Can laser induced relativistic shock waves make a difference?

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34th European Conference on Laser Interaction with Matter

Moscow, Russia, September 18-23, 2016

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CONTENTS

1-Introduction

Who needs shock waves?

- From the time when **Hugoniot completed the theory of shock waves in 1887** this subject is active in many fields of science:

1. Condensed matter physics (including material strength).
2. Astrophysics (supernova, neutron stars etc.).
3. Geophysics (including planetary physics).
4. Nuclear physics (nuclear matter).
5. Particle physics (quark-gluon matter).
6. Plasma physics.
7. Inertial confinement fusion (ICF).
8. etc., etc., etc.

Why SHOCK WAVES?

I. static experiments:

The sample is squeezed between pistons or anvils.

Pressure is limited by the strength of the materials.

(maximum P~5Mbars)

II. **dynamic experiments**: **shock waves** are created.

Passage time of the shock is short in comparison with the disassembly time of the material.

One can do shock wave research for any pressure that can be supplied by a driver, assuming that proper diagnostics are available.

Laser induced shock-waves

Eliezer S. (2013). Shock waves and Equations of state related to laser plasma interaction. *Laser-Plasma Interactions and Applications,* 68th Scottish Universities Summer School in Physics, Eds. McKenna P, Neely

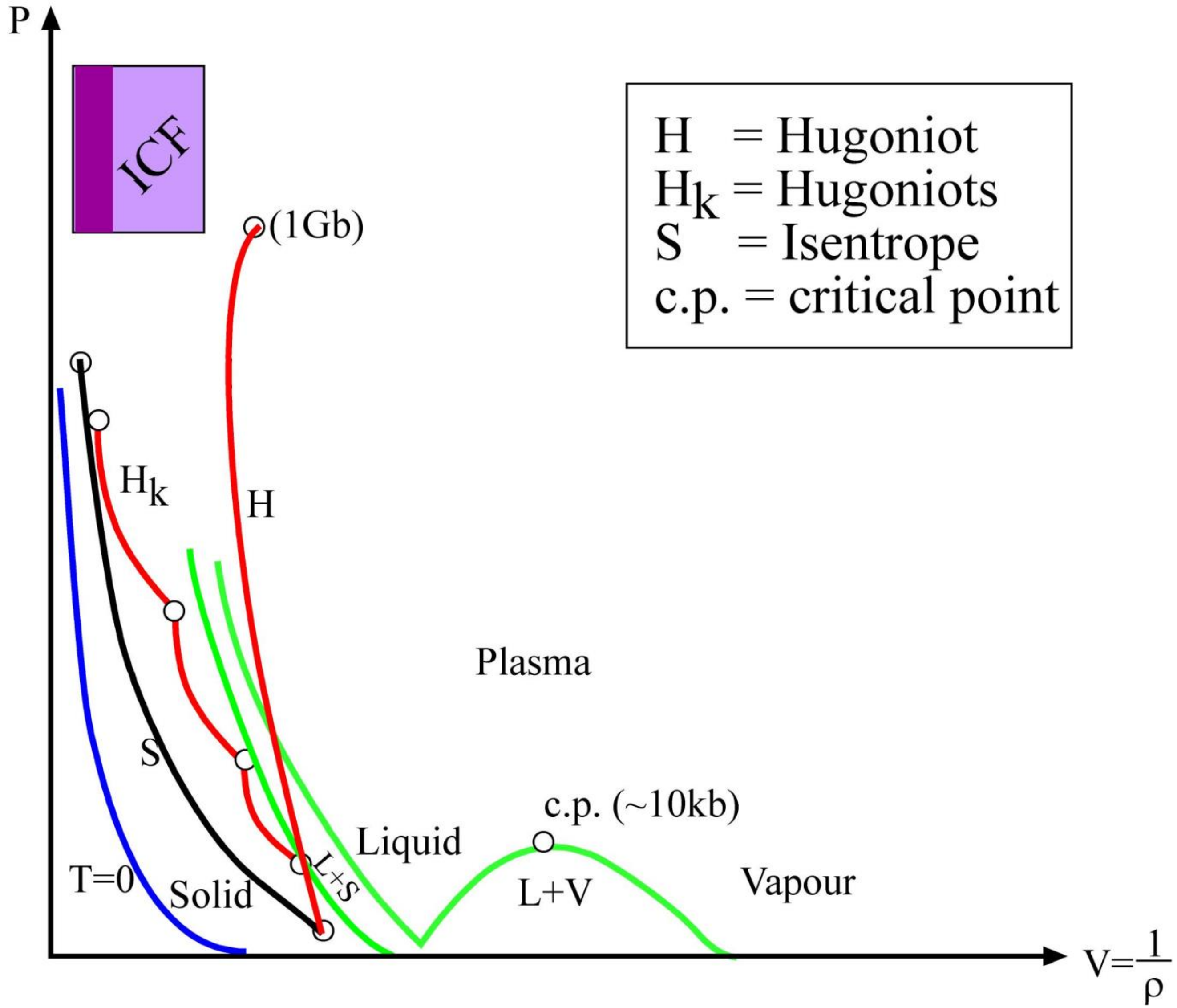
- In 1974 (Garching-Germany) the first direct observation of a laser-driven shock wave was reported : 2 Mbar.
- In 1994 Livermore-USA created a pressure of ~1Gbar (Indirect drive).
- In 2005 Osaka-Japan created a pressure of ~1Gbar (Direct drive).

RELATIVISTIC SHOCK WAVES

With 10^{24} W/cm^2 we expect pressures P ~ 1 Pbar=10^{15} bar

Hugoniot and thermodynamic curves

Eliezer S., Ghatak A., Hora H. and Teller E. (2002) *Fundamental of Equation of State*, Singapore: World Scientific.



2- Micro-foil acceleration

- Transfering momentum from light to macroscopic objects:

P. N. Lebedev, Ann. Der Physik, vol 6, 433 (1901)

- Interstellar vehicle propelled by terrestrial laser beam

G. Marx, Nature 211, 22 (1966)

- Acceleration of foils by ultra-intense lasers for generating relativistic ions.

T. Esirkepov et al. *PRL, 92, 175003 (2004).*

- Relativistic Rayleigh –Taylor instability.

F. Pegoraro and S. V. Bulanov PRL **99,** 065002 (2007)

- S. Eliezer, J. M. Martinez Val, (2012 and 2013)

Notation: Subscript F for foil rest frame; No subscript for laboratory frame.

The laser irradiance I :

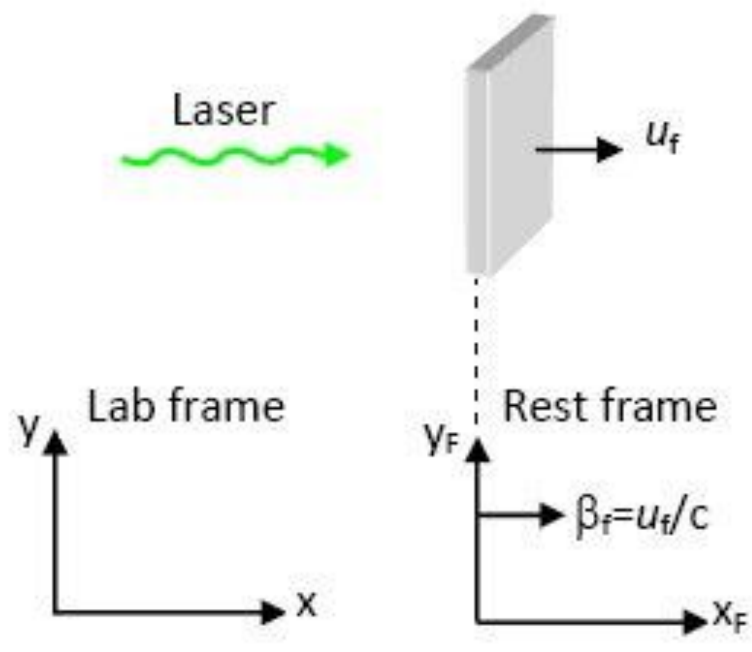
$$I = I_F \left(\frac{\omega}{\omega_F} \right)^2 = I_F \left(\frac{1+\beta_f}{1-\beta_f} \right)$$

The electromagnetic pressure P :

$$P = P_F = \frac{I_F}{c}(1 + R_F - T_F) = \frac{2 I_F R_F}{c}$$

$$R_F + T_F = 1$$

$$\mathrm{R_F} = 1 \;\Rightarrow\; P = \frac{2I}{c} \left(\frac{1-\beta_f}{1+\beta_f} \right)$$



Momentum of the microfoil : $p_{\mathrm{f}} = \mathrm{M}_{0\mathrm{f}} \gamma_f \beta_{\mathrm{f}} \mathrm{c}$, rest mass : $\mathrm{M}_{0\mathrm{f}} = \rho_0 \mathrm{S} l$

$\rho_0 =$ initial density, $\mathrm{S} =$ cross section area, $l =$ the thickness of the microfoil

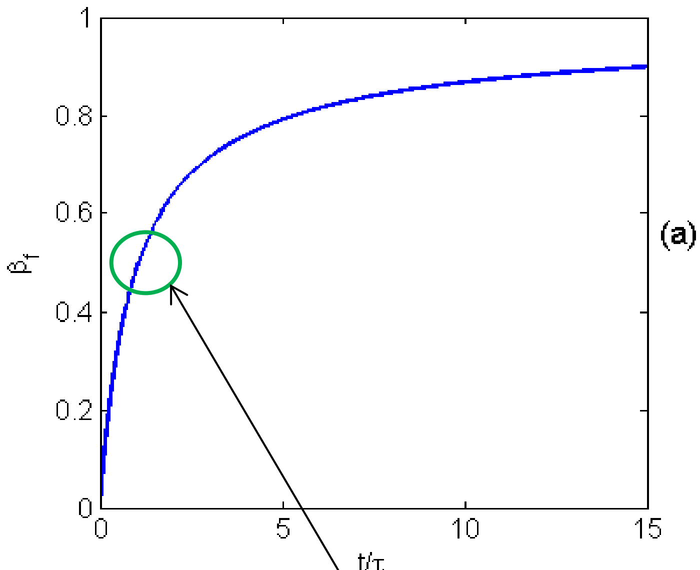
$$\frac{dp_f}{dt} = PS \Rightarrow \frac{d}{dt}\left[(\rho_0 l c) \frac{\beta_f}{\sqrt{1-\beta_f{}^2}} \right] = \frac{2I}{c}\left(\frac{1-\beta_f}{1+\beta_f} \right)$$

