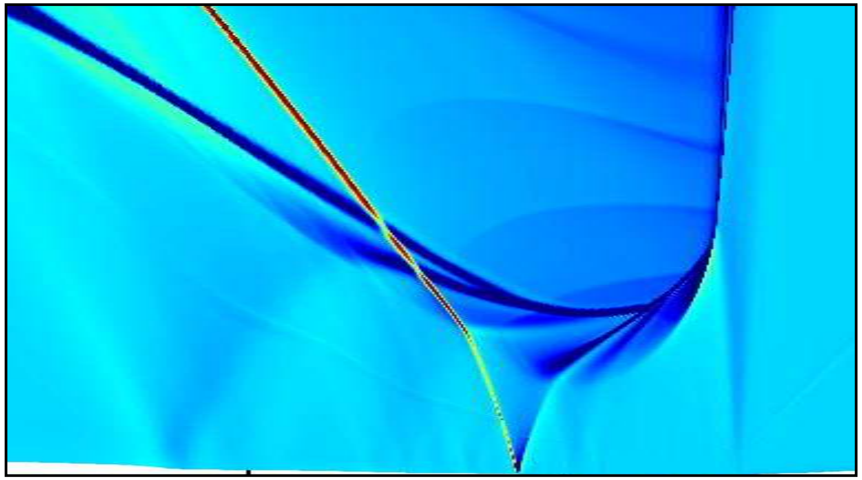
Overview on shock ignition



Ribeyre X.

CELIA, Université Bordeaux 1-CNRS-CEA
33405 Talence, France

10 th DDFIW prague May 27-30

Results from :

- Baton D.
- Batani D.
- Betti R.
- Bell T.
- Canaud B.
- Lafon M.
- Le Bel E.
- Honenberger M.
- Klimo, O.
- Nora R.
- Theobald W.
- Schurtz G.
- Vallet A.
- Tikhonchuk V. T.

Outline

- Shock ignition physics
- Target design optimisation
- 1D gain curve
- 2D simulation results
- Experimental results

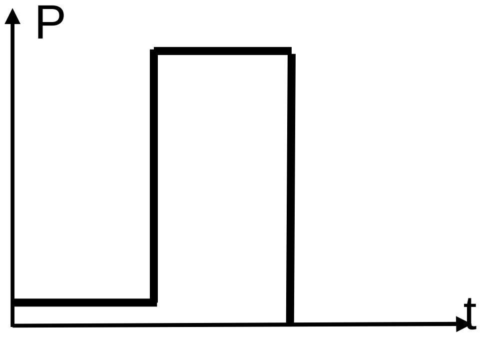
Differentes ways to achieve ignition

High implosion velocity

V_{imp}~450 km/s

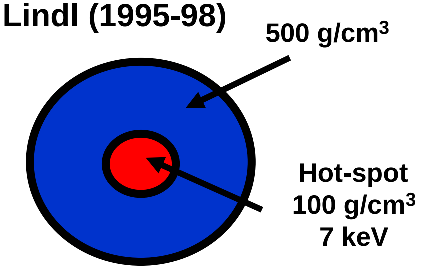
Central hotspot ignition

1–1.8 MJ, ns, 3ω
550 TW



G=10 (Indirect)
G=30 (Direct)

Nuckolls (1972)
Lindl (1995-98)

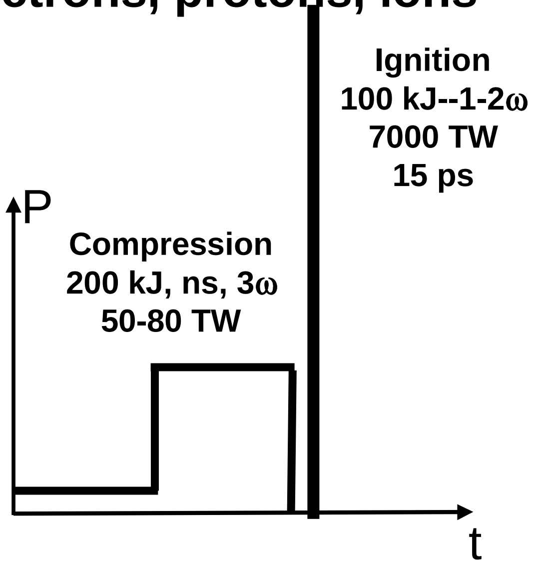

500 g/cm^3

Hot-spot
100 g/cm^3
7 keV

Low implosion velocity

V_{imp}~150-250 km/s

Fast ignition: Electrons, protons, ions

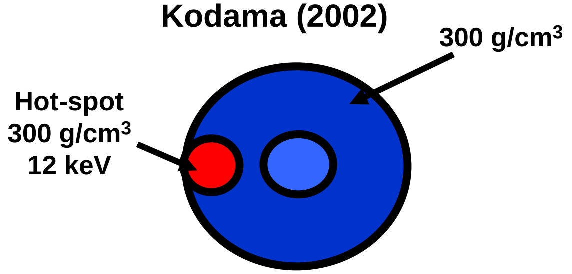


Ignition
100 kJ--1-2ω
7000 TW
15 ps

Compression
200 kJ, ns, 3ω
50-80 TW

G=100

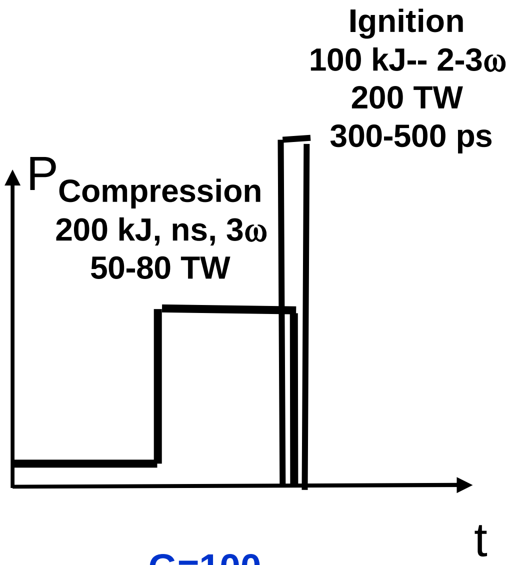
Tabak (1994)
Kodama (2002)


300 g/cm^3

Hot-spot
300 g/cm^3
12 keV

V_{imp}~200-250 km/s

Shock ignition

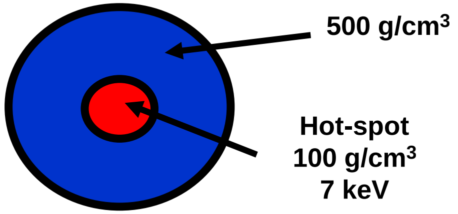


Ignition
100 kJ-- 2-3ω
200 TW
300-500 ps

Compression
200 kJ, ns, 3ω
50-80 TW

G=100

Scherbakov (1983);Betti (2005-07)
Ribeyre (2009)
Schmitt (2010)


500 g/cm^3

Hot-spot
100 g/cm^3
7 keV

Atzeni S.: PPCF 51, 124029 (2009)

Shock ignition or how to ignite low implosion velocity target to achieve high gain

- Low implosion velocity (thicker shell) imply large fuel mass then higher gain for same laser energy

- Thicker shells have good hydrodynamic stability

- Low implosion velocity leads to low hot spot pressure ($P \sim V_i^3$)

- Low pressure the hot spot do not ignite
(Pτ ~10 Gbar ns : Lawson criteria equivalent to $\rho_h R_h T_h \sim 4$ g keV/cm^2)

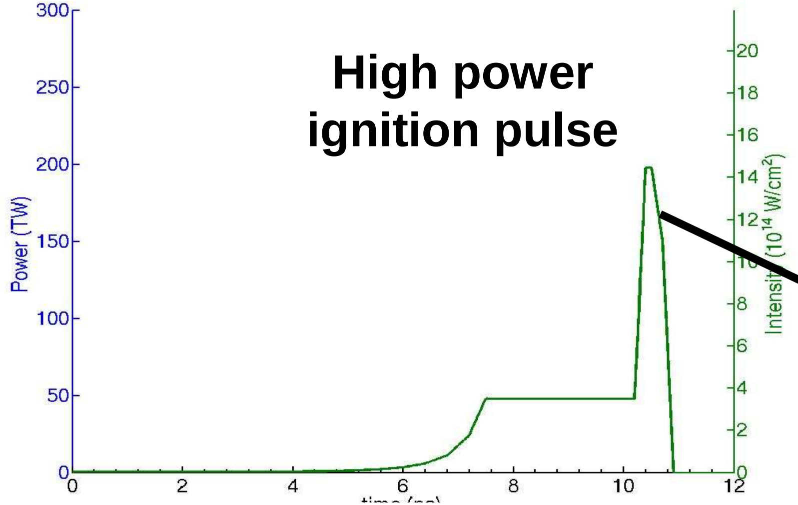
- The energy required for hot spot ignition is $E \sim 1/V_i^6 \sim 1/P^2$

How to ignite low implosion velocity target ?

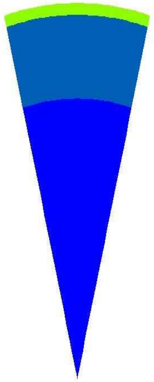
Shock ignition principle

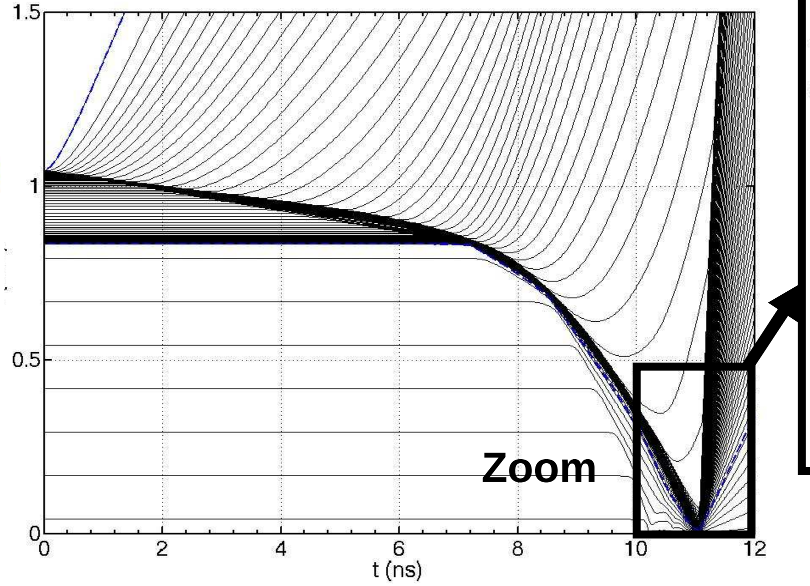
Scheme proposed by V. A. Shcherbakov**
and recently by R. Betti et al.*

High power ignition pulse



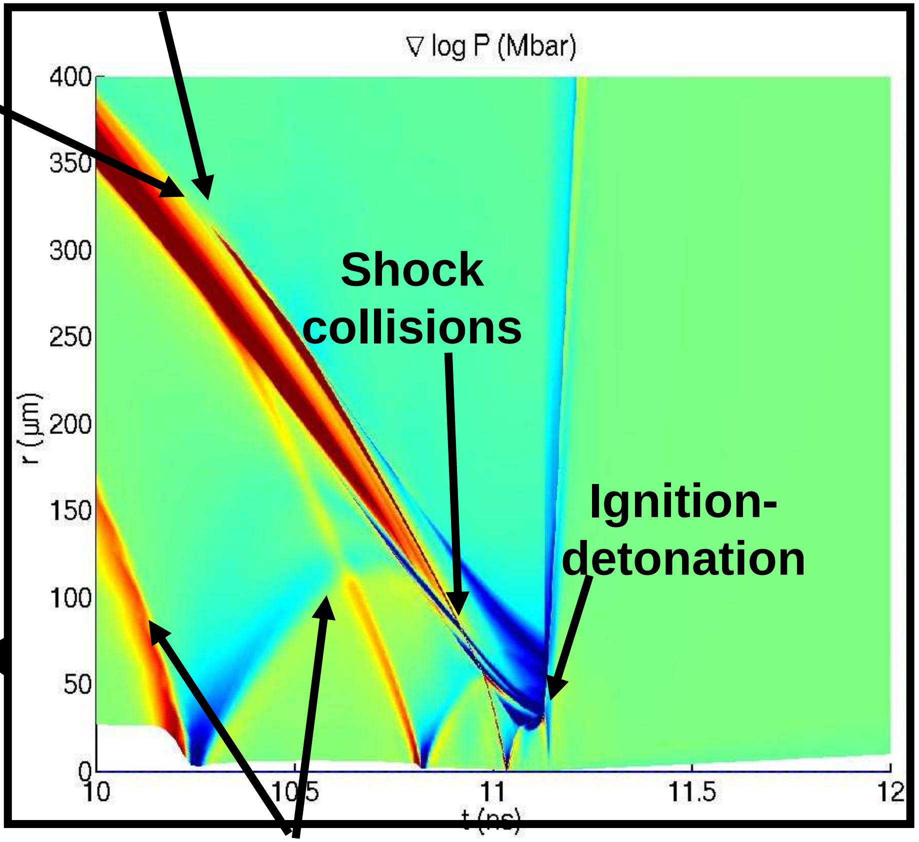
Laser





Zoom

Shock spike convergence



Shock collisions

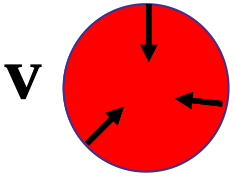
Ignition-detonation

Divergent return shock during the shell stagnation phase

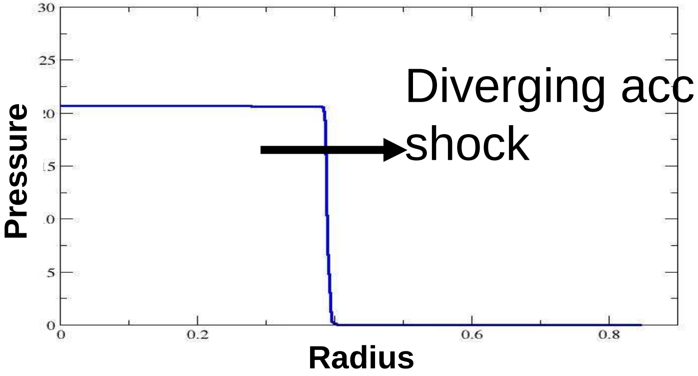
****Shcherbakov V.A., Sov. J. Plasma Phys. 9(2) 240 (1983)**

