz} - \mathrm{THz}$

Current approach

Sources: Short time mass acceleration (GHz-THz)

- Laser-Matter interaction allows to obtain a high mass acceleration in this time scale

$$g \simeq 10^{15} - 10^{20} \text{ cm/s}^2$$

Same acceleration than on Neutron Star Surface

*** Weber J., Phys. Rev. 117, 306 (1960)**
**** Chapline J. F. et al. Phys. Rev. D 10, 1064, (1974)**
***** Rudenko, V. N. Gravitation & Cosmology, 10, 41 (2004)**

Laser-Matter interaction

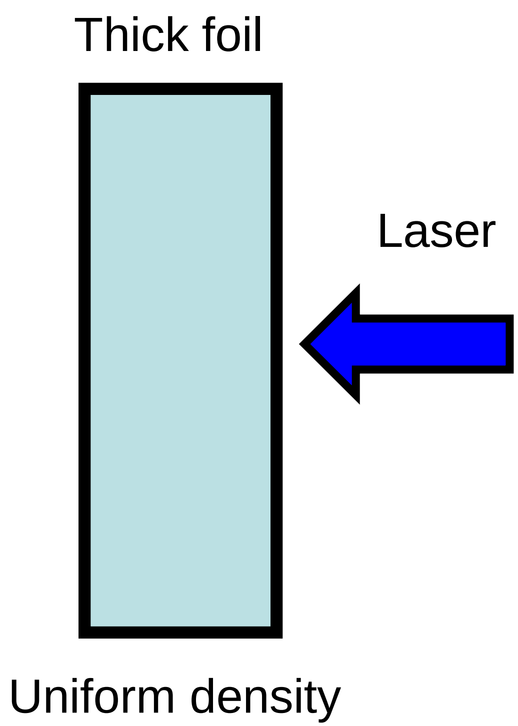
- What GW emissions one can generate at High Laser Intensities ?

  - Nanosecond time scale : GHz domain
    - Shock waves
    - Rarefaction waves
    - Mass acceleration with ablation pressure

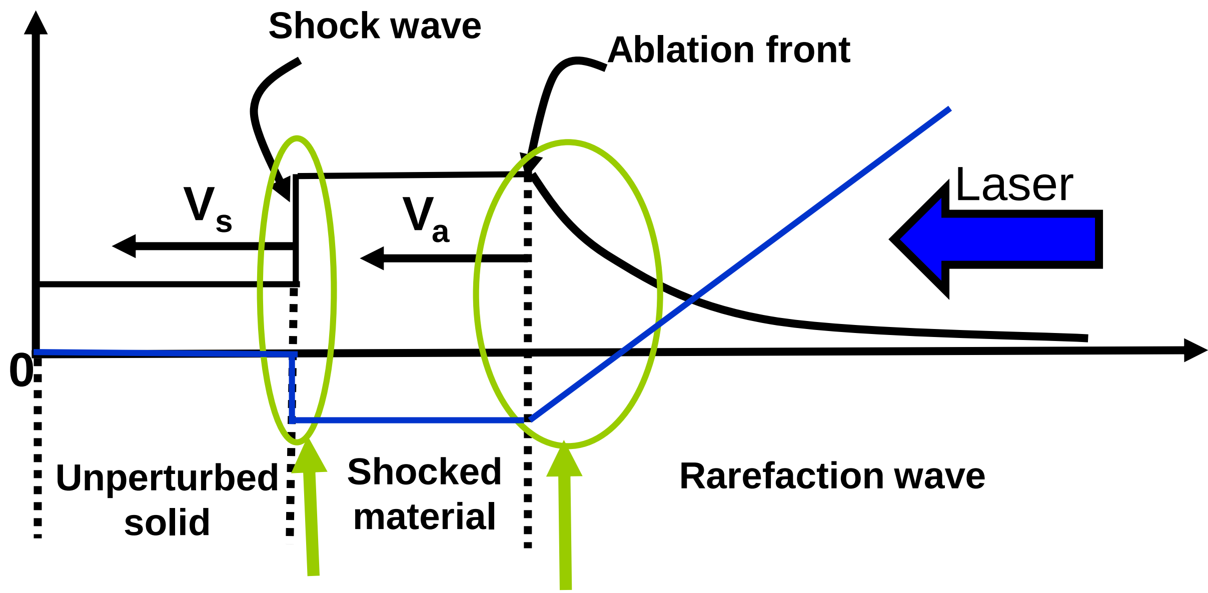
  - Picosecond time scale : THz Domain
    - Mass acceleration with radiation pressure
    - Fusion reactions : explosion

What gravitational luminosity and metric perturbation can be produced with these mechanisms ?