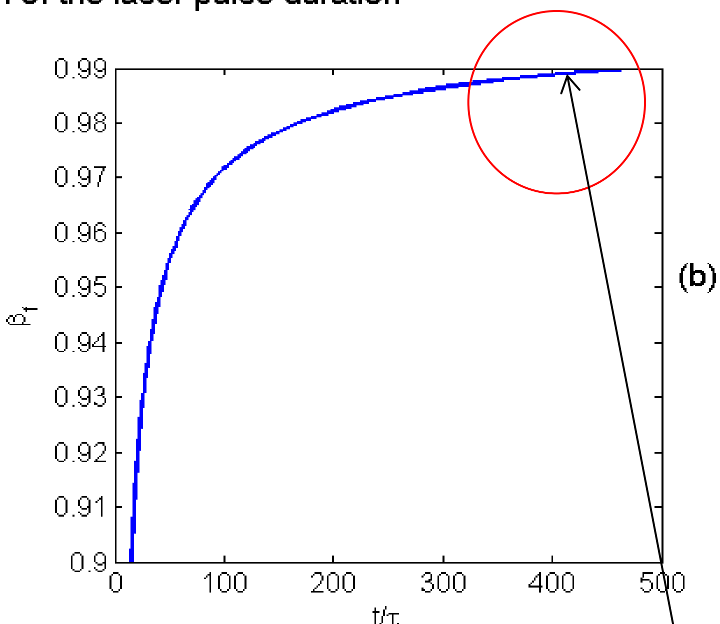
$$\Rightarrow \frac{1}{\left(1+\beta_f\right)^{1/2}\left(1-\beta_f\right)^{5/2}} \frac{d\beta_f}{dt} = \frac{2I}{\rho_0 c^2 l}$$

$$I = const \rightarrow \int_0^{\beta_f} \frac{dx}{(1-x)^{5/2}(1+x)^{1/2}} = \frac{(2-\beta_f)\sqrt{1-\beta_f^{\,2}}}{3(1-\beta_f)^2} - \frac{2}{3} = \frac{2It}{\rho_0 c^2 l} \equiv \frac{t}{\tau}$$

$$W_L = ItS = \frac{\rho_0 c^2 Sl}{2}\left(\frac{t}{\tau}\right) = \left(\frac{\rho_0 c^2 Sl}{2}\right)\left[\frac{(2-\beta_f)\sqrt{1-\beta_f^{\,2}}}{3(1-\beta_f)^2} - \frac{2}{3}\right]$$

Micro-foil velocity as function of the laser pulse duration





$t=\tau_L=\tau \ \rightarrow \beta_f \approx 0.5$
laser pulse duration
$t=\tau_L=\tau = \rho_0 c^2 l/(2I) \rightarrow$ $I_L\tau_L = \rho_0 c^2 l/2$

$\beta_f(t/\tau) \rightarrow 1$ for $t/\tau \rightarrow \infty$
laser pulse duration
$t=\tau_L >> \tau = \rho_0 c^2 l/(2I) \rightarrow$ $I\tau_L >> \rho_0 c^2 l/2$

$I_L\tau_L = 4.5\cdot 10^8$ J/cm^2 for $\rho_0 = 1$g/cm^3
$W_L = I_L\tau_L S = 45$J for $S = 10\mu m^2$

kinetic energy of the foil W_{Kf}

$$\frac{W_{Kf}}{S}=\rho_0 l c^2\left(\frac{1}{\sqrt{1-\beta_f^{\,2}}}-1\right);\ \mathrm{W}_L\equiv W_L(in)>W_{Kf};$$

$$W_L(in)>W_L(reflected)\ \text{also for } \mathrm{R}_F=1 \text{ due to Doppler shift!}$$

Non-relativistic limit $W_{Kf}/S \sim \beta_f^2 \sim t^2$ for $t \rightarrow 0$.

Relativistic limit $W_{Kf}/S \sim t^{1/3}$ for $t \rightarrow \infty$

Kinetic energy per atom $\boldsymbol{\varepsilon_{Kf}}$= W_{Kf}/N

Example (Al):

ρ_0 = 2.7 g/cm^3, l = 0.1μm, S = 10 μm^2

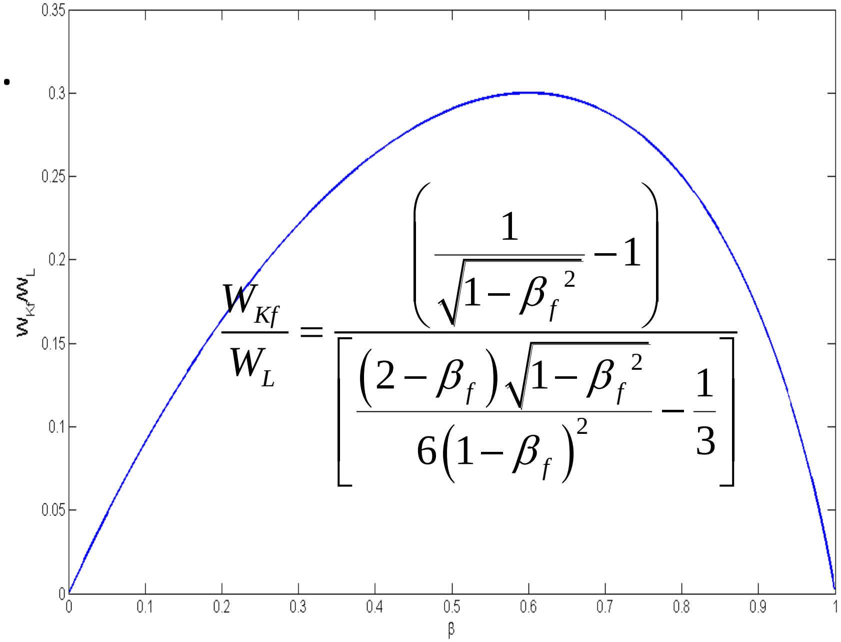
$\rightarrow$N(Al atoms)=$6\cdot10^{10}$

β=0.99 $\rightarrow$ $W_{Kf} \approx$ 1500J, $\varepsilon_{Kf} \approx$ 150GeV

β=0.9 $\rightarrow$ $W_{Kf} \approx$ 300J , $\varepsilon_{Kf} \approx$ 30GeV

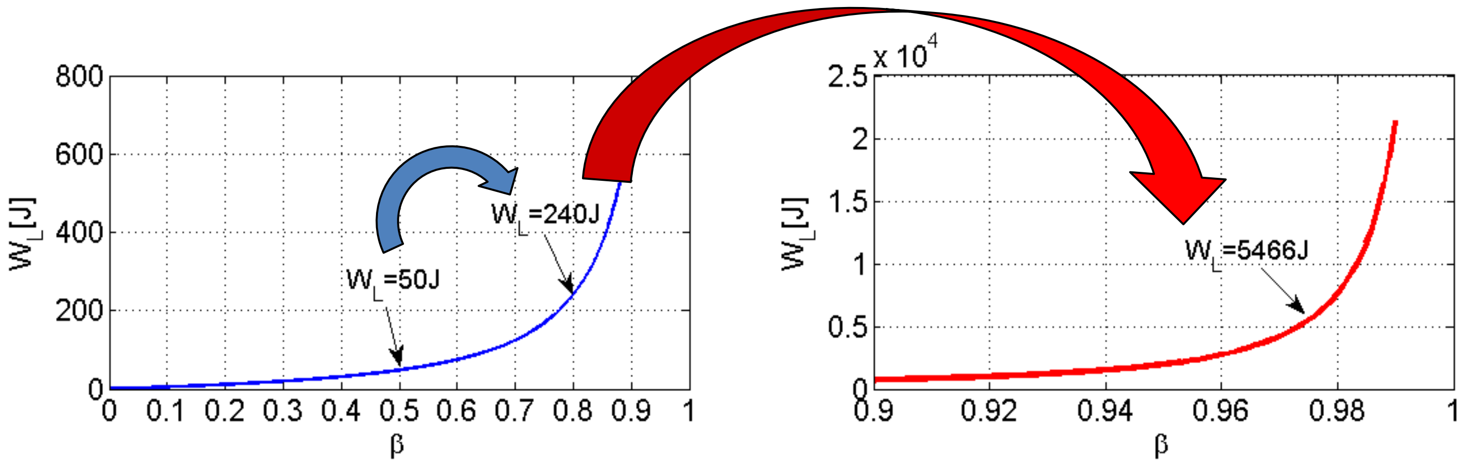
β=0.5 $\rightarrow$ $W_{Kf} \approx$ 40J , $\varepsilon_{Kf} \approx$ 4GeV

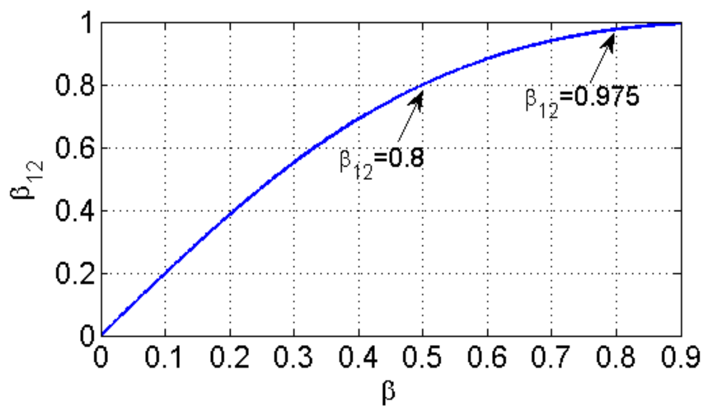
Note: $m_{Al}c^2 \approx 27 m_p c^2 \approx$27GeV

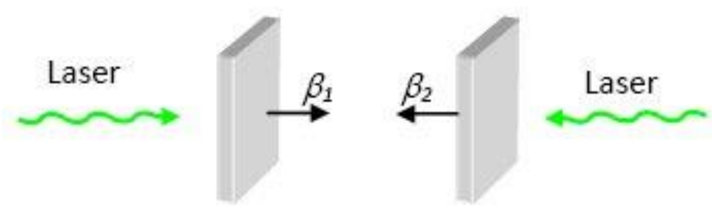


Collisions between 2 accelerated foils

$$W_L = ItS = \frac{\rho_0 c^2 Sl}{2}\left(\frac{t}{\tau}\right) = \left(\frac{\rho_0 c^2 Sl}{2}\right)\left[\frac{\left(2-\beta_f\right)\sqrt{1-\beta_f^{\,2}}}{3\left(1-\beta_f\right)^2} - \frac{2}{3}\right]$$







$$\beta_{12} = \frac{\beta_1 + \beta_2}{1+\beta_1\beta_2}$$

Relativistic Rayleigh-Taylor (RT) instability

$$Non-relativistic\ \text{RT: } \xi_{NR} = \Delta x / x_0 = \exp\left(t / \tau_{NR}\right)$$

$$\text{Re}lativistic\ \text{RT: } \qquad \xi_R = \Delta x / x_0 = \exp\left[\left(t / \tau_R\right)^{1/3}\right]$$

$$\tau_{NR} = \left[\left(\frac{1}{8\pi}\right)\frac{\rho_0 \ell_x \ell_{yz} c}{I_L}\right]^{1/2}; \quad \tau_R = \left[\left(\frac{1}{72\pi^3}\right)\frac{{\ell_{yz}}^3 I_L}{\rho_0 \ell_x c^5}\right]^{1/2}$$

$$foil\begin{cases} \ell_x \text{=thickness=0.1}\mu\text{m; } \ell_{yz} = \text{y-z dimension=10}\mu\text{m} \\ \rho_0 = 1g / cm^3; x_0 = initial\ \text{disturbance amplitude=10nm} \end{cases}$$

$$\text{laser: I}_L = 10^{24} W / cm^2$$

$$foil\ \text{breaks } \xi \sim 10 \Rightarrow \begin{cases} NR: \text{ foil breaks at t=2.5 fs} \\ R: \quad \text{foil breaks at t=50 fs} \end{cases}$$

3- Relativistic Shock Waves

The formalism

$4-\text{velocity}: \ U_\mu = \left(\gamma c, \gamma \mathrm{v}_1, \gamma \mathrm{v}_2, \gamma \mathrm{v}_3\right);$

P=pressure, e=energy/volume (including mass energy), n=number of particles/volume

Metric tensor $\mathrm{g}_{\mu\nu}: \ \mathrm{g}_{00} = -1, \mathrm{g}_{11} = \mathrm{g}_{22} = \mathrm{g}_{33} = 1, \mathrm{g}_{\mu\nu} = 0 \text{ if } \mu \neq \nu.$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}; \quad \beta = \frac{\mathrm{v}}{c}; \ \text{c = speed of light; Lorentz transformtion=} \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \beta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Energy-momentum 4-tensor: $T_{\mu\nu} = (e+P)U_\mu U_\nu + Pg_{\mu\nu}$

Energy-momentum conservation: $\dfrac{\partial T_\mu^\nu}{\partial x^\nu} \equiv \partial_\nu T_\mu^\nu = 0$ for μ=0,1,2,3.