*** Betti R. et al. : PRL 98 (2007)**

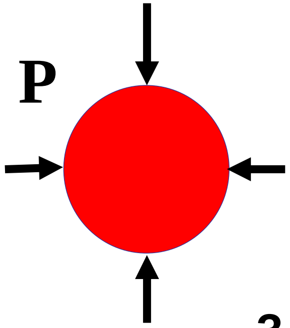
Simple means to increase the pressure at target center



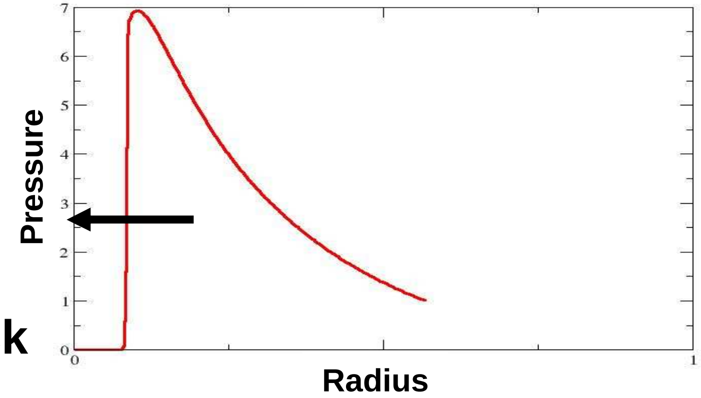
1 – **Implode at uniform velocity**
(Noh's pb (1987) : ro=64, p=64/3)



Diverging accretion shock

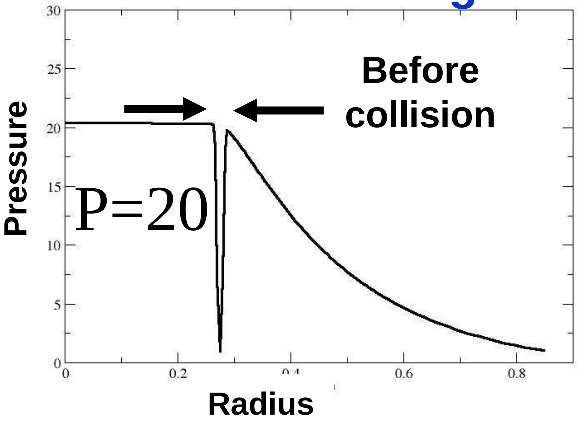


2 – Drive a converging shock :
Guderley's pb (1942)
ro_{max}=30, $P \sim P_0(r_0/r)^{0.9}$



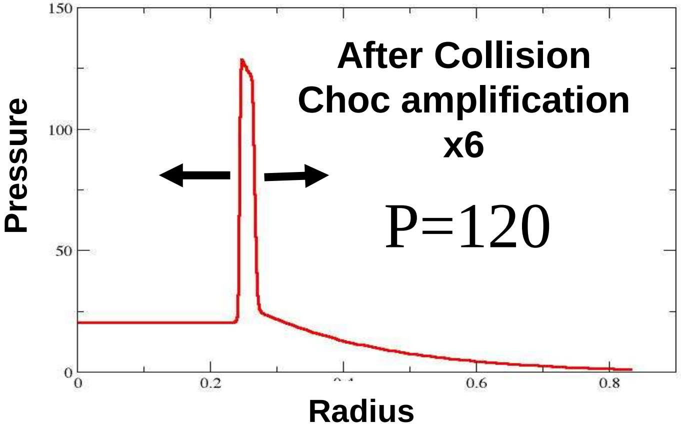
3 – Drive a converging shock and let it collide with the diverging shock

This is shock ignition



Before collision

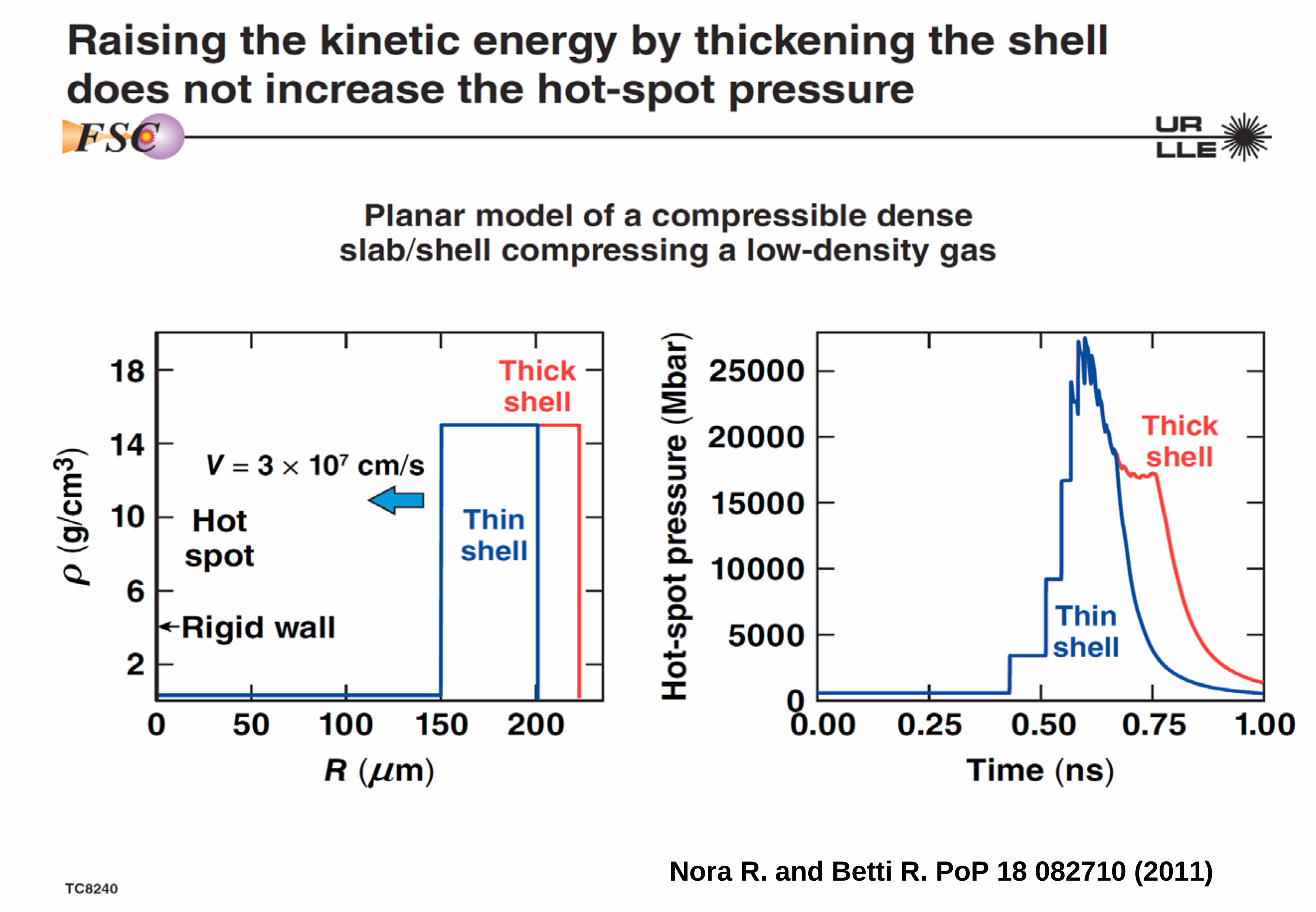
P=20



After Collision
Choc amplification
x6

P=120

Nora & Betti Shock ignition planar model



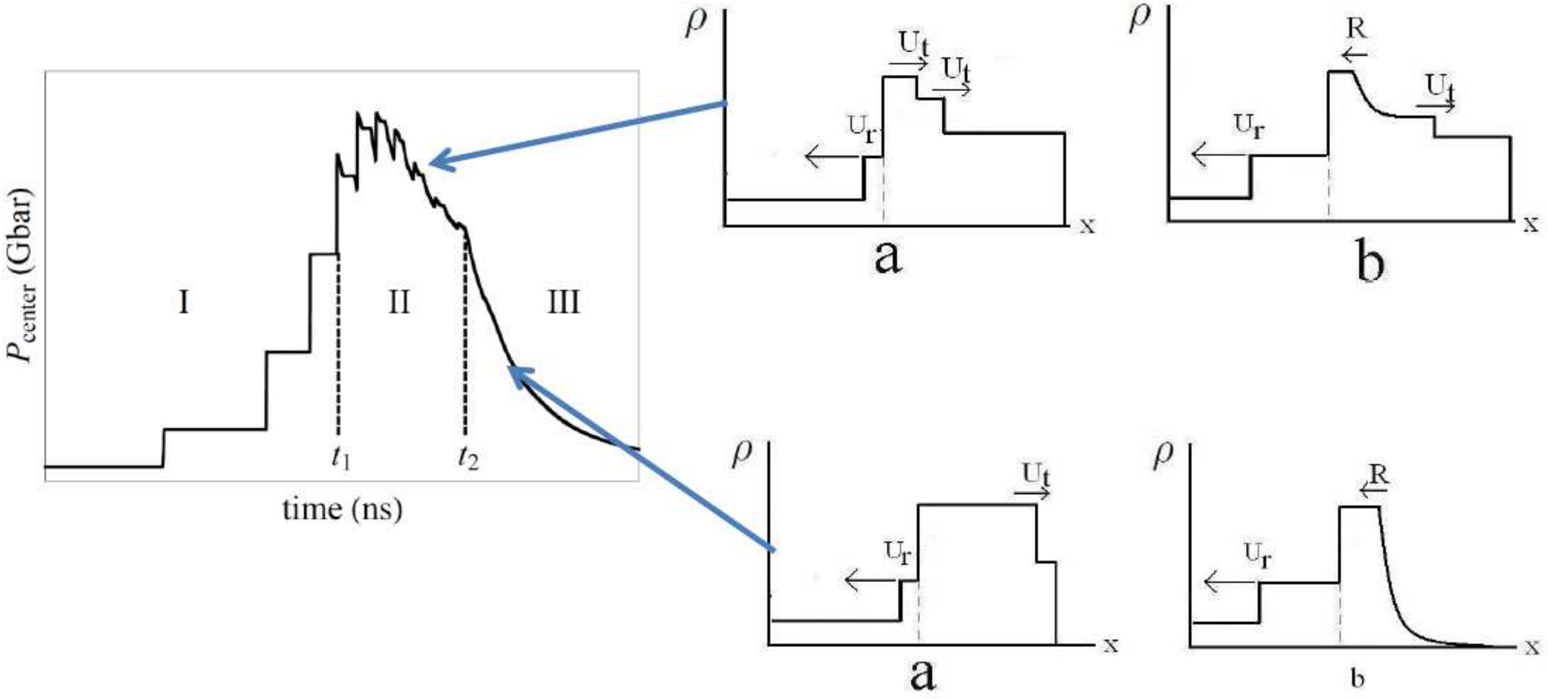
Raising the kinetic energy by thickening the shell does not increase the hot-spot pressure

Planar model of a compressible dense slab/shell compressing a low-density gas

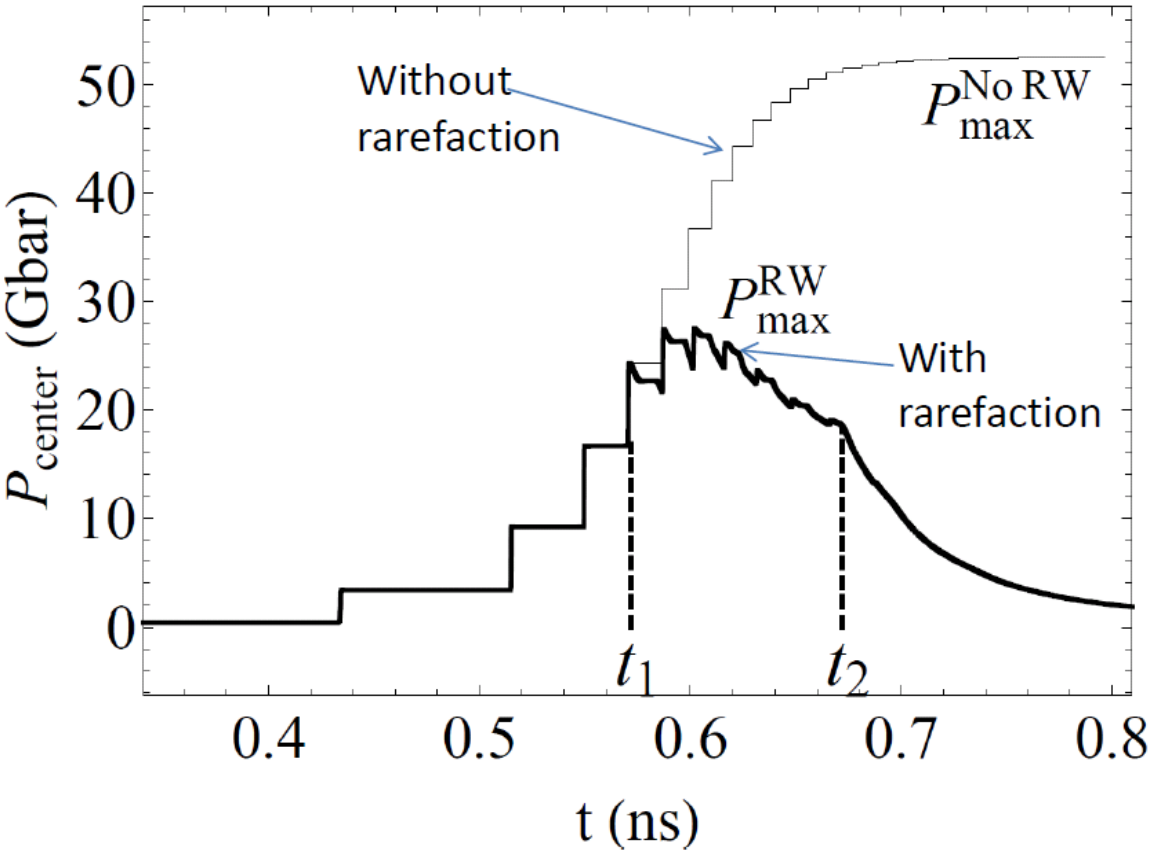
TC8240

Nora R. and Betti R. PoP 18 082710 (2011)