Shock and rarefaction waves



Typical density and velocity profile during the laser interaction*

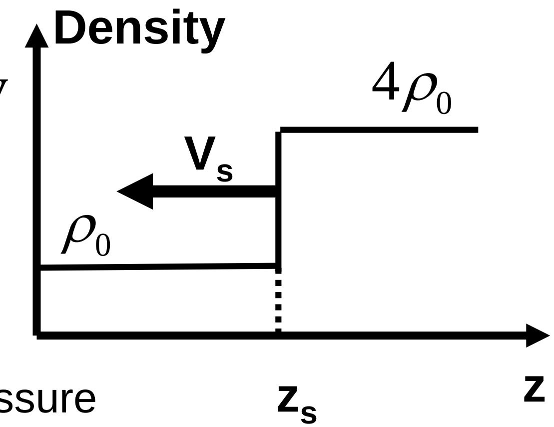


Strong velocity jumps :
High mass acceleration :
Gravitational wave emission region

*** Fabbro et al. Phys. of Plasmas 28 (1985)**

Shock wave HFGW generation

Shock position : $z_s(t) \simeq V_s t$ V_s : Shock wave velocity



$$I_{zz}(t) \simeq S\rho_0 {V_s}^3 t^3 + \text{cst}$$

Assuming strong shock : $V_s \simeq \sqrt{\frac{P_s}{\rho_0}}$

I_L Laser intensity

$P_s \propto {I_L}^{2/3}$

P_s Shock-wave pressure

$$L_{GW} = \frac{G}{5c^5}\dddot{I}_{zz}^{\,2} = 7 \times 10^{-18} \frac{{W_L}^2}{\rho_0} \,[\text{erg/s}]$$

W_L : Laser Power in PW

$\rho_0 : g/cc$

$$h = \frac{G}{rc^4}\ddot{I}_{zz} = 3 \times 10^{-37} \frac{{E_L}^2}{r\sqrt{\rho_0}}$$

E_L: Laser Energy in MJ

r : Detector distance in cm

Laser beam parameters (LMJ/NIF)

$W_L = 0.5$ PW, $\tau = 1$ ns

$E_L = 500$ kJ

$\rho_0 = 30$ mg/cc

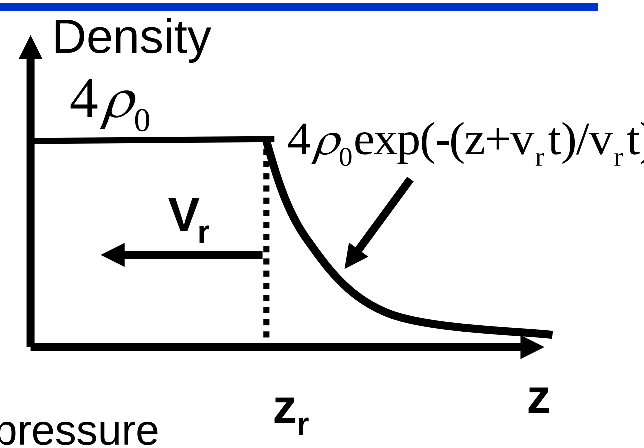
$L_{GW} = 6 \times 10^{-17}$ erg/s $\lambda_g = 30$ cm

$h = 10^{-39}$ r = 10 m $\nu_g = 1$ GHz

Rarefaction wave HFGW generation

Rarefaction wave position :