Particle number conservation: $\dfrac{\partial (nU^\mu)}{\partial x^\mu} \equiv \partial_\mu \left(nU^\mu\right) = 0$

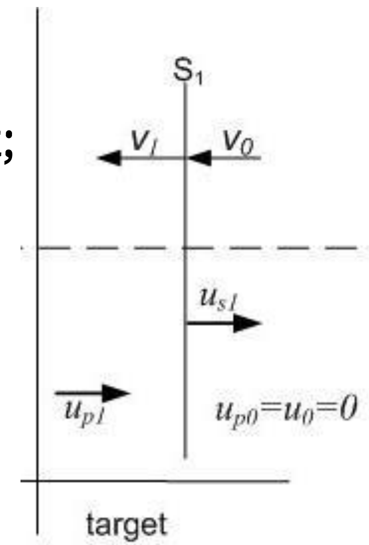
The equation of State: $P{=}P\left(e,n\right)$

Note: Einstein summation is assumed (from 0 to 3) for identical indexes.

Conservation laws in the shock - wave (SW) reference system :

indexes 0 & 1 before and after SW singularity accordingly;

$$\gamma_i = \frac{1}{\sqrt{1-\beta_i^2}}; \quad \beta_i = \frac{\mathrm{v}_i}{c}; \text{ i=0 or 1; c = speed of light;}$$



Conservation of energy: $\gamma_0^2\beta_0(e_0+P_0)=\gamma_1^2\beta_1(e_1+P_1)$

Conservation of momentum: $\gamma_0^2\beta_0^2(e_0+P_0)+P_0=\gamma_1^2\beta_1^2(e_1+P_1)+P_1$

Conservation of number of particles: $\gamma_0\beta_0 n_0=\gamma_1\beta_1 n_1$

$P, e, n, \rho = Mn, T$ defined in the rest frame of reference (of the fluid).

The solution (A. H. Taub, PR **74**, 328 (1948):

Solution in the laboratory frame of reference

$$\frac{u_s}{c} = \sqrt{\frac{(P_1 - P_0)(e_1 + P_0)}{(e_1 - e_0)(e_0 + P_1)}}$$

$$\frac{u_p}{c} = \sqrt{\frac{(P_1 - P_0)(e_1 - e_0)}{(e_0 + P_1)(e_1 + P_0)}}$$

$$\frac{(e_1 + P_1)^2}{\rho_1^{\,2}} - \frac{(e_0 + P_0)^2}{\rho_0^{\,2}} = (P_1 - P_0)\left[\frac{(e_0 + P_0)}{\rho_0^{\,2}} + \frac{(e_1 + P_1)}{\rho_1^{\,2}}\right] \quad \text{(Hugoniot)}$$

$$e_j = \rho_j c^2 + \frac{P_j}{\Gamma - 1};\ \text{j=0,1.} \quad (EOS)$$

P = pressure; e = energy density; ρ = mass density
u_s = shock wave velocity; u_p = particle flow velocity
c = the speed of light.
subscripts 0 and 1 denote the domains before and after the shock arrival

The Hugoniot function

Notation: $\Pi_L \equiv \frac{I_L}{\rho_0 c^3}; \kappa \equiv \frac{\rho_1}{\rho_0}; \kappa_0 \equiv \frac{\Gamma+1}{\Gamma-1}; \Pi = \frac{P_1}{\rho_0 c^2}; \Pi_0 = \frac{P_0}{\rho_0 c^2};$

The nonrelativistic Hogoniot: $\Pi = \left(\frac{\kappa\kappa_0 - 1}{\kappa_0 - \kappa}\right)\Pi_0$

The relativistic Hogoniot for $\kappa \equiv \frac{\rho_1}{\rho_0} \geq 1$:

$$\begin{cases} \Pi^2 + B\Pi + C = 0 \\ \Pi = \left(\frac{1}{2}\right)\left(-B \pm \sqrt{B^2 - 4C}\right) \\ B = \frac{(\Gamma-1)^2}{\Gamma}\left(\kappa_0\kappa - \kappa^2\right) + \Pi_0(\Gamma-1)\left(1-\kappa^2\right) \\ \mathrm{C} = \frac{(\Gamma-1)^2}{\Gamma}\left(\kappa - \kappa_0\kappa^2\right)\ \Pi_0 - \kappa^2\Pi_0{}^2 \end{cases}$$

The non relativistic shock wave equations

e = $\rho c^2 + \rho E$,

P << ρc^2; ρE << ρc^2 and u/c << 1

$$\Downarrow$$

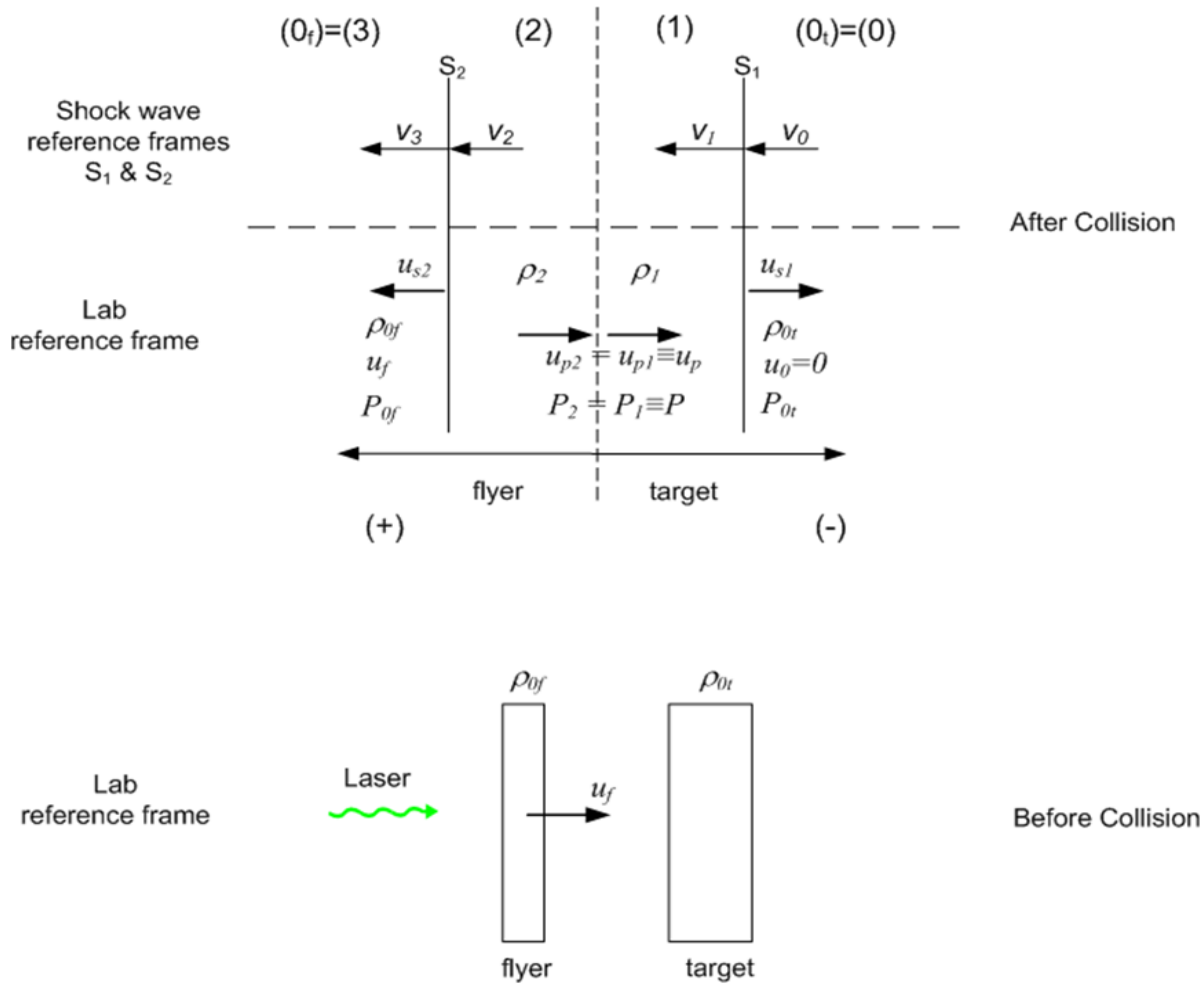
$$(i)\ u_p = \left(P_1 - P_0\right)^{1/2}\left(1/\rho_0 - 1/\rho_1\right)^{1/2}$$

$$(ii)\ u_s = \left(1/\rho_0\right)\left(P_1 - P_0\right)^{1/2}\left(1/\rho_0 - 1/\rho_1\right)^{-1/2}$$

$$(iii)\ E_1 - E_0 = \left(\frac{1}{2}\right)\left(P_1 + P_0\right)\left(1/\rho_0 - 1/\rho_1\right)$$

$$\left.\begin{matrix}(iv)\\(v)\end{matrix}\right\}\ E_j = \left(\frac{1}{\Gamma - 1}\right)\left(\frac{P_j}{\rho_j}\right) \text{ for j=0,1}$$

4- Shock waves in a foil-target collision


(0f)=(3)
(2)
(1)
(0t)=(0)
S2
S1
Shock wave reference frames S1 & S2
v3
v2
v1
v0
After Collision
us2
ρ2
ρ1
us1
Lab reference frame
ρ0f
uf
P0f
up2 = up1≡up
P2 = P1≡P
ρ0t
u0=0
P0t
flyer
target
(+)
(-)
ρ0f
ρ0t
Lab reference frame
Laser
uf
Before Collision
flyer
target

Solution of the Hugoniot equations

$$u_{p1} = -c\sqrt{I_1};\ u_{p2} = -c\left(\beta_f - \sqrt{I_2}\right)\left(1 - \beta_f\sqrt{I_2}\right)^{-1}$$

$$u_{s1} = -c\sqrt{J_1};\ u_{s2} = -c\left(\beta_f - \sqrt{J_2}\right)\left(1 - \beta_f\sqrt{J_2}\right)^{-1}$$

$$I_i = \frac{\Pi_i\left[\Pi_i + (2/3)(\kappa_i - 1)\right]}{(\Pi_i + 1)\left[\Pi_i + (2/3)\kappa_i\right]} \text{ for } i = 1,2$$

$$J_i = \frac{\Pi_i\left[(2/3)\kappa_i + \Pi_i\right]}{\left[(2/3)(\kappa_i - 1) + \Pi_i\right]\left[1 + \Pi_i\right]} \text{ for } i = 1,2$$