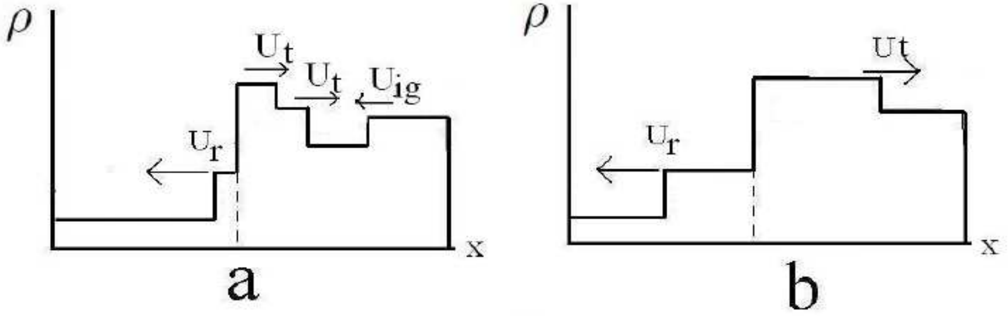
Two different mechanisms related to rarefaction wave propagation limit the hot spot pressure



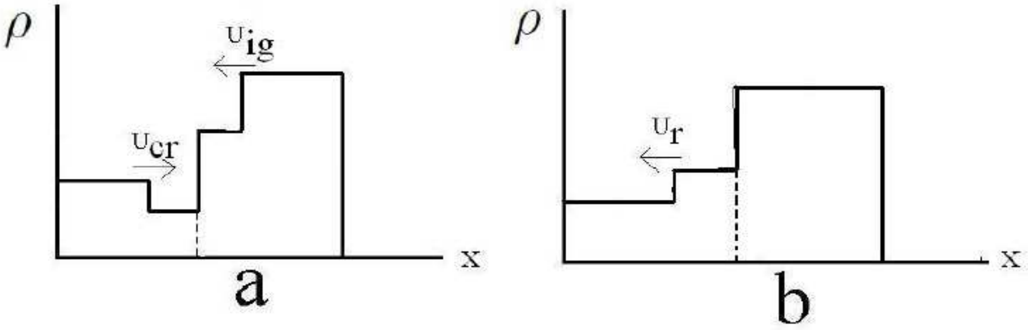
Without rarefaction waves, the peak hot spot pressure would be twice as high



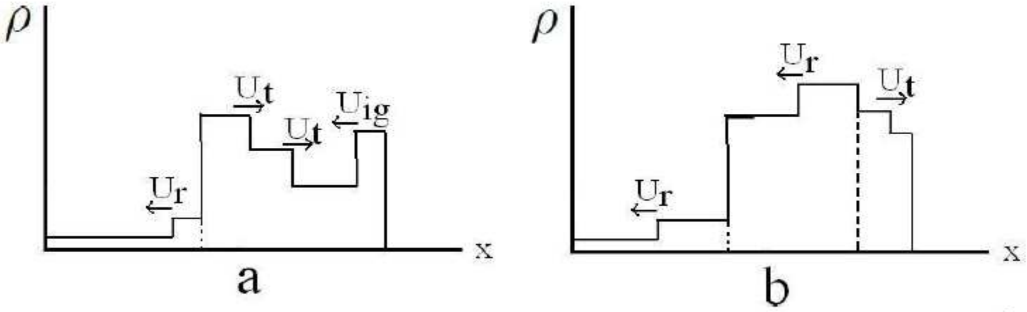
Late shocks can suppress rarefaction waves. There are three ways shocks can be launched.



No-rarefaction technique
(requires many highly-synchronized “weak” shocks)

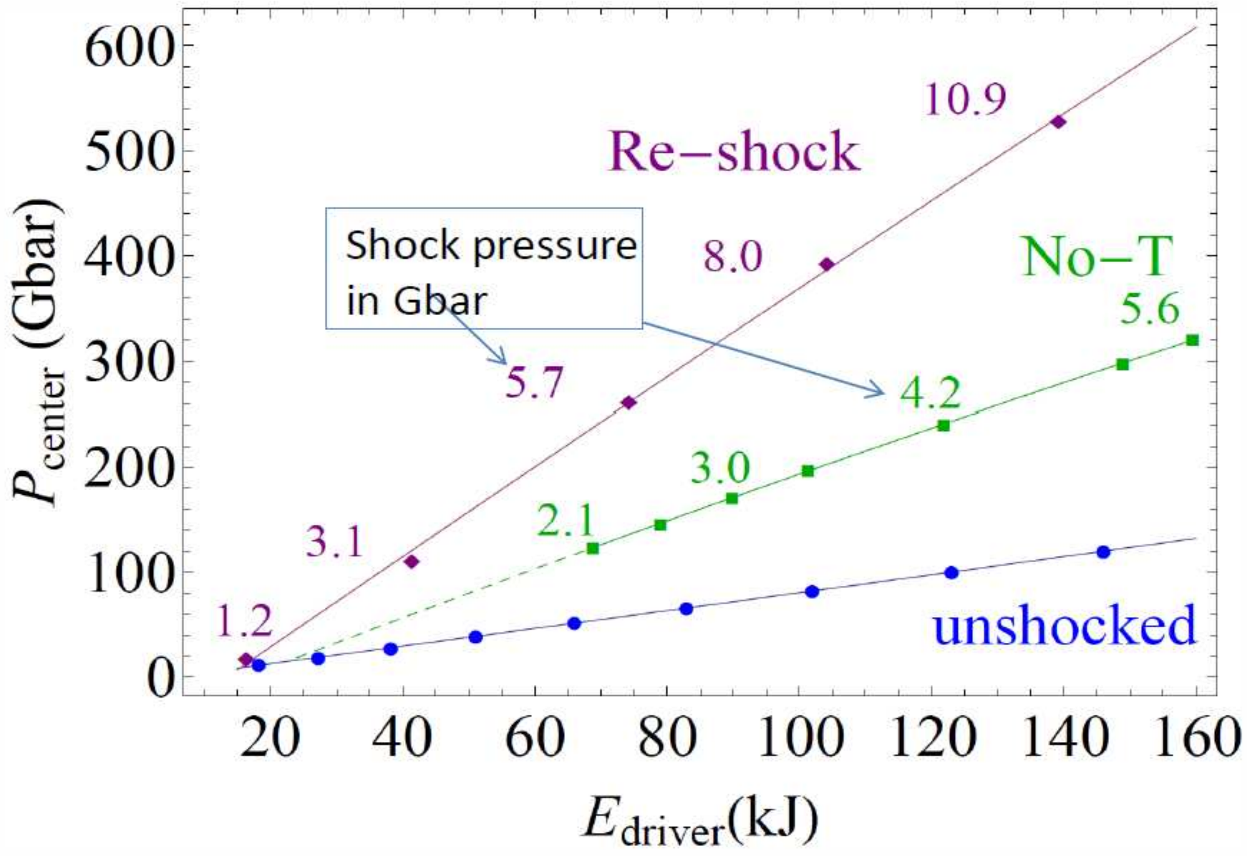


No-transmission technique
(requires one moderate shock)



Re-shock technique
(requires one strong shock)

The re-shock technique produces the highest hot spot pressure



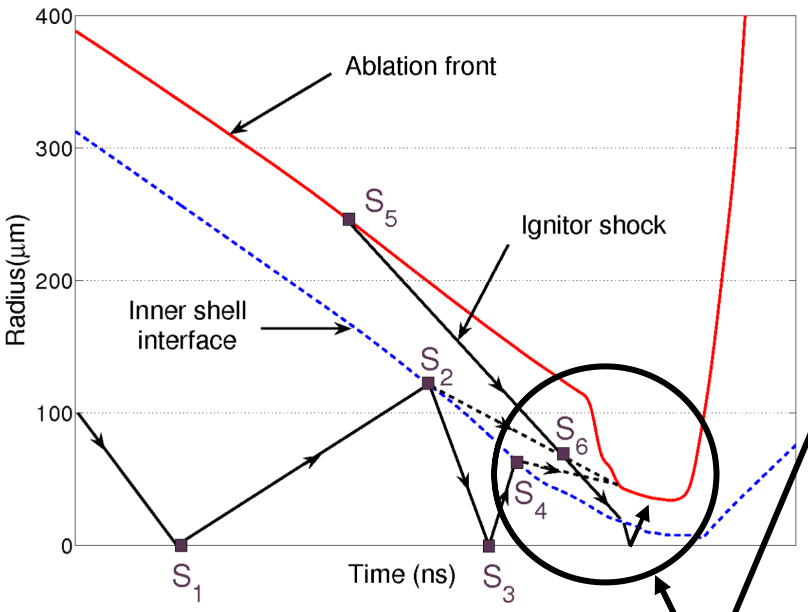
Shock pressure in Gbar

The shock pressure is high because of the planar geometry

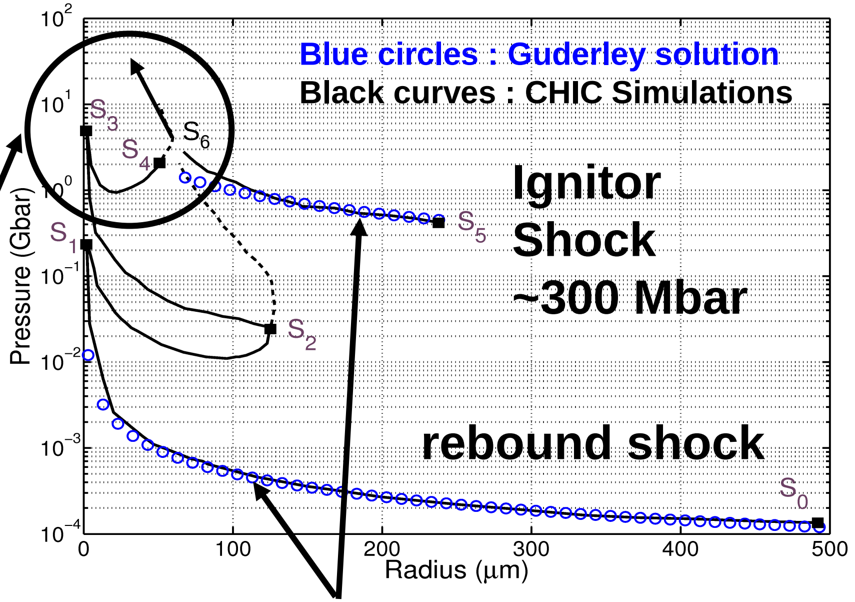
For shock ignition design, the re-shock technique is used

Toward SI spherical model: Converging shock wave pressure follows the Guderley self similar solution *