$z_r(t) \simeq V_r t$ V_r : Rarefaction wave velocity



$$I_{zz}(t) \simeq S\rho_0 {V_r}^3 t^3 + \text{cst}$$

I_L Laser intensity

$P_s \propto I_L^{2/3}$

Subsonic velocity in compressed flow $V_r \simeq C_s = \sqrt{\frac{P_s}{4\rho_0}}$

P_s Shock-wave pressure

$$L_{GW} = 2 \times 10^{-20} \frac{{W_L}^2}{\rho_0} [\text{erg/s}]$$

$$h = 3 \times 10^{-38} \frac{{E_L}^2}{r\sqrt{\rho_0}}$$

Laser beam parameters (LMJ/NIF)

$W_L = 0.5$ PW, $\tau = 1$ ns

$E_L = 500$ kJ

$\rho_0 = 30$ mg/cc

$L_{GW} = 2 \times 10^{-19}$ erg/s $\lambda_g = 30$ cm

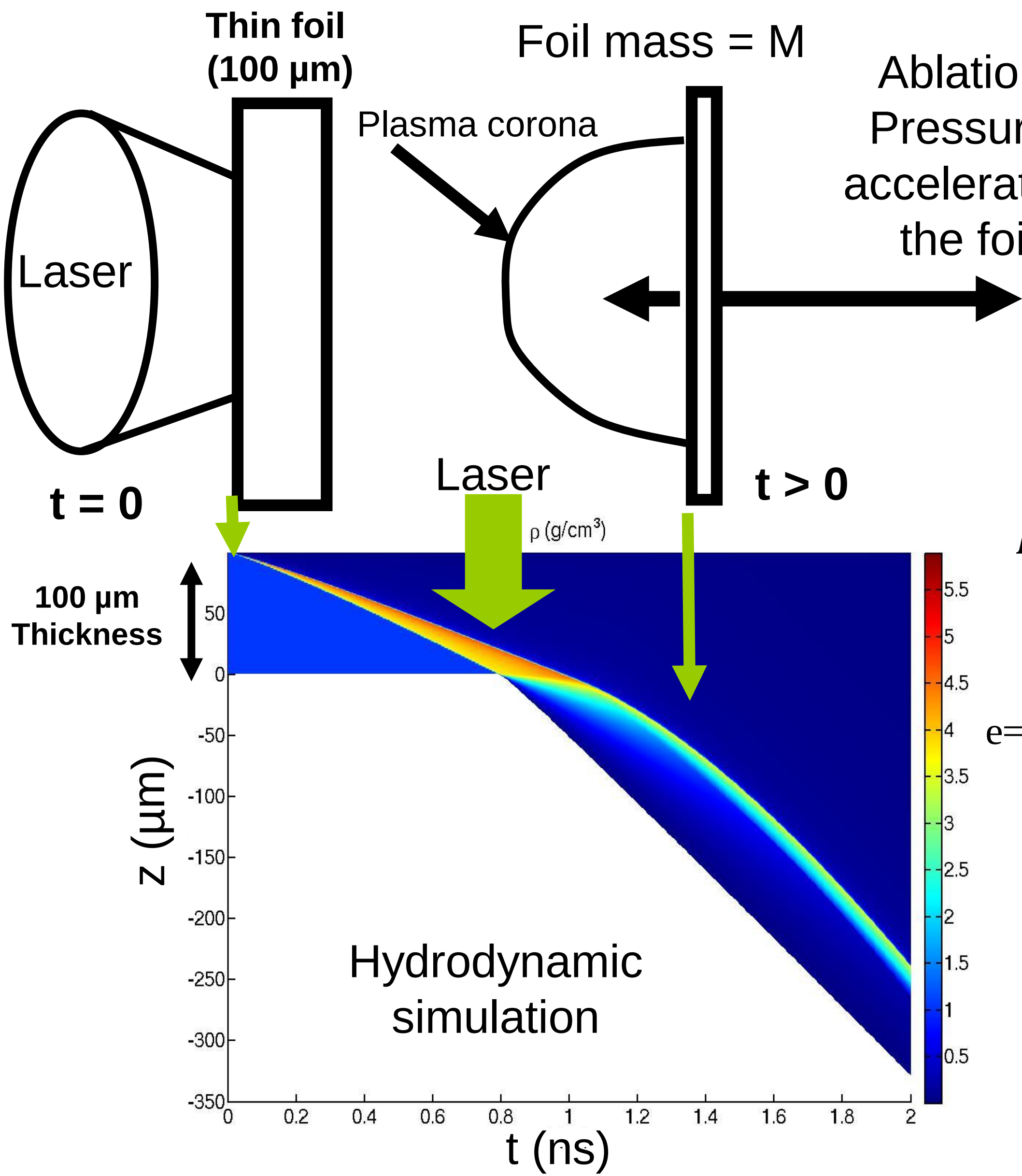