The Continuity Equations

Assume: $\Gamma_t = \Gamma_f \equiv \Gamma = 5/3; \quad \Pi_{0t} = \Pi_{0f} = 0$

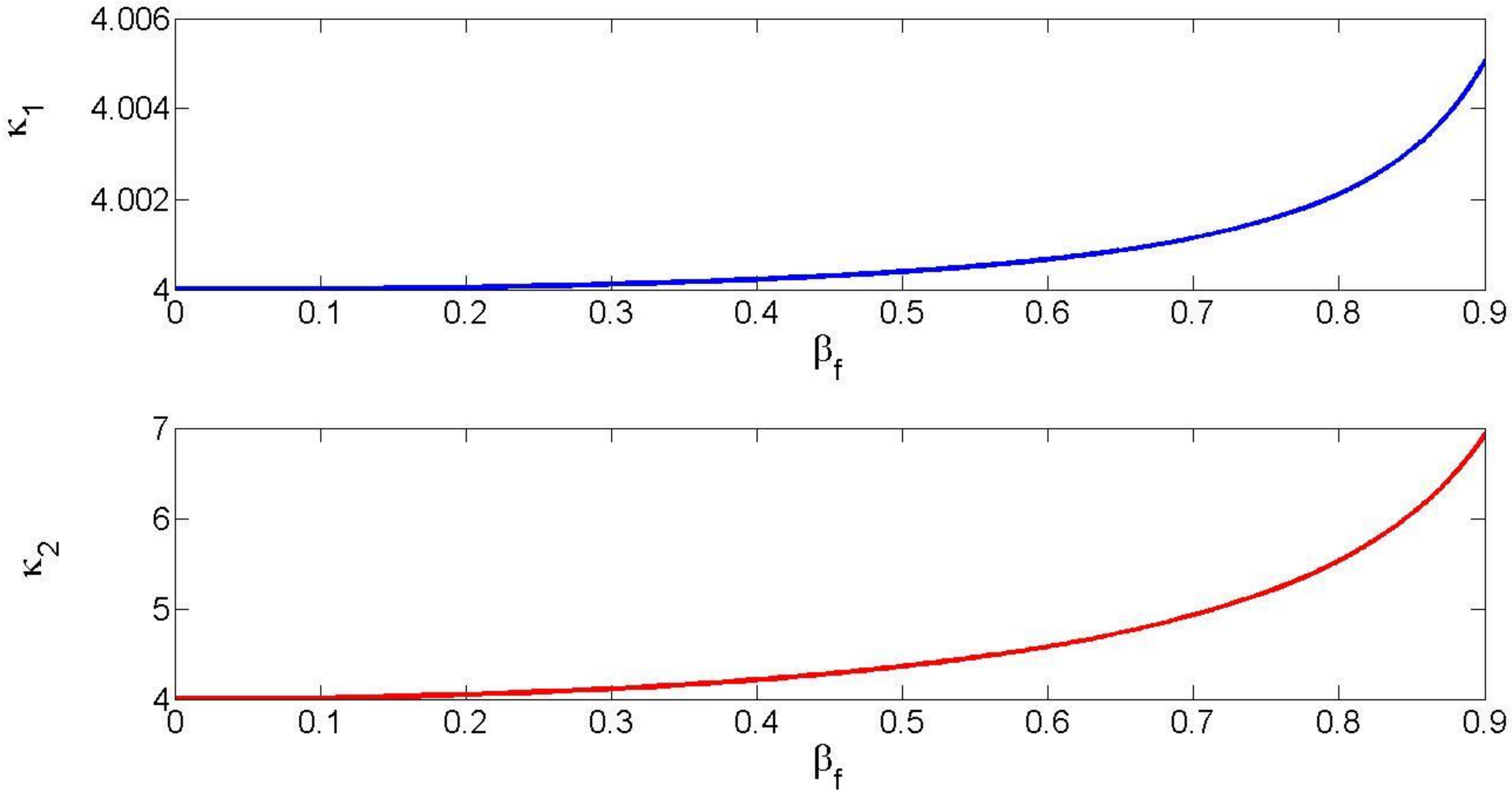
$$P_1 = P_2 \Rightarrow (1)\ \kappa_2^{\,2} - 4\kappa_2 = K\left[\kappa_1^{\,2} - 4\kappa_1\right]$$

$$u_{p1} = u_{p2} \Rightarrow (2)\quad -\sqrt{I_1} + \beta_f\sqrt{I_1 I_2} = \sqrt{I_2} - \beta_f$$

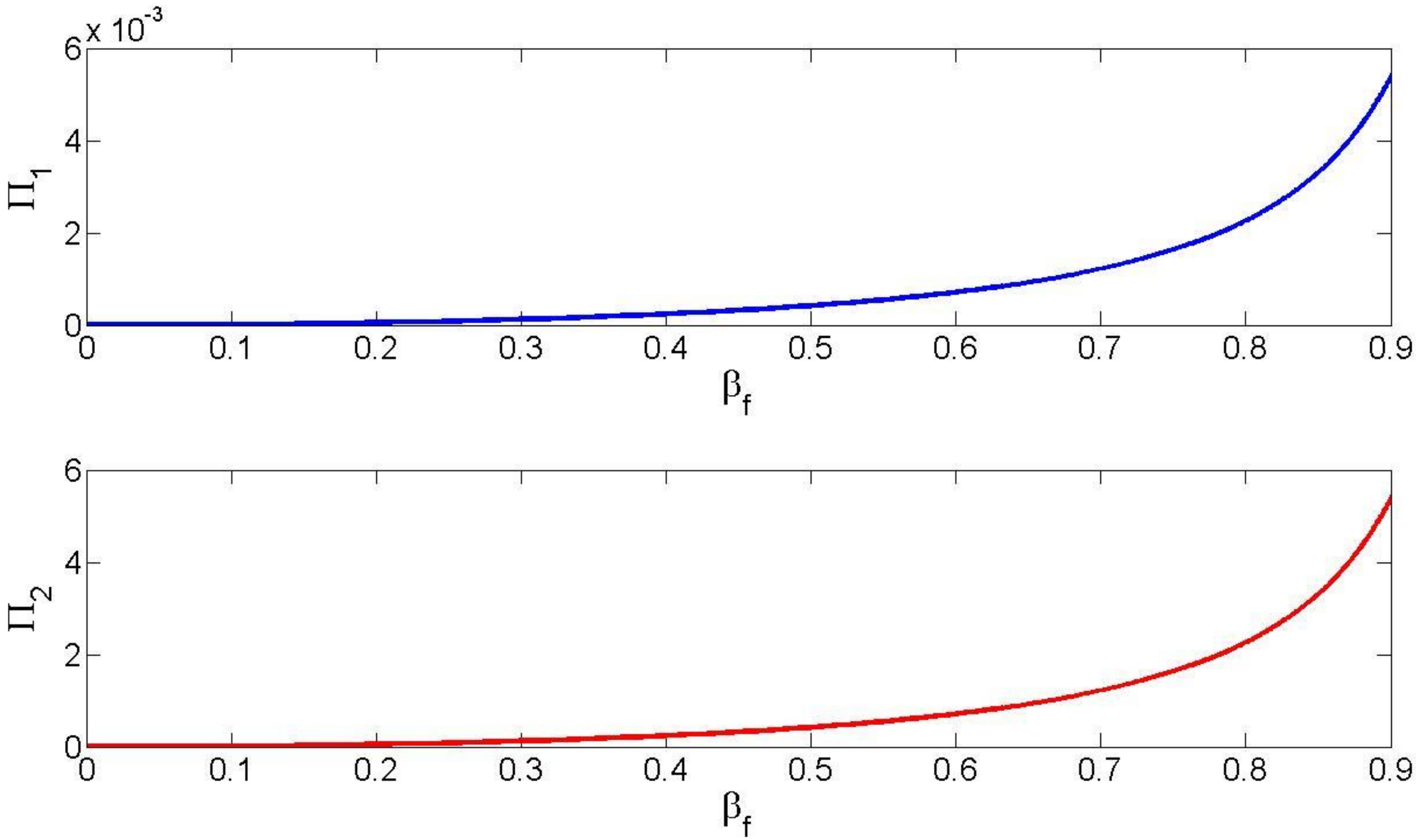
$$I_1 = \frac{\Pi_1\left[\Pi_1 + \left(\frac{2}{3}\right)(\kappa_1 - 1)\right]}{(\Pi_1 + 1)\left[\Pi_1 + \left(\frac{2}{3}\right)\kappa_1\right]};\Pi_1 = \left(\frac{4}{15}\right)\left(\kappa_1^{\,2} - 4\kappa_1\right)$$

$$I_2 = \frac{\Pi_2\left[\Pi_2 + \left(\frac{2}{3}\right)(\kappa_2 - 1)\right]}{(\Pi_2 + 1)\left[\Pi_2 + \left(\frac{2}{3}\right)\kappa_2\right]};\Pi_2 = \left(\frac{4}{15}\right)\left(\kappa_2^{\,2} - 4\kappa_2\right)$$

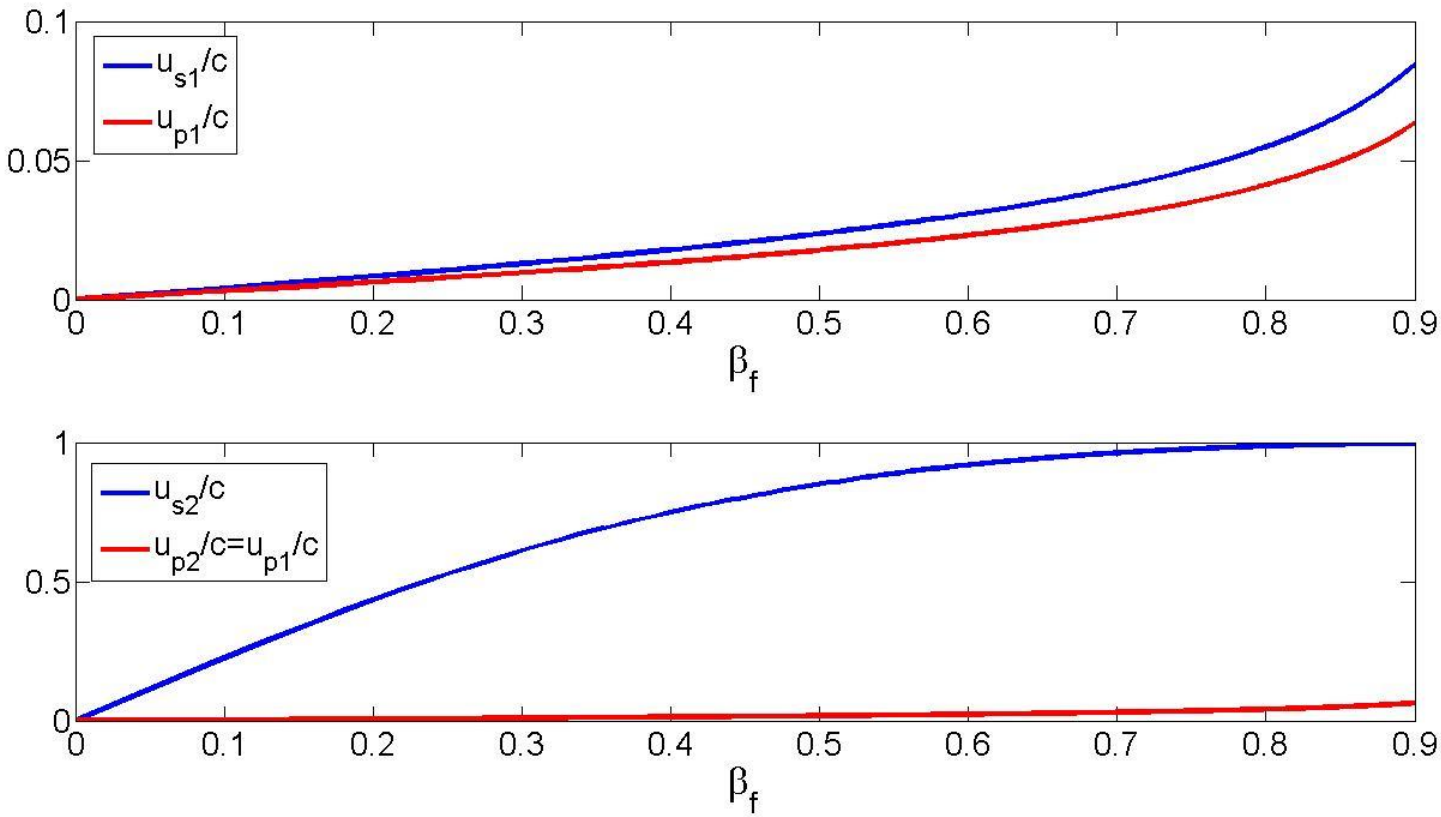
The compressions of the shocked target κ_1 and the shocked flyer κ_2 for ρ_{0t}/ ρ_{0f} = K = 1000.