Shock trajectories shell stagnation



Shock pressure radial evolution



Blue circles : Guderley solution
Black curves : CHIC Simulations

Ignitor Shock ~300 Mbar

rebound shock

In Guderley self-similar solution: the converging shock pressure varies as

$$\boxed{P_{\text{shock}}(r) \propto 1/r^{0.91}}$$

for $\gamma = 5/3$ **

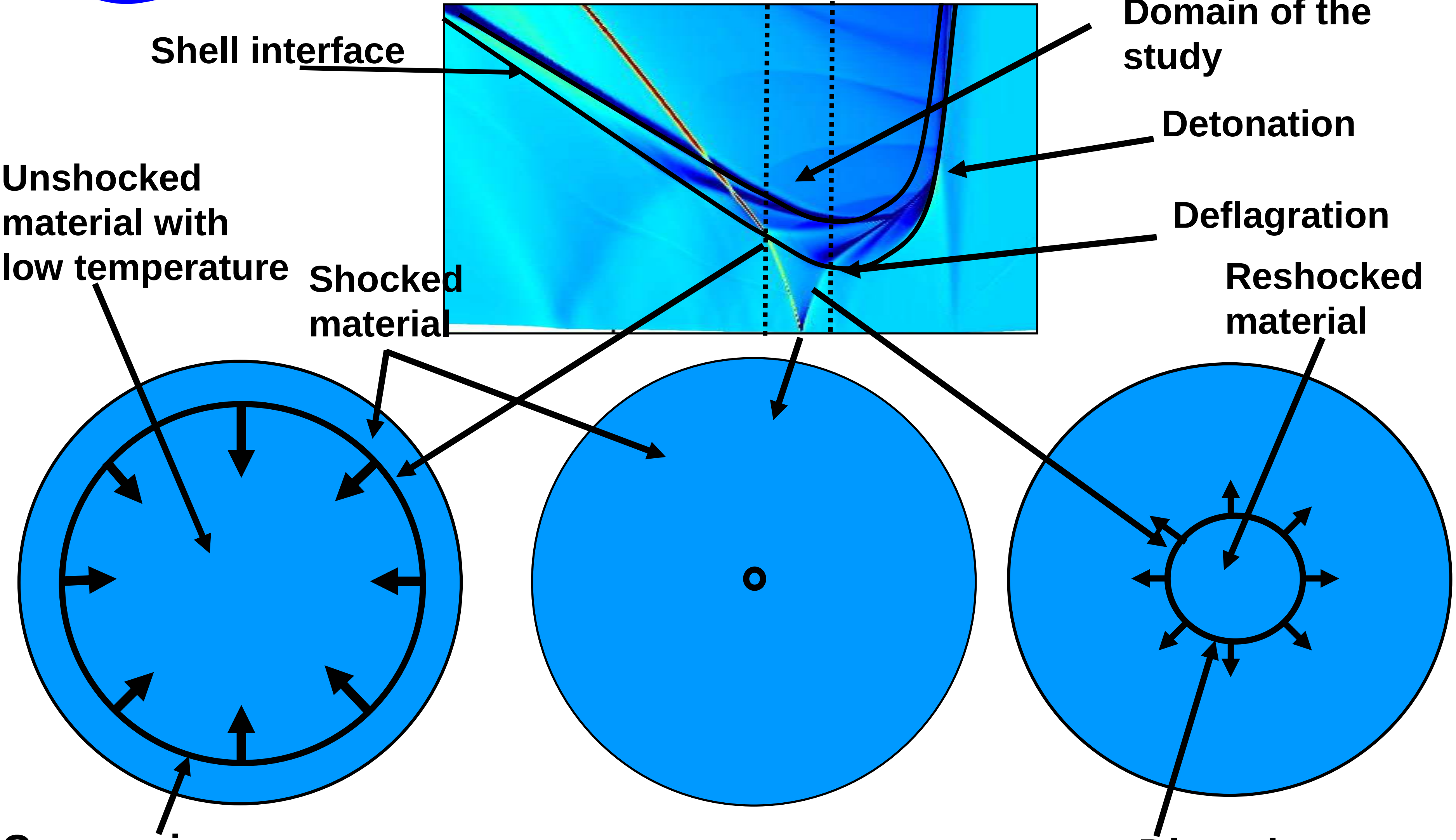
Questions :

- **How the pressure evolves after the ignitor shock converge and diverge ?**
- **What is the conditions to achieve the ignition of central hot spot ?**

***Lafon M. et al. PoP (2010)**

****Von G. Guderley, Luftfahrt-Forsch. 9, 302 (1942)**

Converging-diverging spherical shock wave evolution



Shell interface

Domain of the study

Detonation

Unshocked material with low temperature

Deflagration

Shocked material

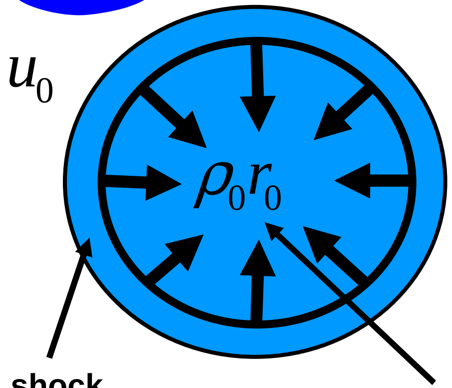
Reshocked material

Converging shock Front

Collapse

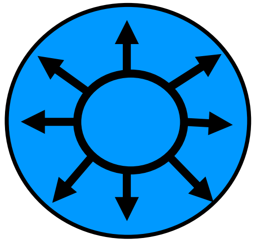
Diverging shock front

Analytical criterion for hot spot shock ignition (1)

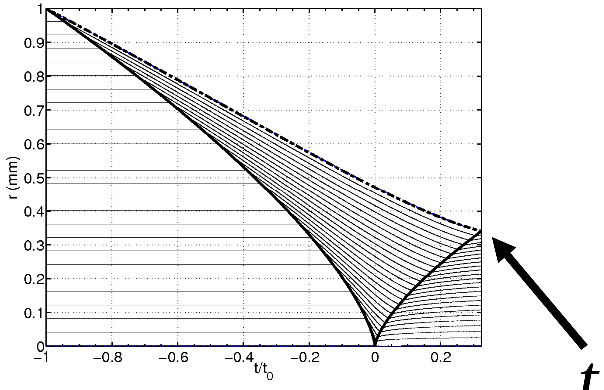


Initial shock velocity

Initial areal density



After collapse



$$t = t_c$$

Collision between
return shock
and boundary condition

Ignition criterion*

$$d_t E_f > d_t E_r + d_t E_e$$

Fusion power

Radiative power

Thermal power

$$t = t_c$$

$$d_t E_f = f_\alpha A_f(t_c)\rho_0^2 u_0^4 r_0^2$$

$$d_t E_r = A_r(t_c)\rho_0^2 u_0 r_0^3$$

$$d_t E_e = A_e(t_c) u_0^7 r_0$$

We assume $\langle \sigma v \rangle \approx \beta T^2 \quad T \in [8, 25]\ \mathrm{keV}$

$f_\alpha : \alpha$ particle energy deposition fraction

Bremsstrahlung emmission

Thermal conduction

***Ribeyre X. et al. PoP 18, 102702 (2011)**

Analytical criterion for hot spot shock ignition (2)

Ignition criterion*

$$d_t E_f > d_t E_r + d_t E_e$$

Fusion power

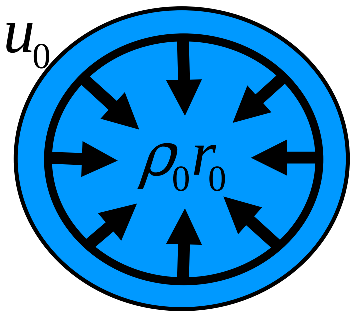
Radiative power

Thermal power

$$\rho_0 r_0 = \sqrt{\frac{A_e u_0^6}{f_\alpha A_f u_0^3 - A_r}}$$

Initial areal density

Initial shock velocity

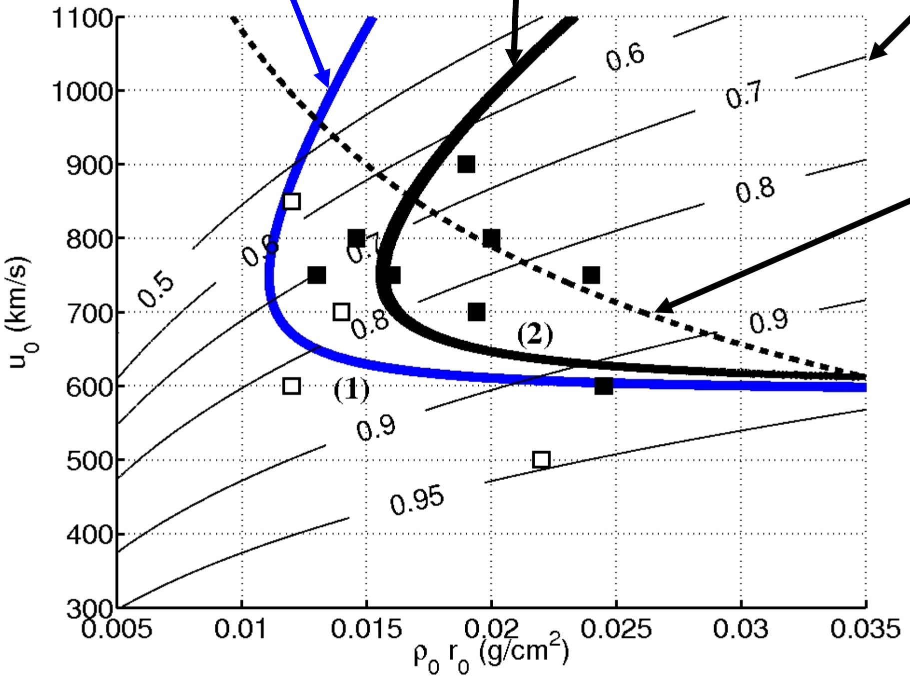


Alpha particle deposited fraction

$$f_\alpha = f(u_0, \rho_0 r_0)$$

Criterion with total α deposition

Criterion with α losses



Shcherbakov criterion**: $\rho_0 r_0 u_0^{2.2} \ge K$

Numerical CHIC
Simulations of SI target

■ Ignition

□ No-ignition

$$\rho_0 r_{0\min} = 15 \text{ mg/cm}^2 \text{and } u_0 = 750 \text{ km/s}$$

$$\rho_0 r_{0\min} \gg 15 \text{ mg/cm}^2 \text{and } u_0 > 600 \text{ km/s}$$

Analytical SI criterion and numerical simulations are in agreement

***Ribeyre X. et al. PoP 18, 102702 (2011)**

****Shcherbakov V.A., Sov. J. Plasma Phys. 9(2) 240 (1983)**

New study on spherical converging-diverging shock propagation

Extension of the Guderley problem to a finite Mach number (A. Vallet Thesis)

The Mach number is define by : $M_s(t) = \dfrac{U_s(t)}{c_0}$ **Now vary in time**

The Ranckine-Hugoniot relations are:

$$\rho_1 = \rho_0 \frac{\dfrac{\gamma+1}{\gamma-1}}{1 + \dfrac{2}{\gamma-1} M_s(t)^{-2}},$$

$$u_1 = c_0 \frac{2}{\gamma+1} M_s(t)(1 - M_s(t)^{-2}),$$

$$c_1{}^2 = c_0{}^2 \frac{\rho_0}{\rho_1} \left(\frac{2\gamma}{\gamma+1} M_s(t)^2 - \frac{\gamma-1}{\gamma+1}\right).$$

There is No self-similar solution,
then we search a power series solutions *

*** Ponchaut, N. F., J. Fluid Mech. Vol. 560 p. 103 (2006)**

Changement of variables and solution

Changement of variable proposed by Sakurai * $x(r,t) = \frac{r}{R_s(t)}, \quad y(t) = \frac{c_0}{U_s(t)}.$

Hydrodynamic variable Transformation:

$$u(x,y) = c_0 \frac{x}{y} \mathcal{U}(x,y),$$

$$c(x,y) = c_0 \frac{x}{|y|} \mathcal{C}(x,y),$$

$$\rho(x,y) = \rho_0 \mathcal{G}(x,y).$$

Power solution in y^2 for the scale functions

$$\mathcal{G}(x,y) = G\left(1 + \sum_{k=1}^{\infty} y^{2^k} G_k(x)\right)$$

$$\mathcal{U}(x,y) = U\left(1 + \sum_{k=1}^{\infty} y^{2^k} U_k(x)\right)$$

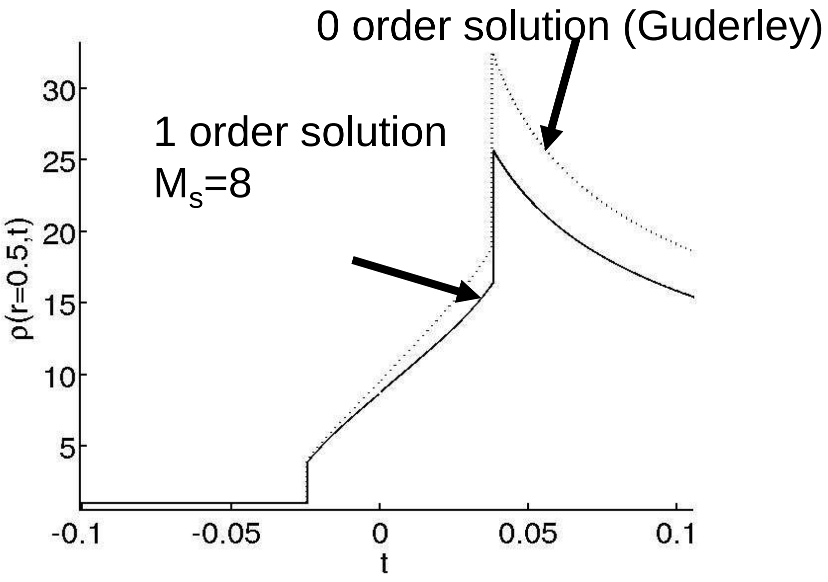
$$\mathcal{C}(x,y) = C\left(1 + \sum_{k=1}^{\infty} y^{2^k} C_k(x)\right)$$

$y \rightarrow 0$ **Gurdeley solution**

Solve of N ODE

$$\mathbf{A}\begin{pmatrix} G'_N \\ U'_N \\ C'_N \end{pmatrix} + \mathbf{B_N}\begin{pmatrix} G_N \\ U_N \\ C_N \end{pmatrix} + \lambda_N \mathbf{D} = \mathcal{F}(\{G_{1..N-1}, U_{1..N-1}, C_{1..N-1}\})$$

Density profile in Eulerian coordinate



0 order solution (Guderley)