$h = 10^{-42}$ r = 10 m $\nu_g = 1$ GHz

Shock-rarefaction wave structure the shock-wave emission dominates :

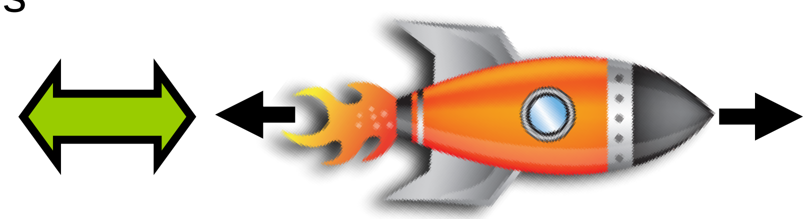
$L_{GW} = 6 \times 10^{-17}$ erg/s $\lambda_g = 30$ cm

$h = 10^{-39}$ r = 10 m $\nu_g = 1$ GHz

Mass acceleration driven by laser



Rocket model



M≃ cst $\quad I_{zz}(t) \simeq M\, z^2$

$$L_{GW} \simeq \frac{G}{5c^5}(\dot{z}\,\ddot{z}\,\mathrm{M})^2 \qquad h = \frac{G}{rc^4} M \dot{z}^2$$

Laser parameters (LMJ/NIF)

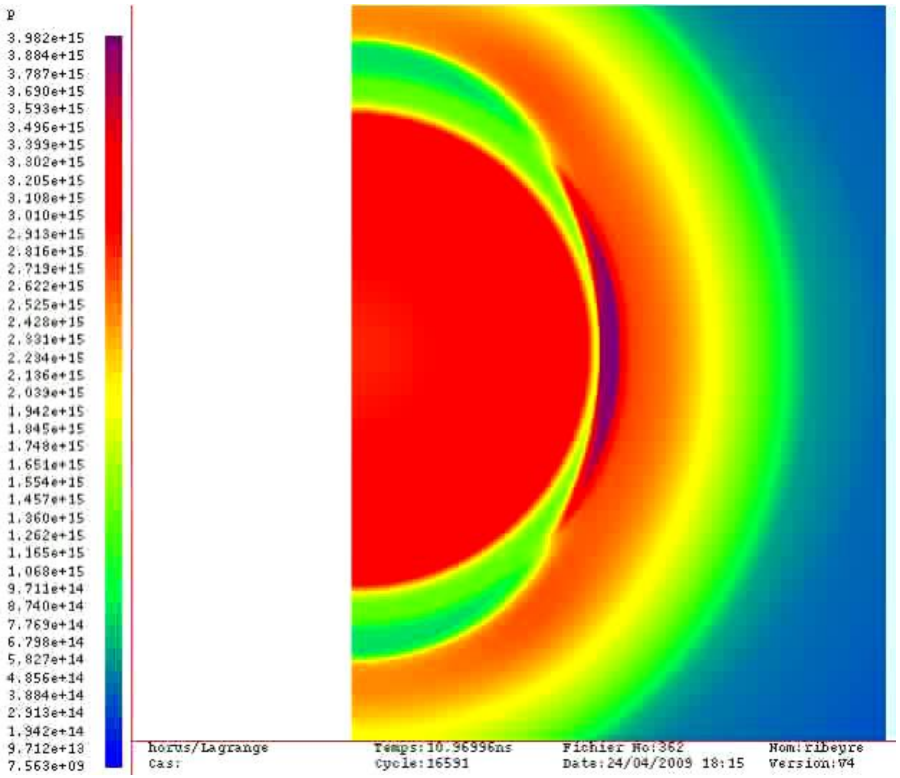
e=100 µm; S=0.2 cm^2; τ=2 ns ; M=2 mg; E_L = 800 kJ