The pressures of the dimensionless shocked target Π_1 and the shocked flyer Π_2 for ρ_{0t}/ρ_{0f} = K = 1000.

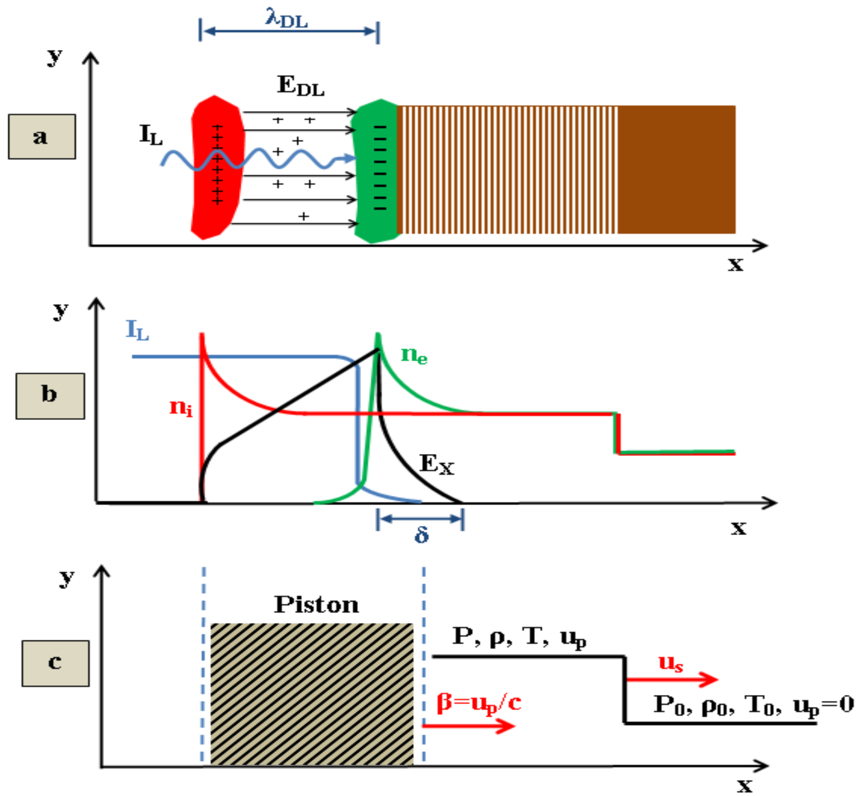


The shock and particle velocities accordingly, u_s and u_p, for ρ_{0t}/ ρ_{0f} = K = 1000.
(subscript 1 for target, subscript 2 for flyer)



5- Shock waves in a laser-target collision

Dominance of radiation pressure: The piston model

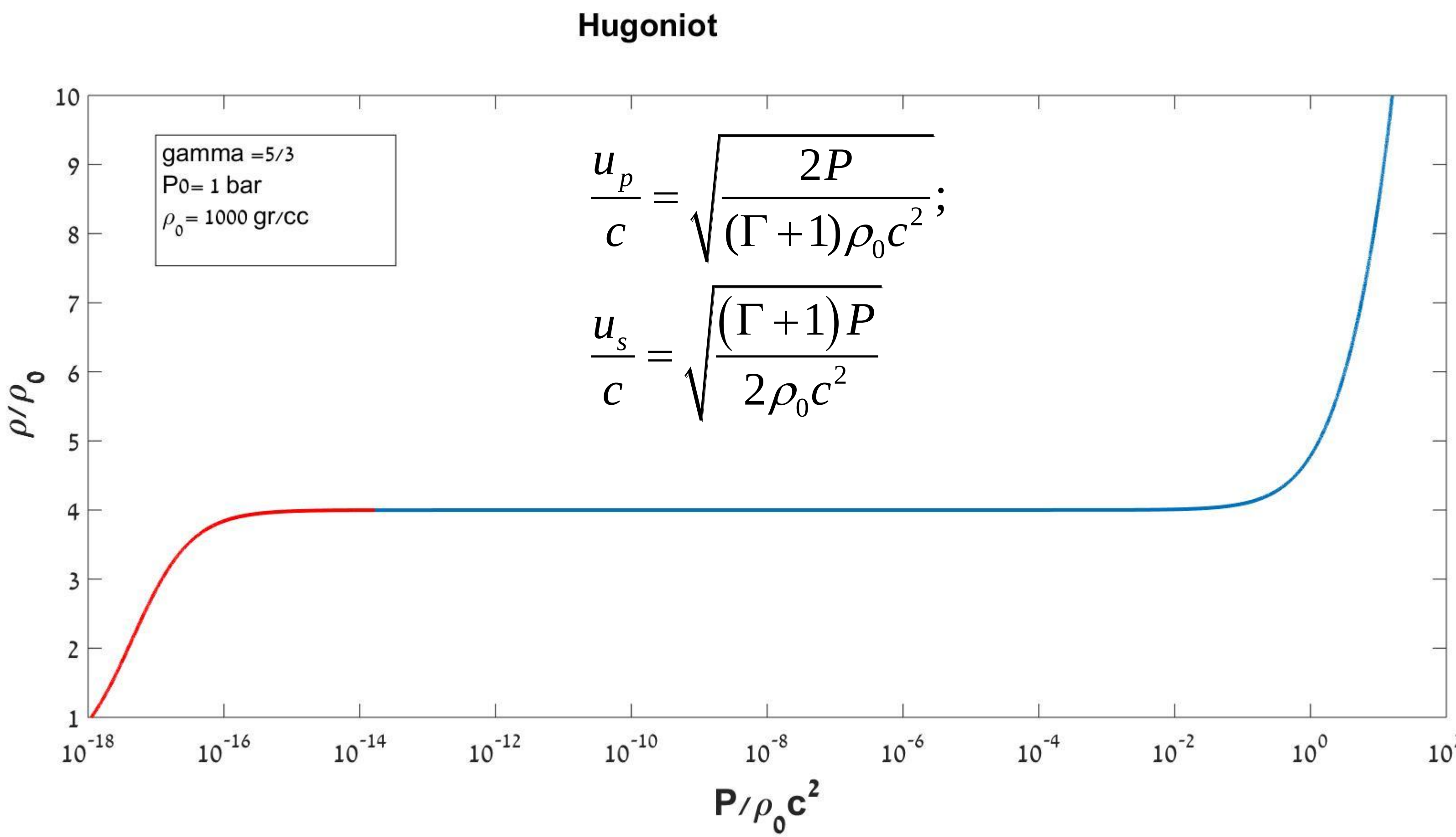


$$P = \frac{2I_L}{c}\left(\frac{1-\beta}{1+\beta}\right)$$

$$\beta \equiv \frac{u_p}{c}$$

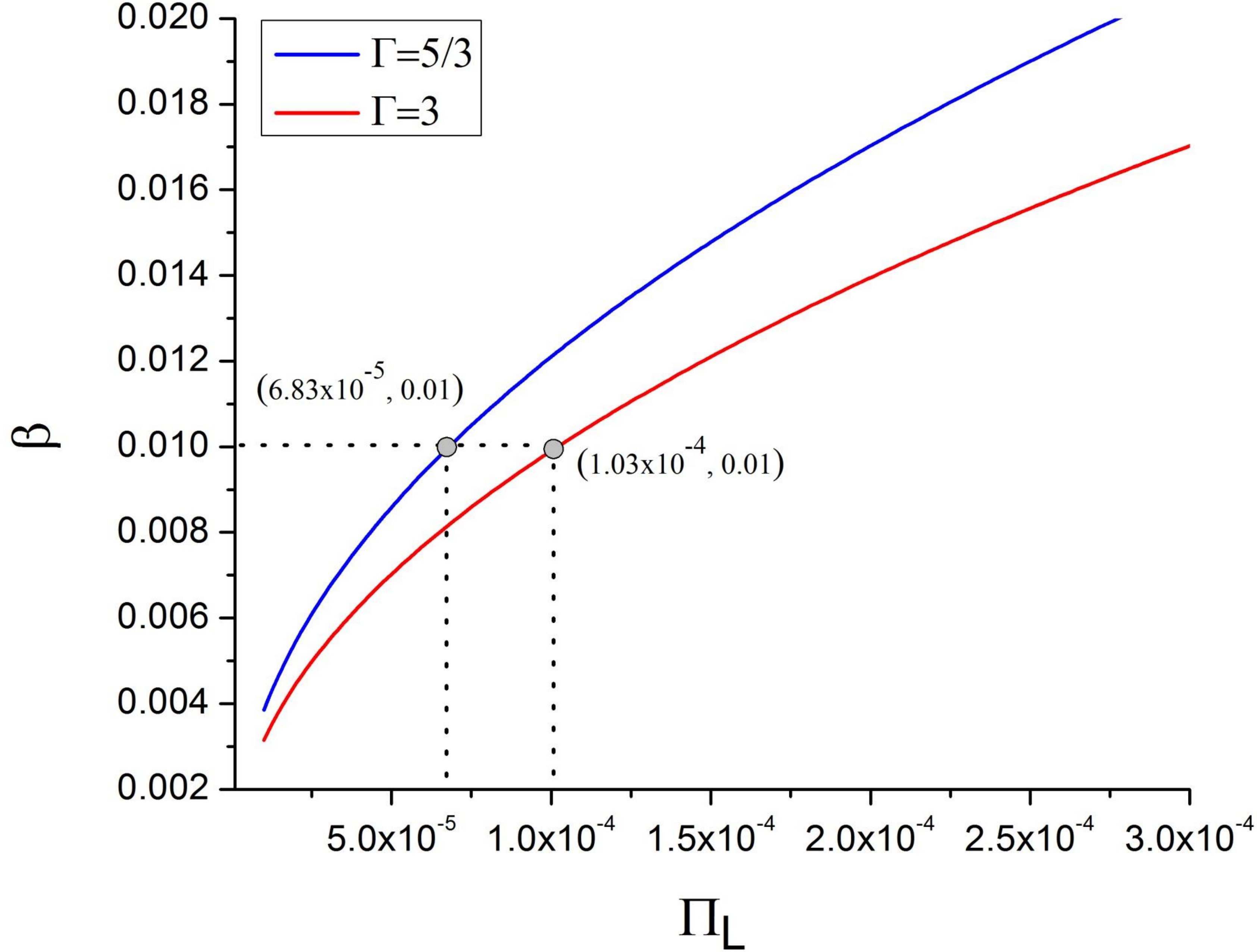
Hora H., Lalousis P. and Eliezer S. (1984), *Phys. Rev Letters* **53**, 1650-1653.
Esirkepov T., et al.. (2004), *Phys Rev Lett.*, **92**, 175003/1-4.
Eliezer S., et al. (2014) *Laser Part. Beams* **32,** 211-216.