1 order solution M_s=8

* **Sakurai, I, J. of Physical society of Japan, Vol. 8, N°5 (1953)**

Shock ignition : Stagnation conditions
Two steps process

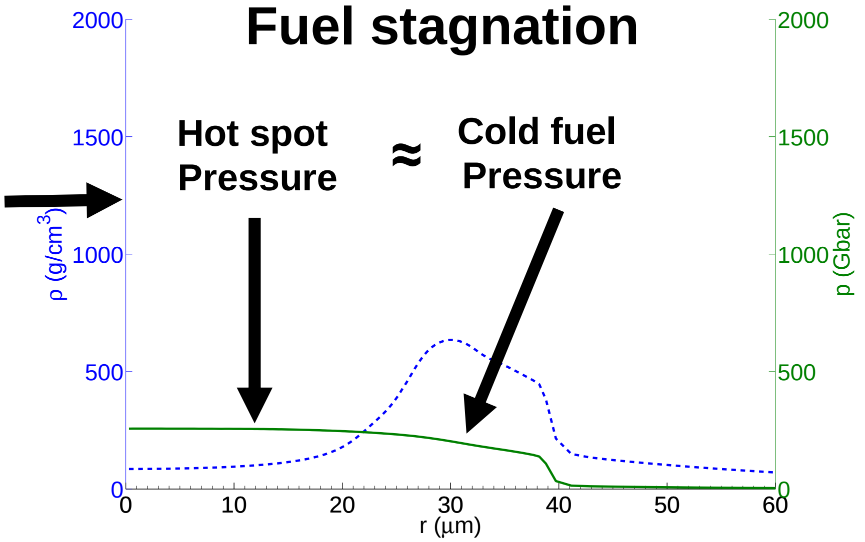
1 Compression phase

Standard <u>quasi-isobaric configuration</u>

- Low implosion velocity: V_{imp} **< 300 km/s**

- Hot spot ignition fails

Identical to fast ignition compression


Fuel stagnation

Hot spot Pressure ≈ Cold fuel Pressure

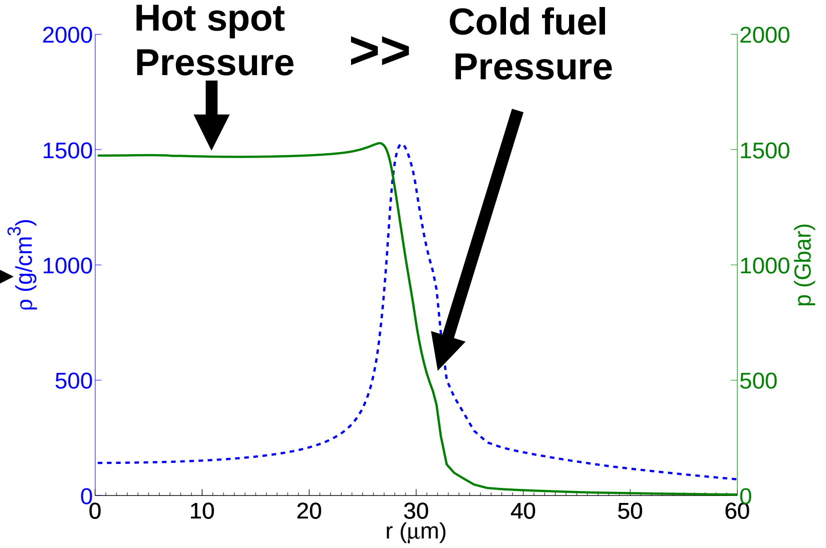
2 Ignition phase

With converging shock

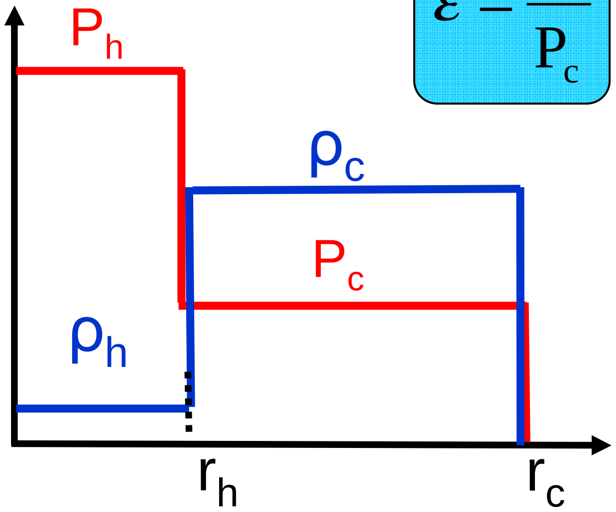
<u>Non-isobaric configuration</u>

Increased central pressure and temperature

ignites a central hot-spot

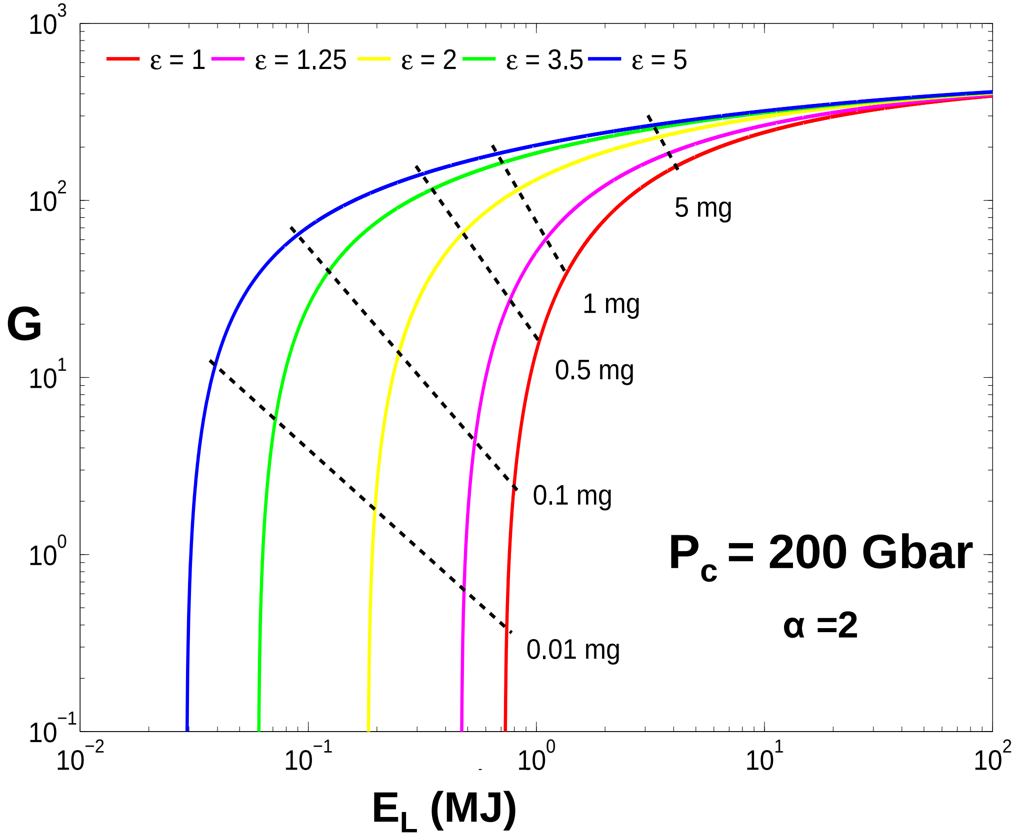

Hot spot Pressure >> Cold fuel Pressure

Gain of non-isobaric fuel assembly and Rosen model *



$$\varepsilon = \frac{P_h}{P_c}$$

← **Non-isobaric parameter**



$$G = \frac{\Phi Q_{DT}}{E_L}(M_h + M_f) \propto \frac{\varepsilon^{0.27}}{\alpha^{0.9}} E_L^{\ 0.17}\left(1 - \frac{cst}{E_L}\right)$$

α: Adiabat at stagnation

E_L: Laser energy

Rosen model shows the low threshold and high gain possibility of a non-isobaric configuration

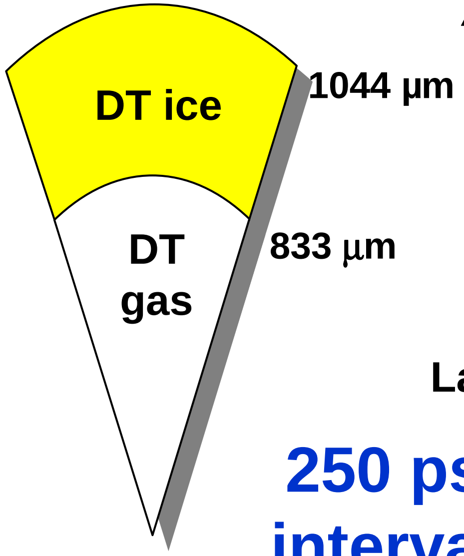
Lafon M. et al. PoP (2010)

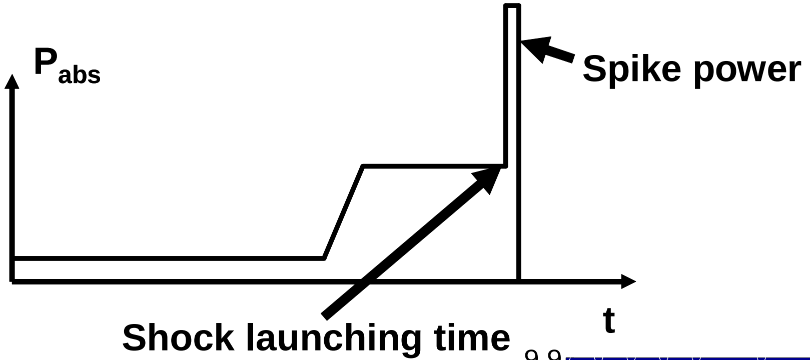
*** M.D. Rosen and J.D. Lindl (1984) UCRL-50021-83**

Shock igniting of HiPER target

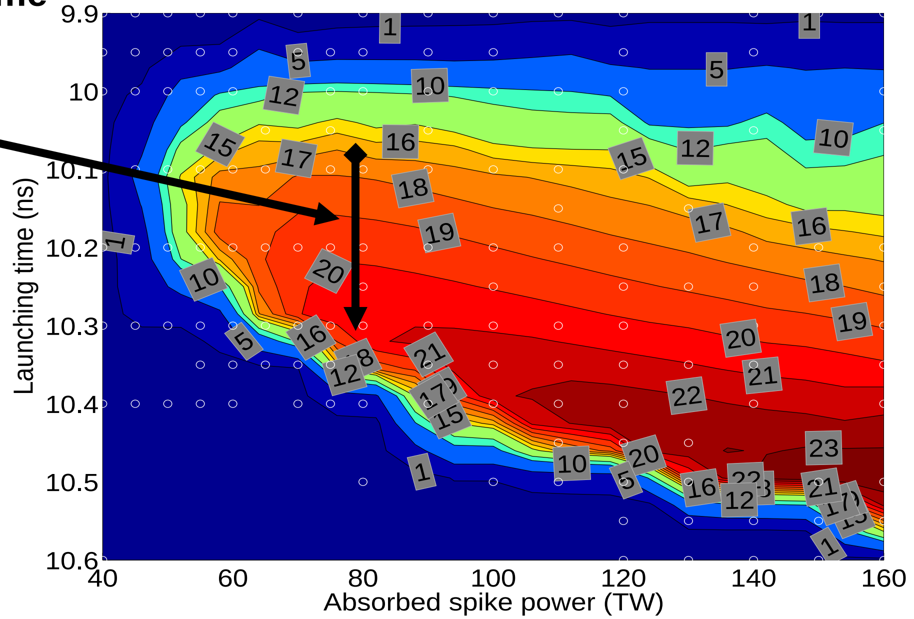
Prelimirary results : Robustness study

All DT HiPER target:





Iso-energy



Launching window

250 ps confidence interval at 80 TW

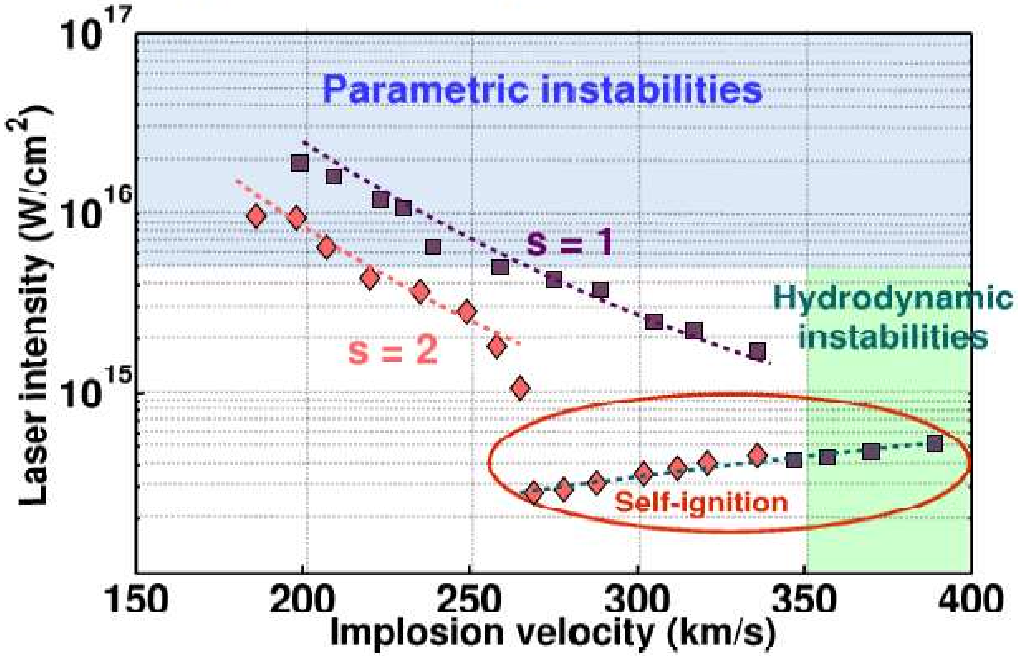
180 kJ, 10 ns - 50 TW for compression (3ω)
+
70-100 kJ, < 500 ps – 150-200 TW for ignitor (3ω)