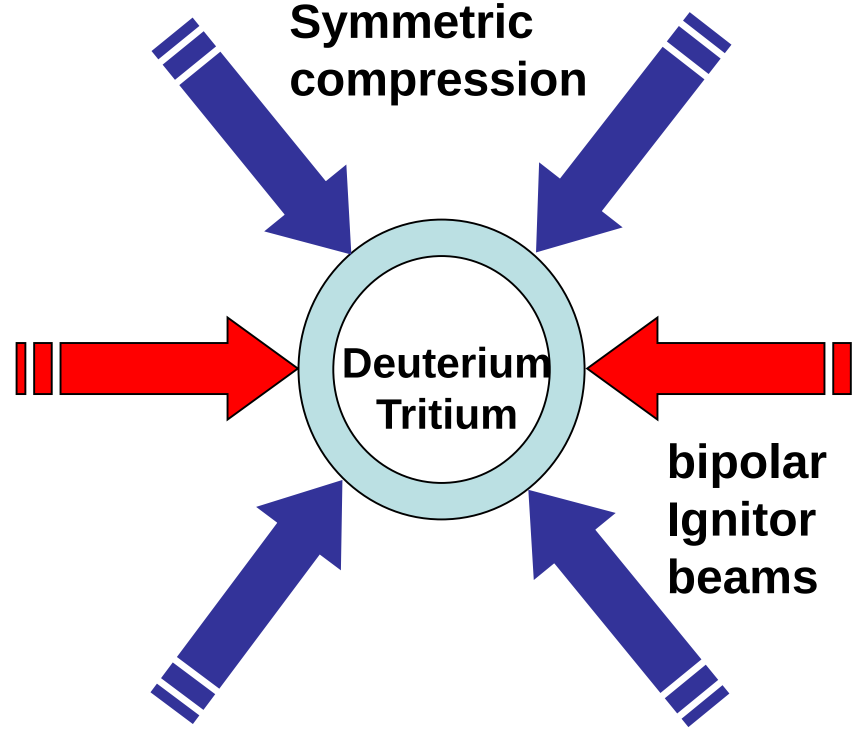
$L_{GW} = 5 \times 10^{-19}$erg/s $\quad \lambda_g = 60$ cm

$h = 10^{-40} \quad$ r = 10 m $\quad \nu_g = 0.5$ GHz

HFGW emission in fusion experiments

Pressure at stagnation bipolar shock (1)