Relativistic and non-relativistic shock waves



$$\frac{u_p}{c} = \sqrt{\frac{2P}{(\Gamma+1)\rho_0 c^2}};$$

$$\frac{u_s}{c} = \sqrt{\frac{(\Gamma+1)P}{2\rho_0 c^2}}$$



Γ=5/3
Γ=3
(6.83x10^-5, 0.01)
(1.03x10^-4, 0.01)
β
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
5.0x10^-5
1.0x10^-4
1.5x10^-4
2.0x10^-4
2.5x10^-4
3.0x10^-4
Π_L

The Temperature problem

$$\text{An Example}: \mathrm{I}_L = 2.5\times 10^{22}\,\mathrm{W/cm^2};\ \rho_0 = 0.2\ \mathrm{g/cm^3}\ \Rightarrow \begin{cases} \rho = 0.82\ \mathrm{g/cm^3} \\ \mathrm{P} = 2\cdot 10^{13}\,\text{atmospheres} \end{cases}$$

$$P = P_i + P_e + P_r;\ P_i = n_i k_B T_i;\ P_e = n_e k_B T_e;\ P_r = (1/3) a T_r^{\,4};\ a = \left(\frac{1}{15}\right)\left(\frac{k_B^{\,4}}{h^3 c^3}\right) = 7.56\cdot 10^{-15}[erg/(cm^3 K^4)].$$

$$T_i = T_e = T;\qquad \mathrm{T}_r = 0 \Rightarrow \qquad k_B T = m_p c^2 \left(\frac{A}{Z+1}\right)\left(\frac{P}{\rho c^2}\right)$$

$$k_B T = 31.6 MeV$$

$$\mathrm{T_i} = \mathrm{T_e} = \mathrm{T_r} = \mathrm{T} \Rightarrow$$

$$P = (Z+1) n_i k_B T + \left(\frac{1}{3}\right) a T^4;$$

$$\Rightarrow k_B \mathrm{T} \sim 26.2\,\mathrm{keV}.$$

$$\left(\frac{m_p}{k_B}\right)\left(\frac{A}{Z+1}\right)\left(\frac{P}{\rho}\right) > T > \left(\frac{3P}{a}\right)^{1/4}$$

If k_BT >1 MeV is possible then

1) For $k_BT>1MeV$ we have e^+e^- production

$\Longrightarrow$ New Physics $\Longrightarrow$ New calculations required

2) For $k_BT>150$ MeV we have quark-gluon plasma

$\Longrightarrow$ New Physics $\Longrightarrow$ New calculations required

6- Nuclear fusion detonation wave.

Theory

- we are using a 1D plane detonation wave following Chapman-Jouguet (CJ) – Zeldovich-Landau conditions.
- chemical based detonation: the energetic material entering the shock front is compressed and thus its temperature rises.
- the material transforms exothermally into gasses releasing energy per unit mass (Q) that supports the shock.
- Our detonation is analogous to above description by changing the chemical energy Q to nuclear fusion energy.

For DT fusion (17.6MeV fusion energy per reaction) the 3.52MeV of the α supports the desired steady state detonation wave.

D [cm/s] = The detonation wave velocity

u [cm/s] = fluid velocity; c_s[cm/s] = speed of sound

P$\left[\mathrm{erg/cm^3}\right]$ = pressure,

$\rho\left[\mathrm{g/cm^3}\right]$ = density,

Q$\left[\mathrm{erg/g}\right]$ = nuclear fusion energy that supports the shock

$$\left(\frac{\rho}{\rho_0}\right)_{CJ} = \frac{\Gamma+1}{\Gamma}; P_{CJ} = \frac{\rho_0 D^2}{\Gamma+1}$$

$$\frac{u}{D} = \frac{1}{\Gamma+1}; \frac{c_s}{D} = \frac{\Gamma}{\Gamma+1}$$

$$\frac{Q}{D^2} = \frac{1}{2(\Gamma^2-1)}$$

In our model

$$Q\left[\frac{J}{kg}\right]=\left(\frac{E_\alpha}{\rho}\right)\int_0^{t=\tau_L} dt\left(\frac{dn_\alpha}{dt}\right)\frac{1}{2}\left(1+f_\alpha\right)$$

f_α is given in

S. Yu. Guskov and V. Rozanov

Nuclear fusion by Inertial Confinement

pp293-320, CRC press

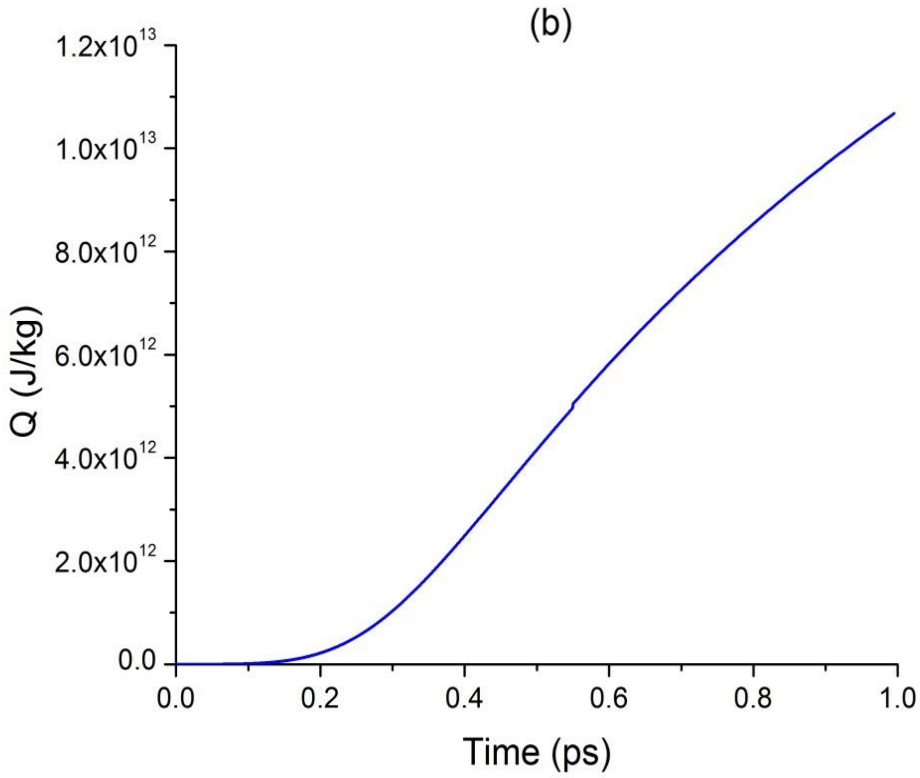
Eds. G. Velarde, Y. Ronen and J. M. Martinez Val

$$f_\alpha=\begin{cases}\frac{3}{2}x_\alpha-\frac{4}{5}x_\alpha{}^2 & x_\alpha<\frac{1}{2}\\ 1-\frac{1}{4x_\alpha}+\frac{1}{160x_\alpha{}^3} & x_\alpha\geq\frac{1}{2}\end{cases}$$

$$x_\alpha(\tau)=\frac{R}{R_\alpha};\mathrm{R}\ =\ \left(u_s\text{ - }u_p\right)\tau_{\mathrm{L}}$$

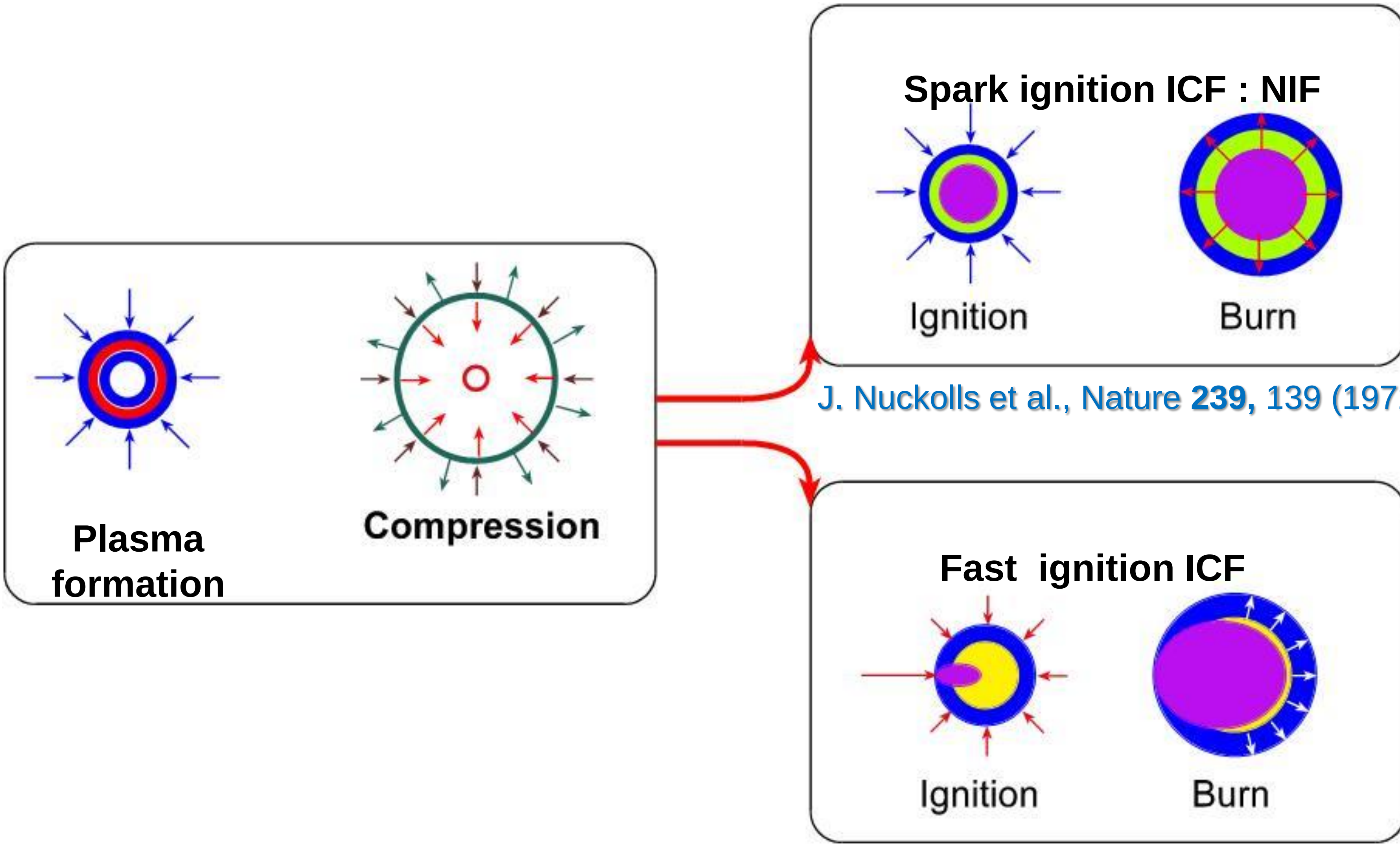
$$R_\alpha[cm]=\frac{1}{\kappa\rho_0}\left[\frac{1.5\times10^{-2}T_e\left(keV\right)^{5/4}}{1+8.2\times10^{-3}T_e\left(keV\right)^{5/4}}\right]$$

The fusion energy Q per unit mass released in the forward shock wave direction as a function of time for a detonation with $\Gamma = 3$.
(the laser: $I_L = 1.75\times10^{23}$ W/cm^2/$\tau_L = 1$; the target: pre-compressed to 900 g/cm^3.)



7. A Novel fast ignition scheme

Inertial Confinement Fusion (ICF)



J. Nuckolls et al., Nature **239,** 139 (1972)

N. Basov et al., J. Soviet Laser Res., **13,** 396 (1992)
M. Tabak et al., Phys. Plasmas **1,** 1626 (1994)

Fast ignition needs less laser energy (~300 kJ) than central spark scheme (~3MJ).