20 MJ (TN) : Gain ~ 80

Ribeyre el al : PPCF (2009)

The peak laser intensity for ignition thresholds of shock-ignited relevant targets evolves from 1×10^{15} to 2×10^{16} W/cm²

- Target design for shock ignition requires implosions that provide safety margins for ignition performance and gain

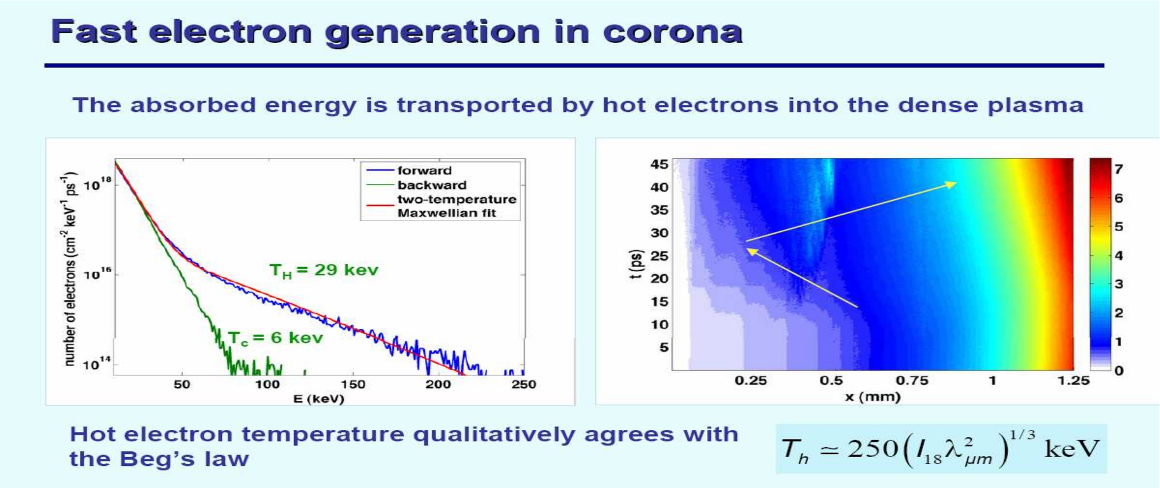


- The laser intensity reduces with the implosion velocity of shock-ignited targets:

$$\boxed{I_L \propto s^{-3/2}\left(\frac{V_I(km/s)}{300}\right)^{-5.6}}$$

M. Lafon Thesis (2012)

Raman accelerated hot electrons are probably harmless



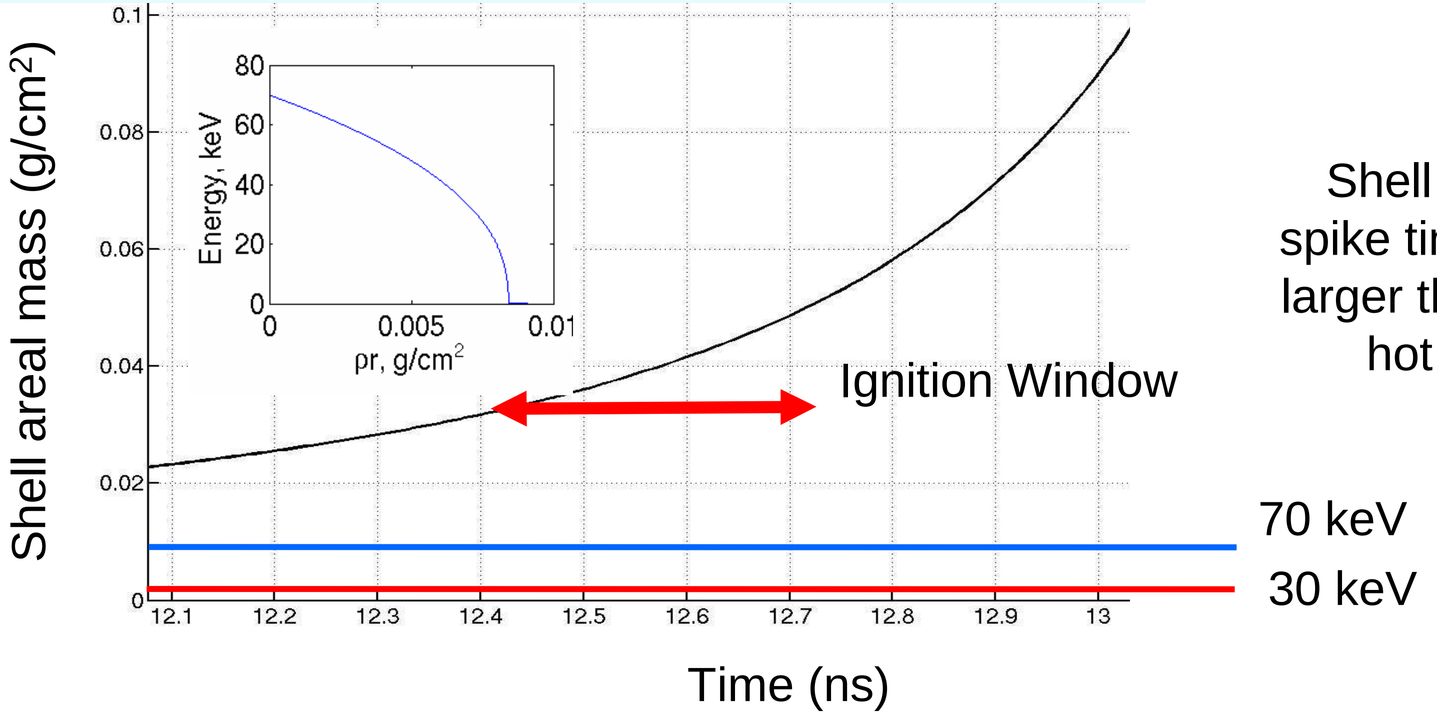
Fast electron generation in corona

The absorbed energy is transported by hot electrons into the dense plasma

Hot electron temperature qualitatively agrees with the Beg's law

$$T_h \simeq 250\left(I_{18}\lambda_{\mu m}^2\right)^{1/3}\ \mathrm{keV}$$

PIC simulations indicate that a large fraction of the spike energy is converted into 30 keV hot electrons ⁽¹⁾

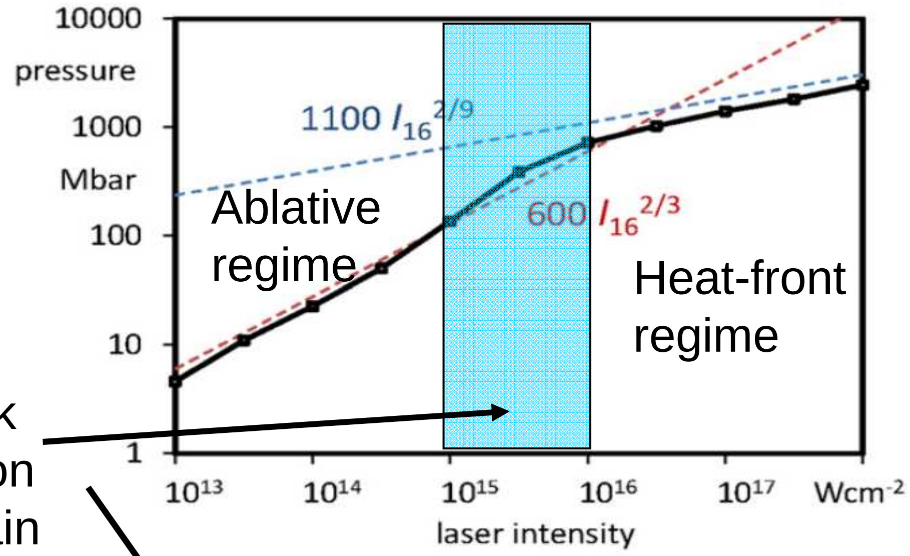


Shell areal mass at spike time is 5-20 times larger than the range of hot electrons ⁽²⁾

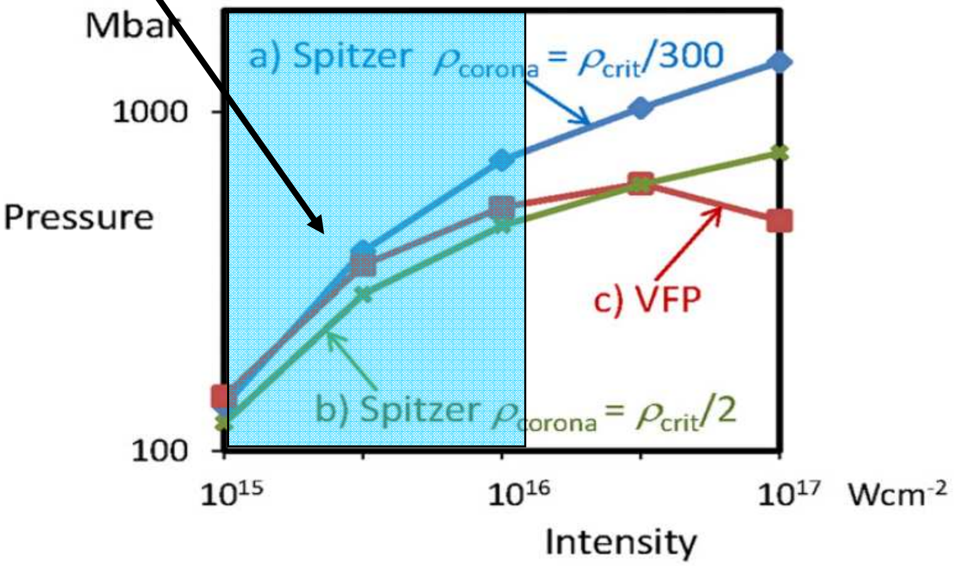
(1) Klimo O. et al. : PPCF **52** 055013 (2010)

(2) Betti, R. et al. IFSA **112** 022024 (2008)

Hot electrons can generate pressure ?



Shock ignition domain



Pressure with spitzer conductivity

Pressure slope change at $5x10^{15}$ W/cm^2

P~ 400 Mbar

Pressure obtained from Vlasov-Fokker-Planck simulations same behavior

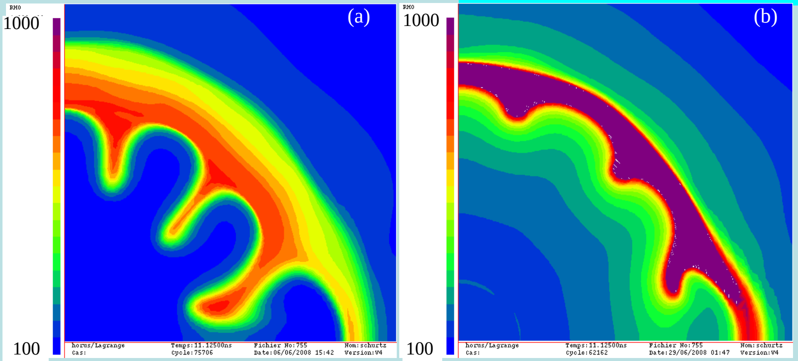
Encouraging results but need to be confirmed

(1) Bell T. & Tzoufras. : PPCF **53** 045010 (2011)

Rayleigh-Taylor stabilisation by shock during the stagnation (2,3)

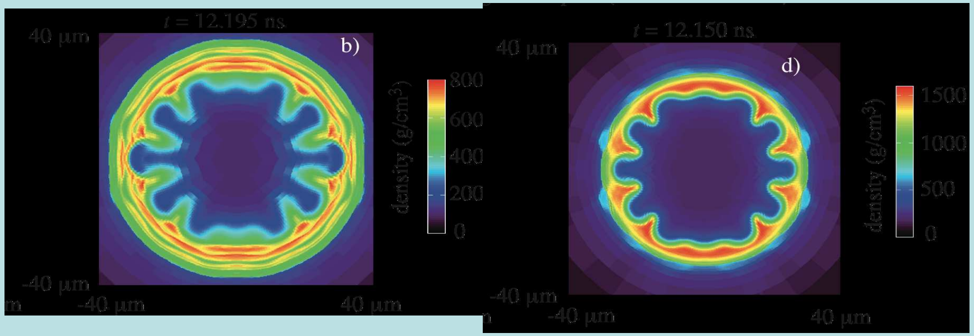
Pressure perturbation only due to low Mode laser illumination (1)