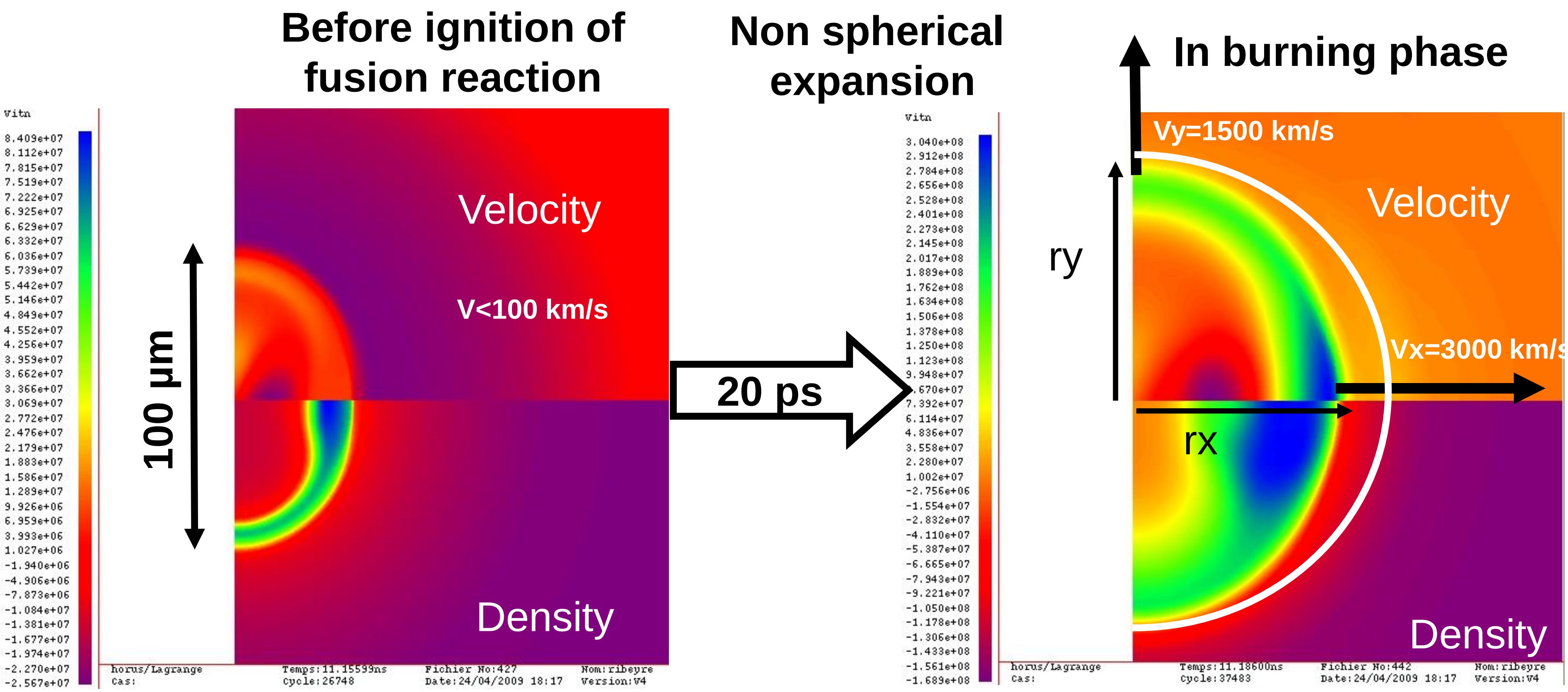




Non-spherical compression : quadrupolar emission

* Ribeyre et al. PPCF 5, 015013 (2009)

Gravitational waves emission in fusion experiments



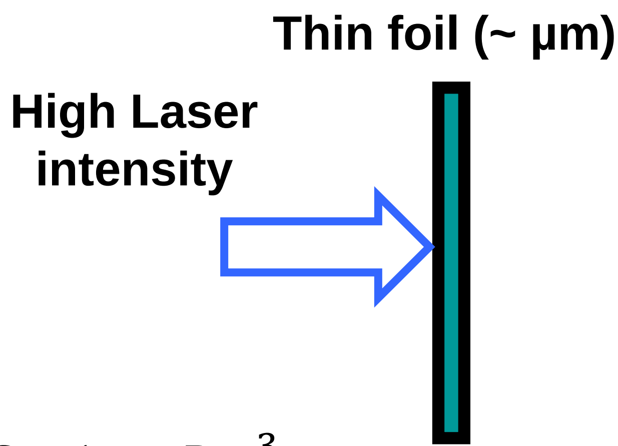
$$L_{GW} \simeq \frac{G}{5c^5}(\epsilon \dot{z}\, \ddot{z}\, \mathrm{M})^2 \qquad h = \frac{G}{rc^4}\epsilon M \dot{z}^2$$