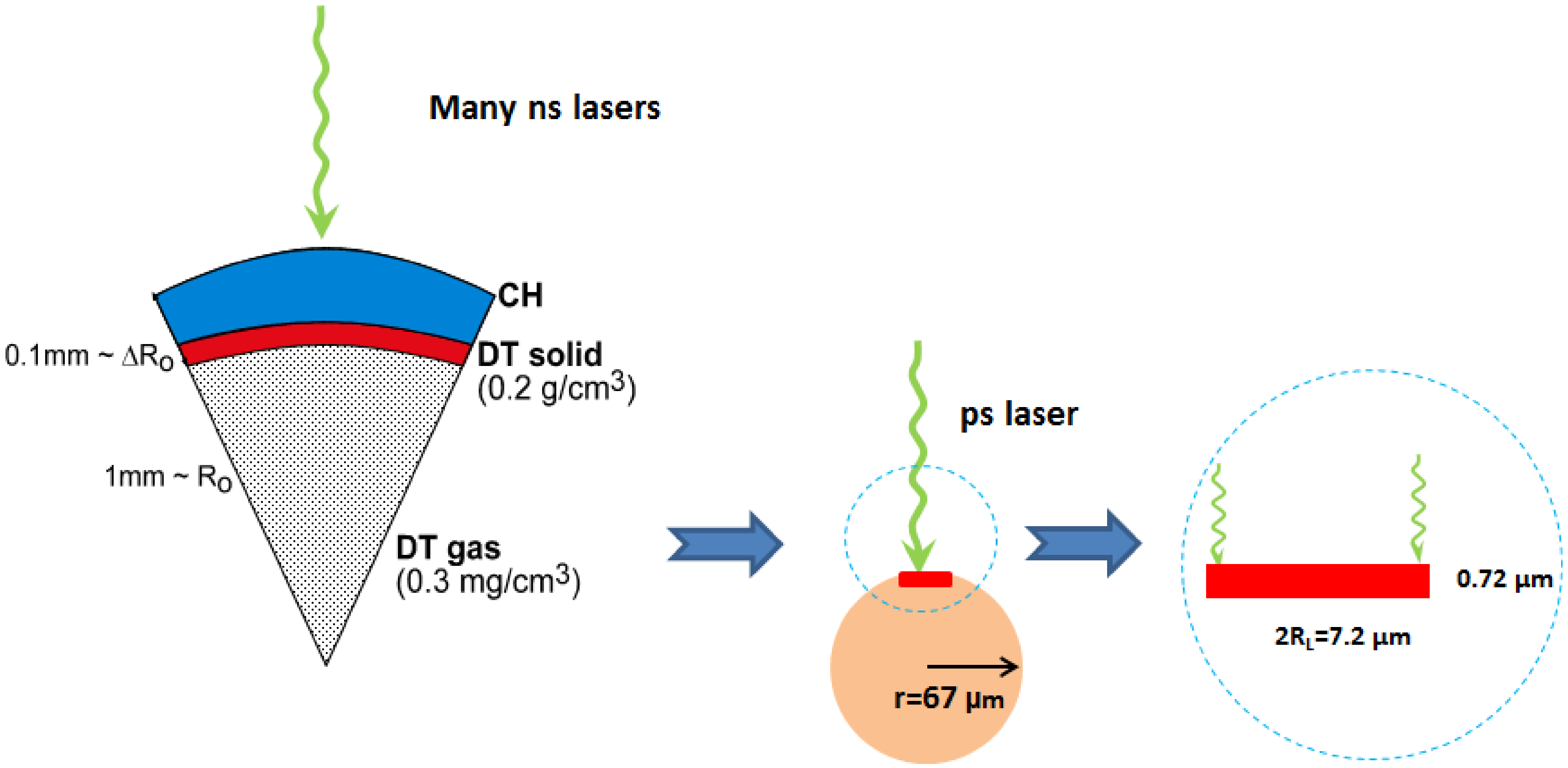
Therefore

Fast ignition has the potential to be the best route to achieve nuclear fusion as an energy source

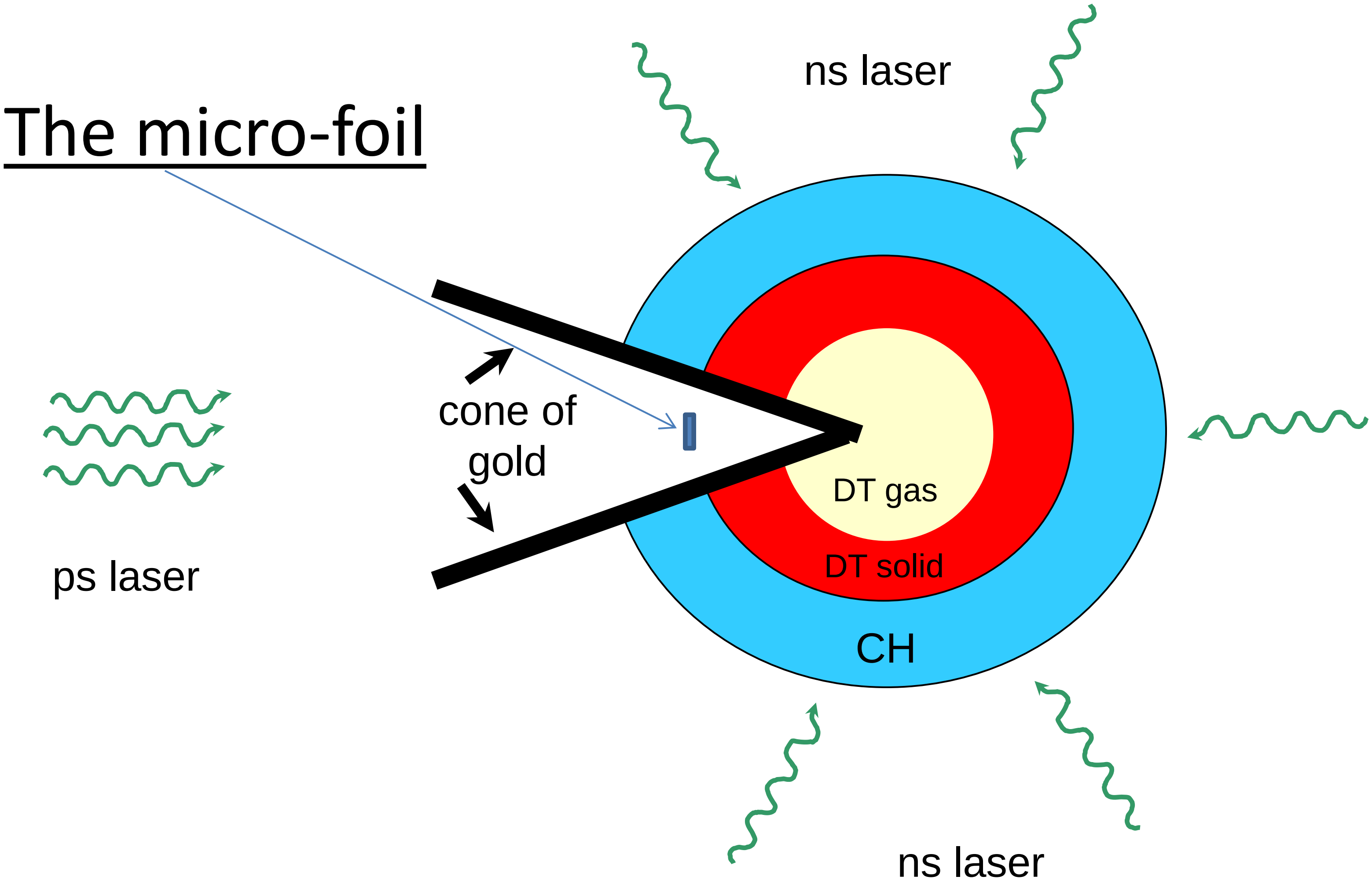
But there are many schemes of fast ignition:

A comprehensive review: **Sergey Yu. Guskov** (2013) *Plasma Physics Reports* **39,** 1-50.

Ignition by laser shock wave



Ignition by laser accelerated foil impact



DT ignition

$$\Pi_L = 6.65\times10^{-5};\quad \tau_L = 1ps;\quad \rho_0 = 250\left[\frac{g}{cm^3}\right] \Rightarrow$$

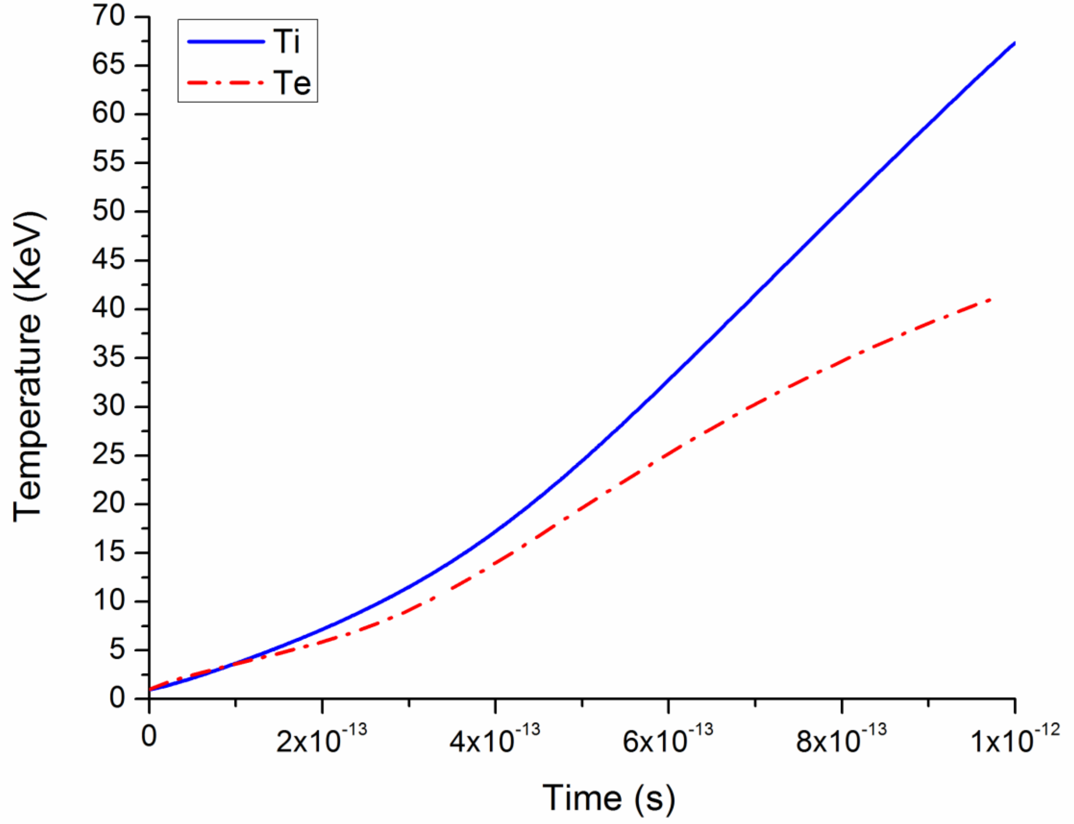
$$\rho = \kappa\rho_0 = 10^3\left[\frac{g}{cm^3}\right]$$