Compression only | Compression + Shock



RTI stabilisation : RMI is reversed by the shock + Ablation par les α

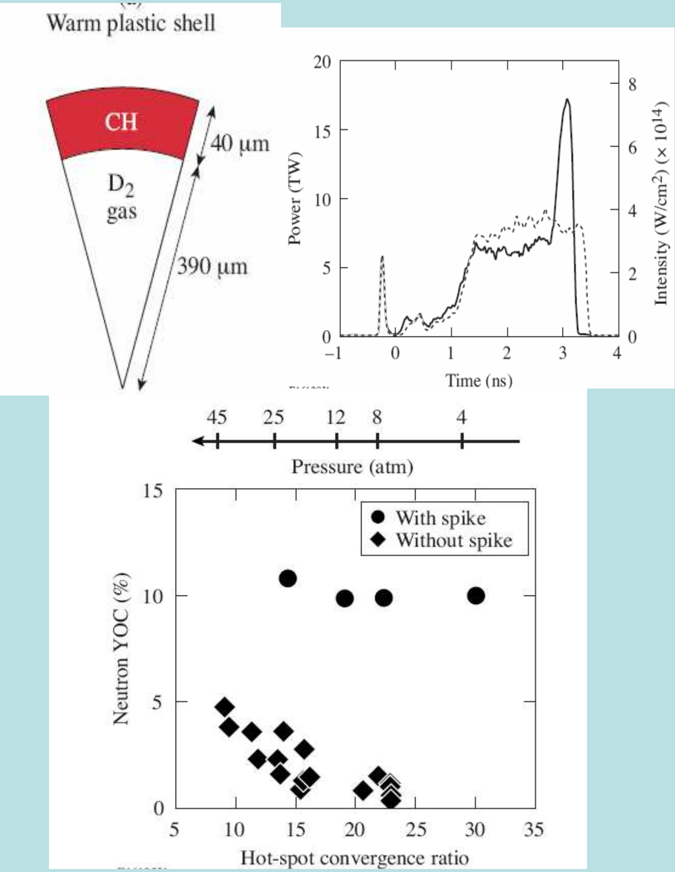
(2) Ribeyre et al : PPCF (2009)



Atzeni results confirmed the mitigation mecanism

RTI was observed
In shock igntion OMEGA

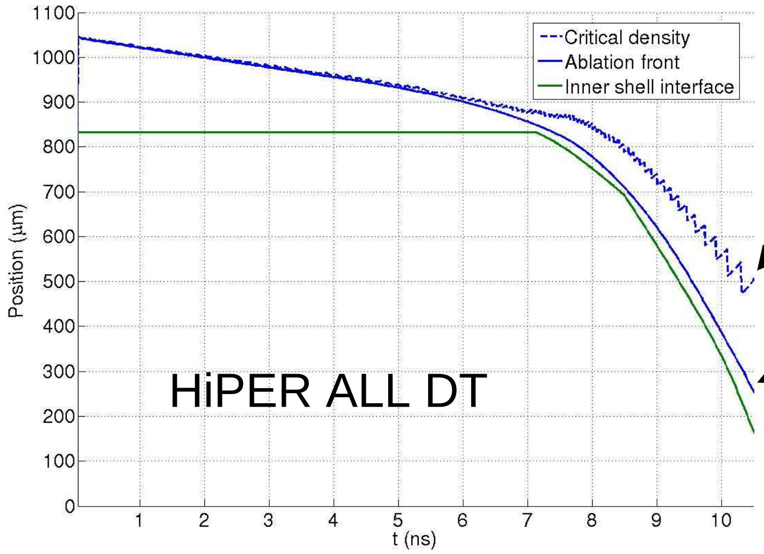
Experiment (3)



(3) Theobald et al : PoP (2008)

(3) Atzeni et al. PPCF (2011) **(1) Hallo et al. : PPCF (2009)**

Spike Symmetry



Critical density is half its initial value at spiketime

➔ ***use specific RPP and beams for the shock***

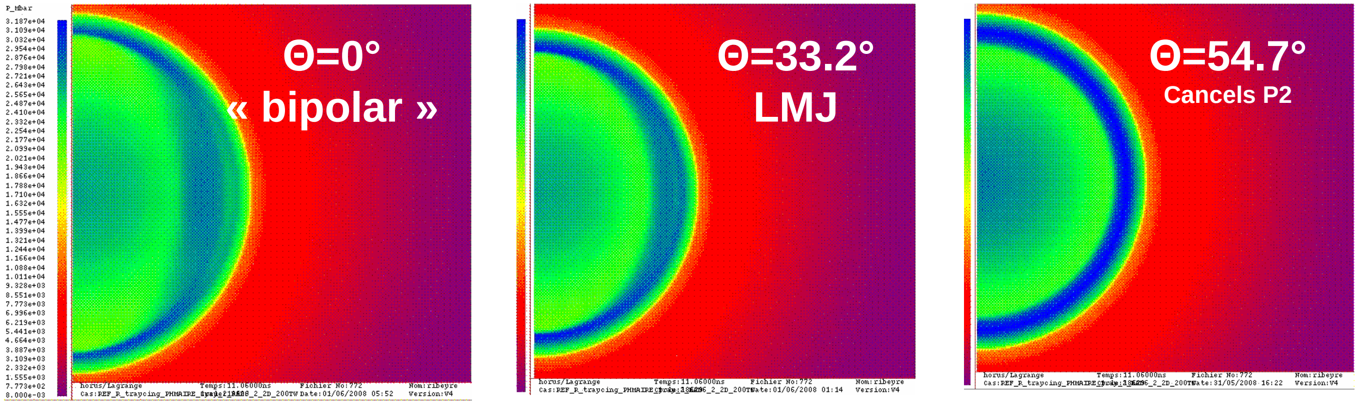
Ablation radius ~1/2 critical radius

➔Efficient thermal smoothing

➔***Spike illumination symmetry probably not stringent***

According to 2D simulations,the Hiper target still ignites for non symmetric spikes

Pressure at shock launch (CHIC code)



Ribeyre et al. : PPCF 51 015013 (2009)

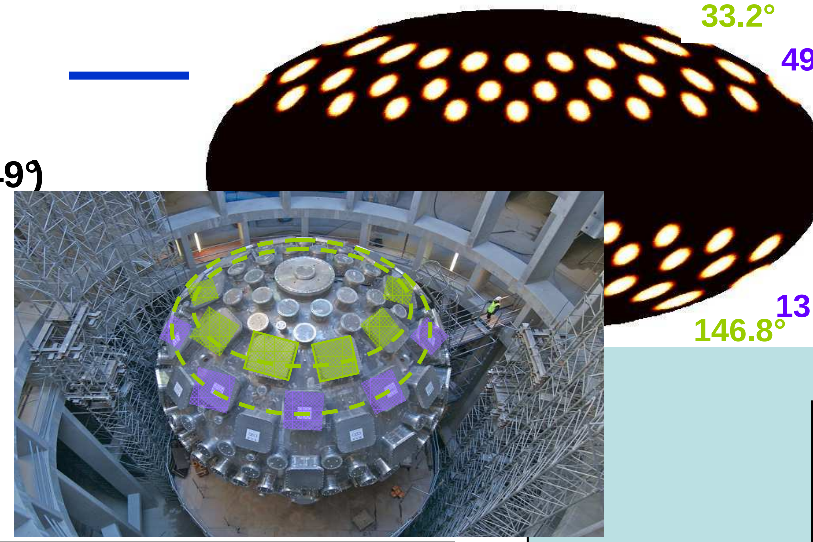
Shock ignition challenges for LMJ

- 1.2 MJ, 390 TW
- 40 quadruplets (33°, 49°)

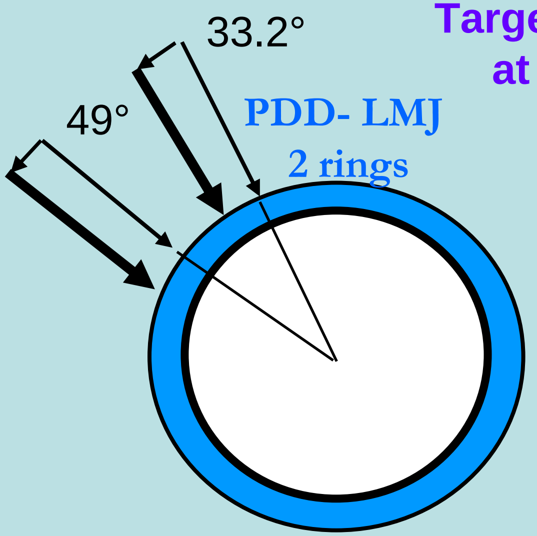
160 beams 40 x 40 cm^2

- May be split

and repointed

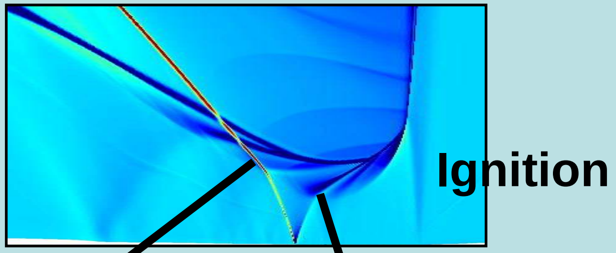


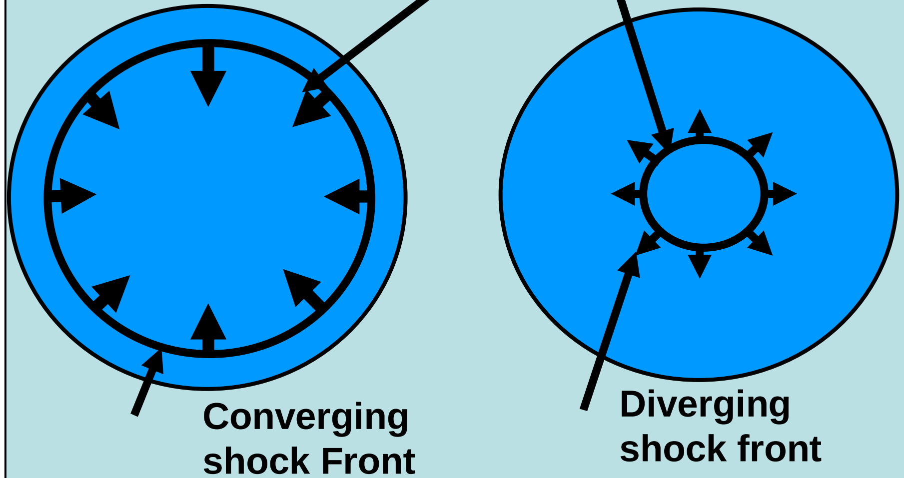
First step: Target compression at low velocity 250 km/s



Polar Direct Drive configuration:
Need to have a good
laser uniformity < 2% ?

Second step: Shock ignition

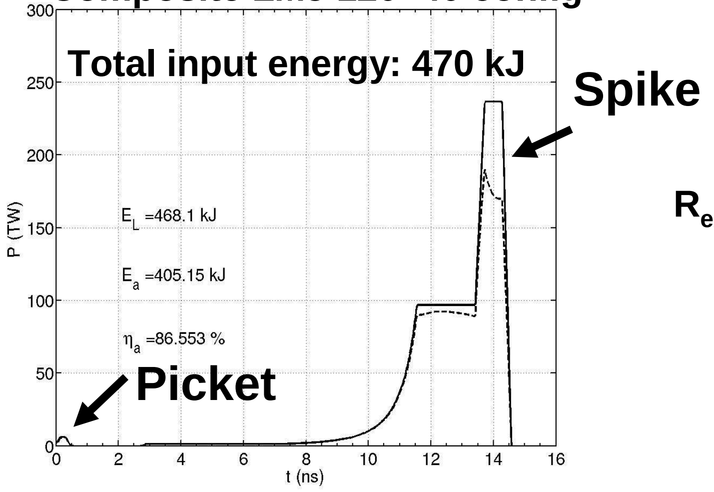




Need to generate a strong shock
200-300 Mbar
1-5x10^{15} W/cm^2 (3ω)

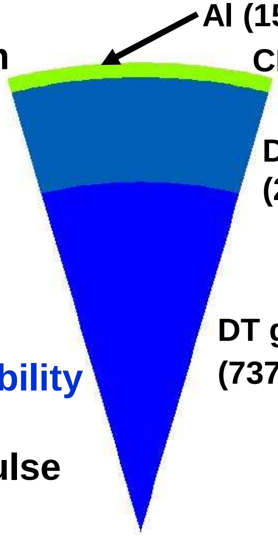
A robust target designed for NIF/LMJ class lasers

Composite LMJ 120+40 config



Fat target

Mass: 0.89 mg



R_{ext} =988 µm

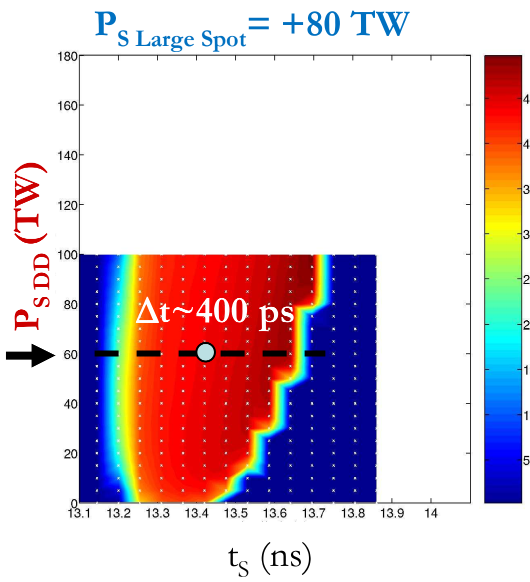
Al (15 nm)

CH (31 µm)

DT ice (220 µm)

DT gas (737 µm)

SI-Window

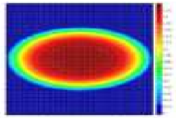


- **Low aspect ratio + Picket: Improves Target Stability**
  - **=> peak IFAR ~ 33 IFAR and 0.75R_{inner} =17**
- **Al coating : Target protection from IR and prepulse**
- **CH ablator : Higher Absorption fraction**

$$\left\langle \alpha_{if} \right\rangle = 1.2$$

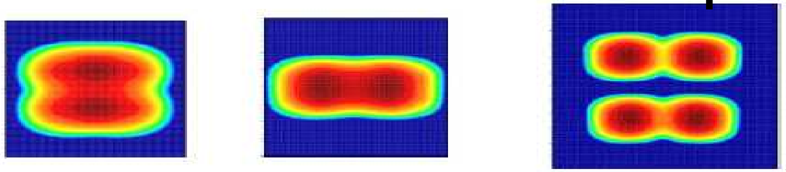
120b PDD Compression **+ shock spike**	**Implosion velocity**	**Performances**	**40b DD Shock Spike**	**Implosion velocity with shock**	**Yield t_s~13.4 ns**	**Gain**	**Stable Ignition window**
100 TW **+80TW**	**240 km/s**	**662 g/cc** **2.0 g/cm²**	**60 TW**	**265 km/s**	**44 MJ**	**94**	**400 ps**