Ellipticity: ε=(ry-rx)/[(ry+rx)/2] ≈ 0.2

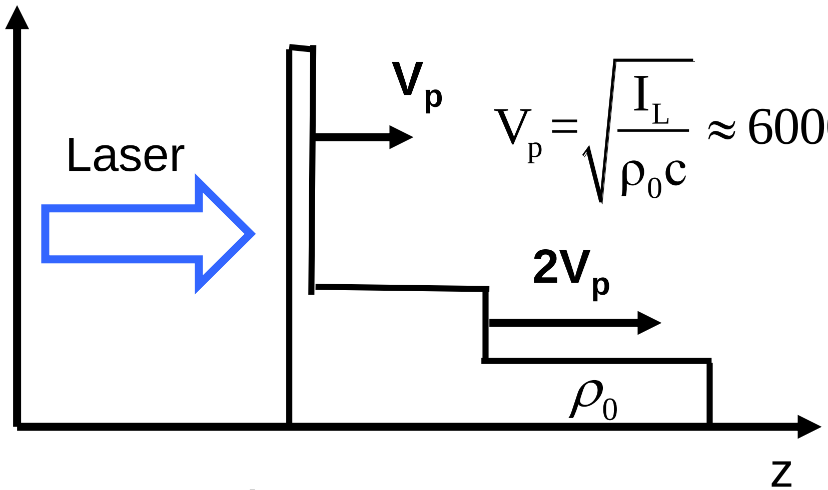
M=0.2 mg $\quad \dot{z} = 3 \times 10^8$ cm/s ; $\ddot{z} = 1.5 \times 10^{19}\ cm/s^2$

$L_{GW} = 5 \times 10^{-14}$erg/s $\quad$ r = 10 m $\quad h = 10^{-39}$ $\quad \lambda_g = 0.6$ cm $\quad \nu_g = 50$ GHz

HFGW emission with radiative piston[(1)]



V_p : Piston velocity



$$V_p = \sqrt{\frac{I_L}{\rho_0 c}} \approx 6000 \text{ km/s}$$

$$L_{GW} \simeq \frac{\pi^2 G}{5c^5} \frac{1}{\rho_0 \phi_L^2} \left(\frac{P_L}{c}\right)^3$$

$$L_{GW} \simeq 5 \times 10^{-25} \frac{1}{\rho_0 \phi_L^2} \left(\frac{P_{L(\mathrm{PW})}}{c}\right)^3$$

$$h \simeq 8 \times 10^{-40} \frac{1}{r} \left(\frac{P_{L(\mathrm{PW})}}{\tau_L(\mathrm{ps})}\right)$$

Laser beam parameters
(PETAL, FIREX1, OMEGA EP…)

P_L=7 PW

$\tau_L = 1$ ps; $\rho_0 = 1$ g/cc

ϕ_L =30μm; focal spot size

$L_{GW} = 2 \times 10^{-17} \mathrm{erg/s}$ r = 10 m $h = 10^{-42}$ $\lambda_g = 300$ μm $\nu_g = 1$ THz

*** Nomova et al. PRL 102, 025002 (2009)**

Conclusion

- First estimation of the GW source luminosity in laser-matter interaction*

- GHz domain
- Shock and rarefaction wave : L_{gw}~10^{-19}erg/s, h~10^{-39}

- Inertial Fusion experiment : L_{gw}~10^{-14}erg/s, h~10^{-39}

- THz domain
- Radiative pressure piston : L_{gw}~10^{-17}erg/s, h~10^{-42}

- First step towards a GW-Hertz experiment

- Need to improve the GW emision (efficiency, power and h) by new idea
- Need to detect this perturbation h in lab ?

* Ribeyre X. & Tikhonchuk V. T., 12 th Marcel Grossmann Meeting on General Relativity, p. 1640 (2009)

Futures studies

HFGW emission

- Other laser-matter interaction experiment will be considered and studied :
Non-linear interaction of travelling waves: $h \sim 10^{-37}$
GW emission from molecular quadrupole (see Rudenko V. 2003 gr-qc/0307105)
- Gravitons production from photon-photon collision on High Power Laser * ??

- Gravitons production from Gertsenshtein effect (photon-gravition conversion in static field)**

HFGW detection

- Progress in HFGW detection : sensitity $h \sim 10^{-26}$ in GHz band°
or $h \sim 10^{-22}$ in 0.1MHz band°°

* Pike, O. J., Nature Photonics, Vol 8, 434, (2014)
** Chen, P., PRL 74, 5 (1995)
° Li F.-Y. et al., Phys. Rev. D 80,064013 (2009), Li, F.-Y. et al., Chin. Phys. B 22, 12 (2013)
°° Arvanitaki A. & Geraci A. PRL.,110, 071105 (2014)