$$I_L = \rho_0 c^3 \Pi_L = 4.5\times10^{22}\left[\frac{W}{cm^2}\right]$$

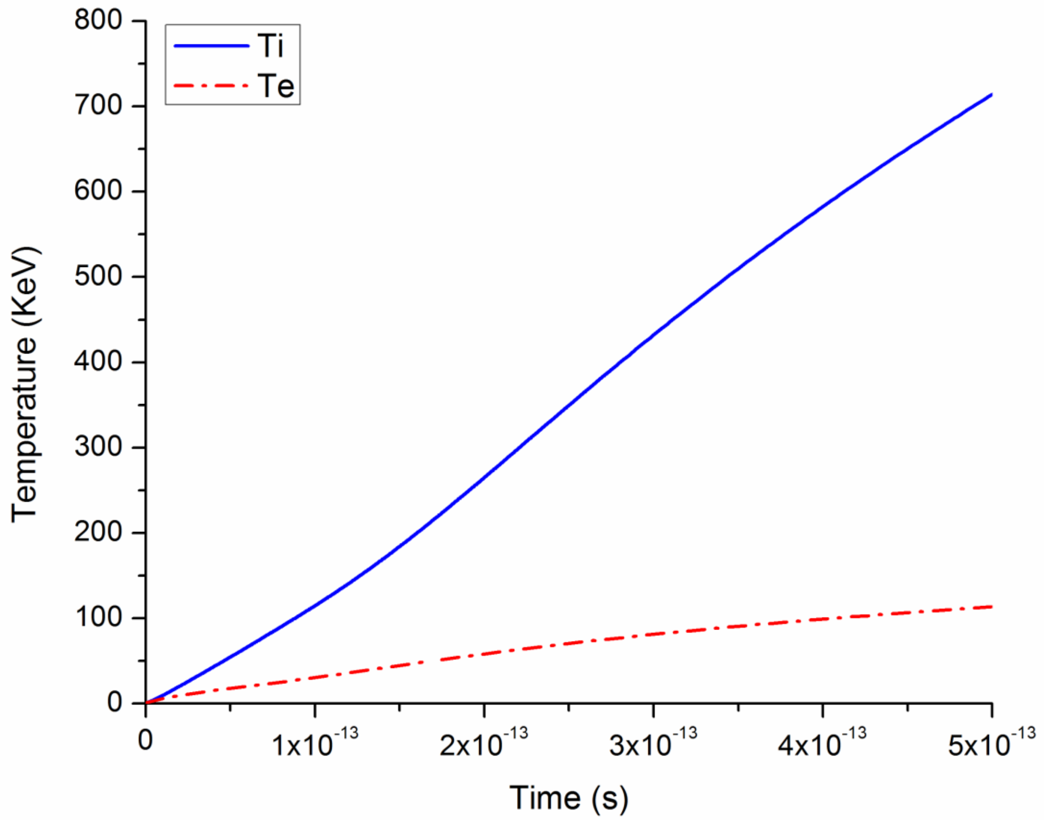
$$\ell_s = \left(u_s - u_p\right)\tau_L \simeq 1\mu m; S = \pi R_L{}^2 = \pi\left(1.5\ell_s\right)^2 = 7.04\times10^{-8}\left[cm^2\right]$$

$$W_L\left[J\right] = I_L S \tau_L = 3.2\ kJ$$

T_e and T_i as a function of time for DT satisfying the ignition criterion



T_e and T_i as a function of time for pB^{11} satisfying the ignition criterion



8- The 2-temperatures ignition criteria for DT and pB^{11}

$$A_1 + A_2 \to A_3 + A_4 + E_f$$

$$E_f = E_\alpha + E_{others}$$

$$W_f \left[\frac{erg}{cm^3 \cdot s} \right] = n_1 n_2 < \sigma v >_{12} E_\alpha$$

$$W_f - \sum W\left(losses\right) \geq 0$$

$$f_\alpha W_f - W_B - W_{he} - W_m \geq 0$$

Two temperature equations

$$\left(\frac{3}{2}\right)\frac{d}{dt}\left(n_e k_B T_e\right) = \eta_d W_d + W_{ie} - W_B + f_\alpha \eta_f W_f$$

$$\left(\frac{3}{2}\right)\frac{d}{dt}\left(n_i k_B T_i\right) = \left(1-\eta_d\right) W_d - W_{ie} + f_\alpha \left(1-\eta_f\right) W_f$$

For DT fusion: $\dfrac{dn_D}{dt} = \dfrac{dn_T}{dt} = -\dfrac{dn_\alpha}{dt} = -n_D n_T < \sigma \mathrm{v} >_{DT}$

For pB^{11} fusion: $\dfrac{dn_p}{dt} = \dfrac{dn_B}{dt} = -\left(\dfrac{1}{3}\right)\dfrac{dn_\alpha}{dt} = -n_p n_B < \sigma \mathrm{v} >_{pB}$

$$D + T \rightarrow n + \alpha + 17{,}589\ keV$$

$$n_e\left[cm^{-3}\right] = n_i\left[cm^{-3}\right] = \left(\frac{\rho}{2.5m_p}\right) = 2.39\times10^{23}\rho$$

$$W_{f,DT}\left[\frac{erg}{cm^3\cdot s}\right] = 8.07\times10^{40} < \sigma \mathrm{v} >_{DT}\ \rho^2$$

$$W_B\left[\frac{erg}{cm^3\cdot s}\right] = 8.58\times10^{21}\rho^2 T_e\left(eV\right)^{0.5}\left(1+\frac{2T_e(eV)}{0.511\times10^6}\right)$$

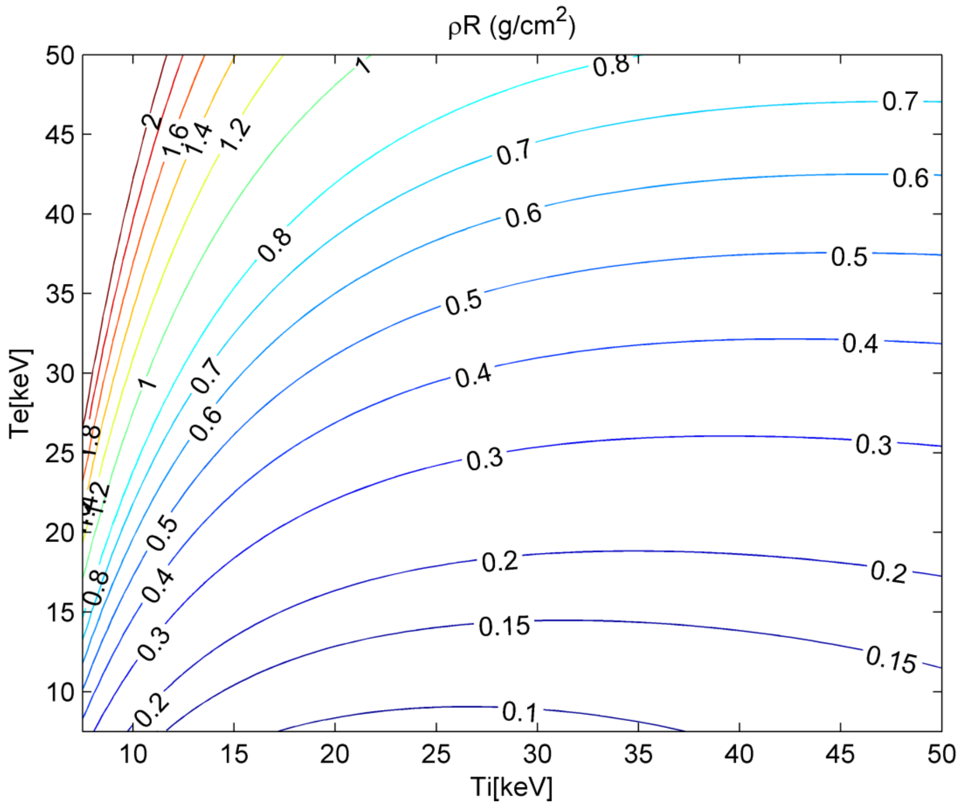
$$W_m\left[\frac{erg}{cm^3\cdot s}\right] = 1.02\times10^{18}\left[T_e\left(eV\right)+T_i\left(eV\right)\right]^{1.5}\left(\frac{\rho}{R}\right)$$

$$W_{he}\left[\frac{erg}{cm^3\cdot s}\right] = \frac{3.11\times10^9 T_e(eV)^{7/2}}{R^2\ln\Lambda}$$

$$\text{Ignition requirement} :\Rightarrow a(T_e,T_i)\left(\rho\cdot R\right)^2 + b(T_e,T_i)\left(\rho\cdot R\right) + c(T_e)\geq 0$$

Equal ρR as a function of ions and electrons temperatures for DT ignition

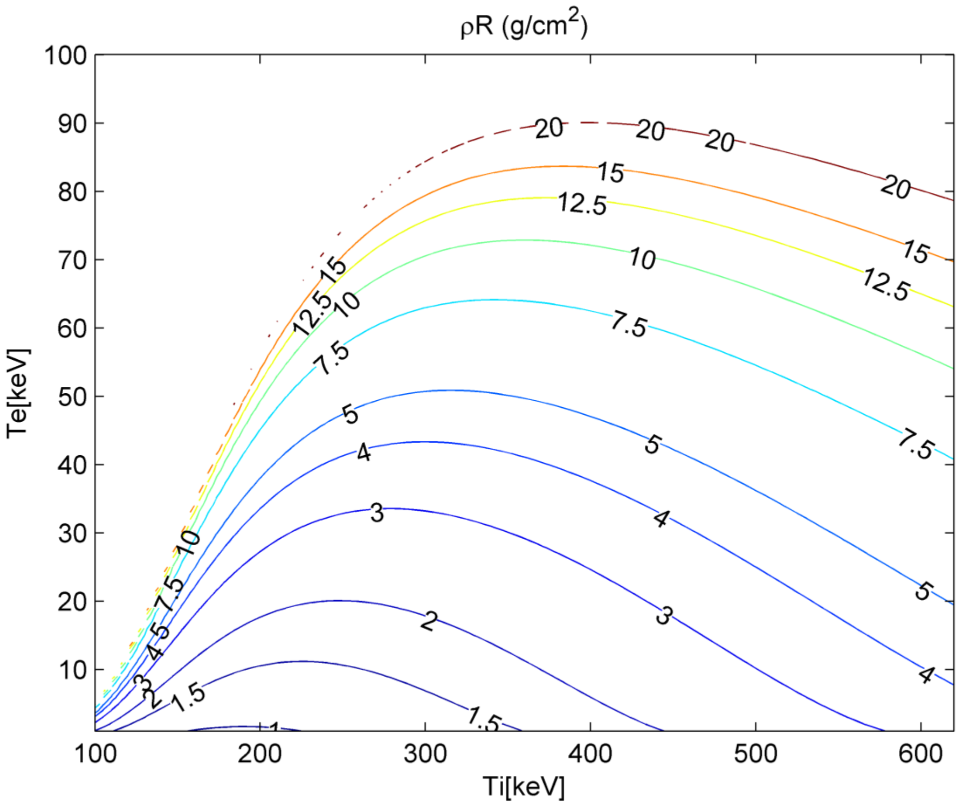
S. Eliezer et al., *Laser and Particle Beams* **33**, 577-589 (2015).



Equal $\rho \cdot R$ as a function of ions and electrons temperatures for pB^{11} ignition for $\varepsilon = n_B/n_p = 1/3$

$$p + {}^{11}B \rightarrow 3\alpha + 8{,}700 \; keV$$

S. Eliezer et al., *Laser and Particle Beams* **33**, 577-589 (2015).



9- Summary and Conclusions

NOVEL PROPOSALS:

The Recent and future developments of high power lasers in the multi Petawatt domain

1-Relativistic Shock Waves in the laboratory (P ~ 10^{15} atmospheres)

2-New scheme for Fast ignition by a shock wave

3- Micro-accelerators to relativistic velocities (colliding foils)

4-Quark-gluon plasma?

Solving the Energy Problem

Mark Twain (1835-1910)

"And what is a man without energy? Nothing-nothing at all"

ICF solution:

1. **Understanding the Physics**

2 **Energy conservation**

3 Economically practical

Gain=Output energy/laser input energy>100

Cost per target ~0.10 US $

4. Simplicity

~10^8 laser shots per year

What I learned from Noah's Ark?

The Bible: book of GENESIS

ECLIM 2006 (Madrid)

- One: Don't miss the boat
- Two: Remember that we are all in the same boat
- Three: Plan ahead. It wasn't raining when Noah built the Ark
- Four: Stay fit. When you're 600 years old, someone may ask you to do something really big
- Five: Don't listen to critics; just get on with the job that needs to be done
- **Remember, the Ark was built by amateurs; the Titanic by professionals**

THANK YOU