Optimize Polar Drive

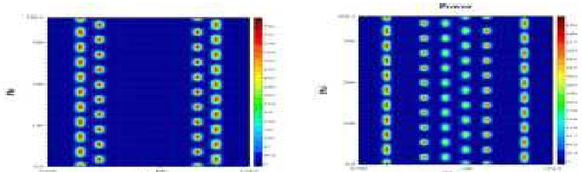


LMJ Focal spot is elliptical

- Repointing Beams
- Defocusing Beams



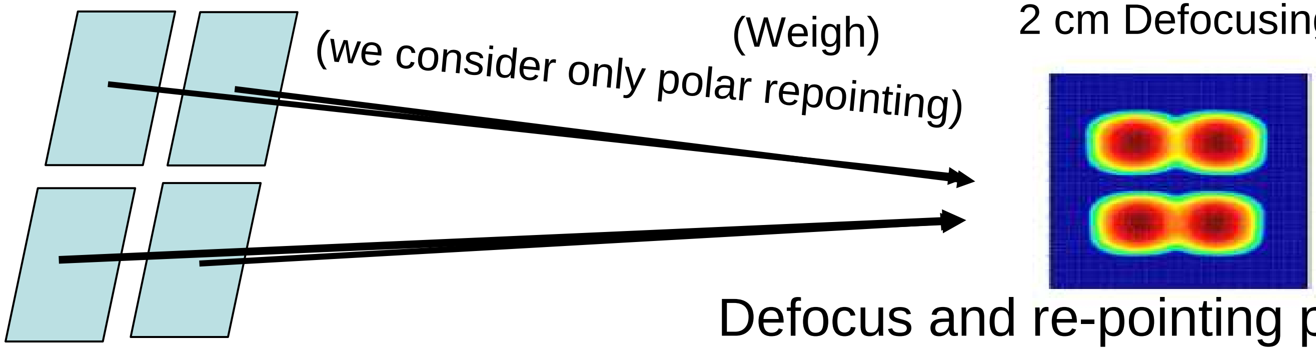
- Splitting quads



LMJ: 33°, 49°   PDD 6 cones

- Tuning Power Balance : w_b
  - Intensity on target is linear function of w_b: $I(\theta,\varphi)=\sum_b A_{\theta\varphi b} w_b$
  - Solve for w_b $I(\theta,\varphi)=\overline{I} \Rightarrow (A^{\dagger}.A)w_b = A^{\dagger}\overline{I}$

LMJ quad



(Weigh)

(we consider only polar repointing)

2 cm Defocusing

Defocus and re-pointing possibilties ?

- Other possibilities are studied using 49° and 59.5° cones for compression and 33.2° for the shock with new Phase Plate design **(Canaud et al. : PPCF 2011)**

PDD platform on LMJ (day 1 hardware) : 160 beams Illumination

Cones : 33.2° + 49°

Quad splitting + Defocusing (1.8 cm)
+ Tache focale elliptique

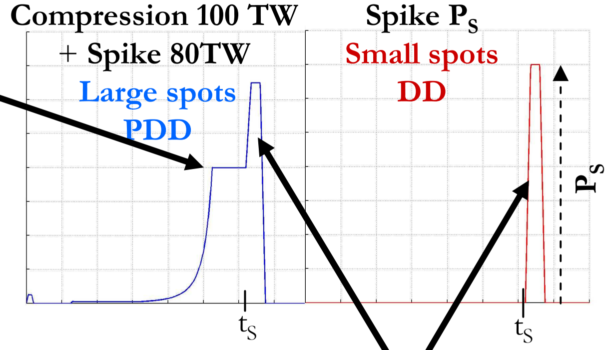
Compression:
Split 33a 49a-b

Split 33 b: Spike

120 + 40 beams

6 cônes
Composite

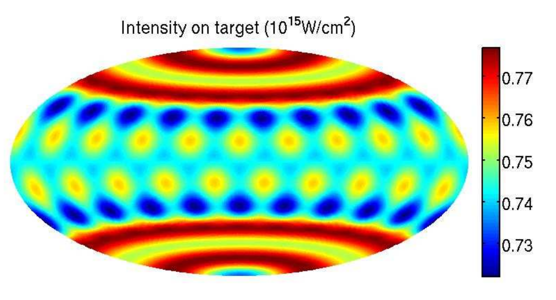
PDD LMJ

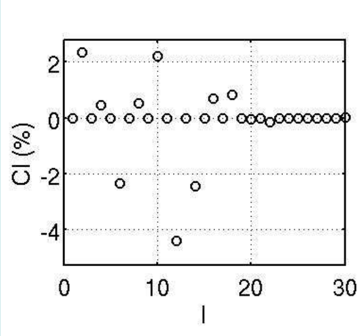


Compression:

« uniform » Illumination : 1.8%

$\langle I_c \rangle$=7.5x10^{14}W/cm^2 R=R$_0$





**Legendre mode
dominant l=2-6-10-12-16**

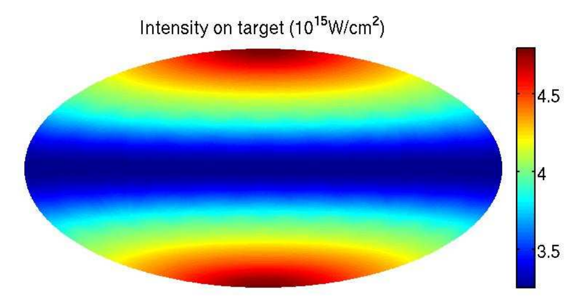
Spike

I_{smax}=4.8x10^{15} W/cm^2

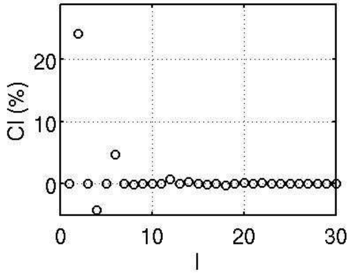
R=0.6*R$_0$

$\langle I_s \rangle$=3.8x10^{15} W/cm^2

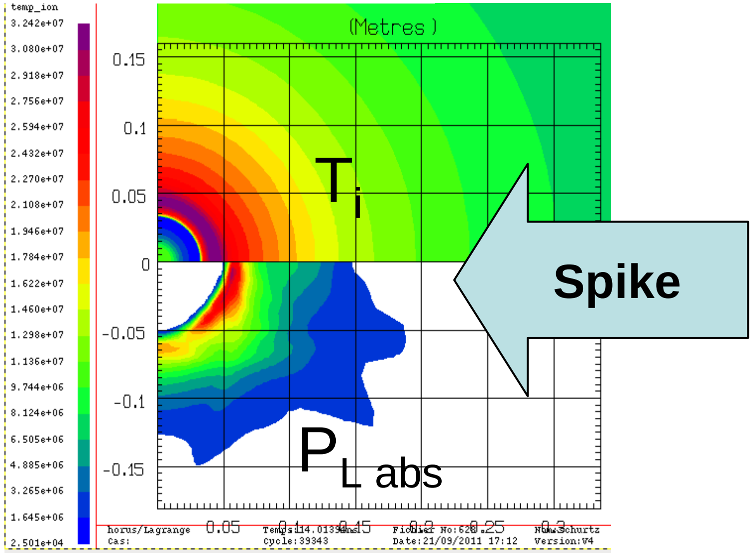
**Bipolar
illumination:
Uniformity: 10%**



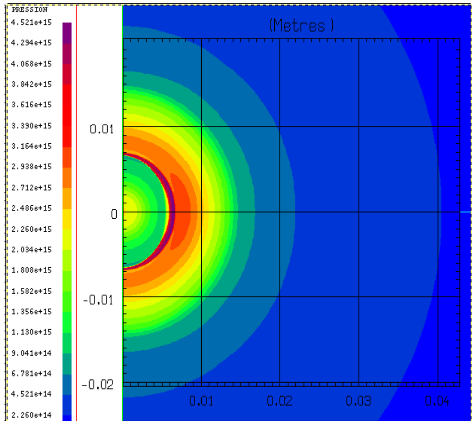
**Legendre mode
dominant l=2**



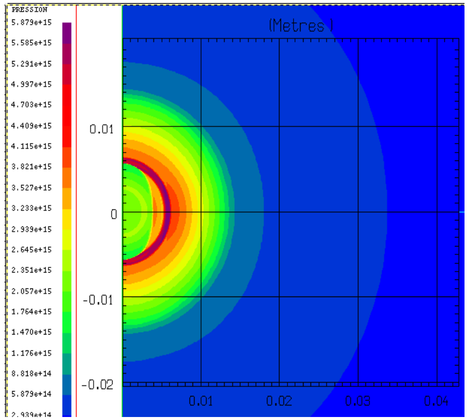
2D CHIC simulation of SI LMJ case @ 350 TW
Bipolar Ignition*



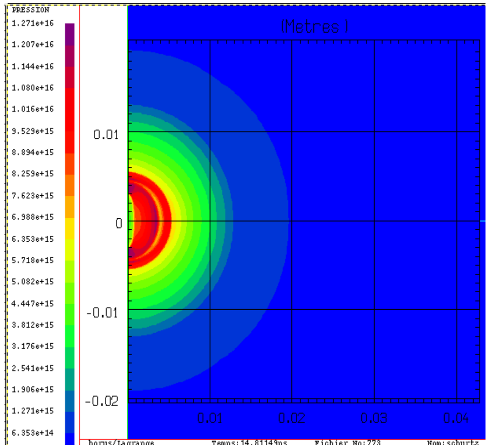
t=14.75 ns, P ~ 4.5 Gbar



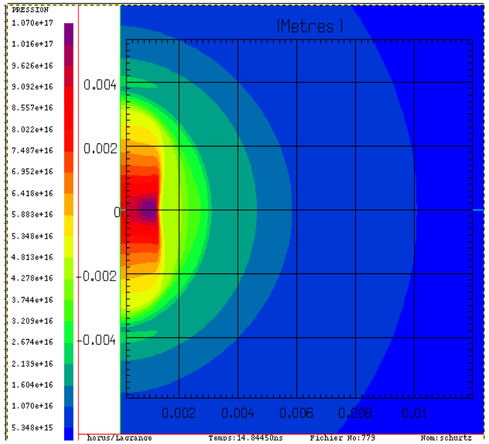
t=14.77 ns, P ~ 5.9 Gbar



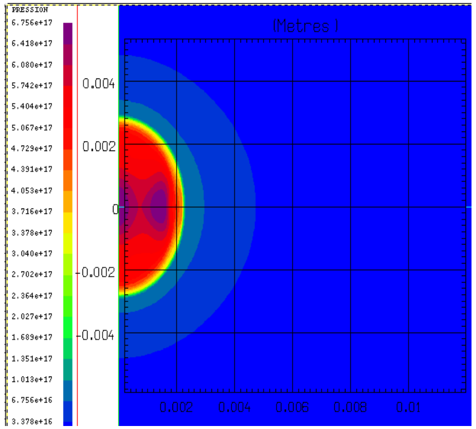
t=14.81 ns, P ~ 12.7 Gbar



t=14.84 ns, P ~ 100 Gbar



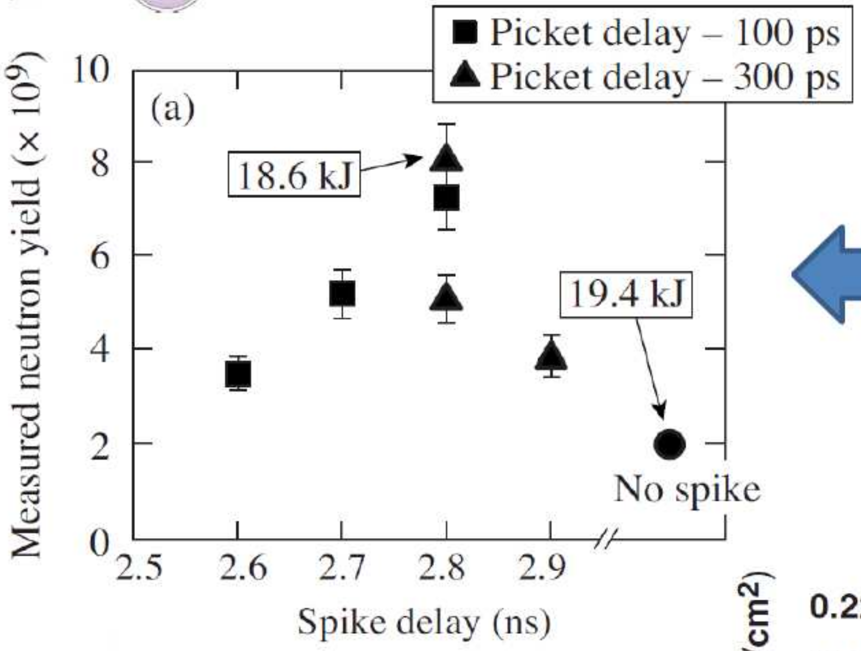
t=14.9 ns,
P ~ 650 Gbar, T_i=10 keV



IGNITION

*** In HiPER context see :Ribeyre et al. : PPCF 51 015013 (2009)**

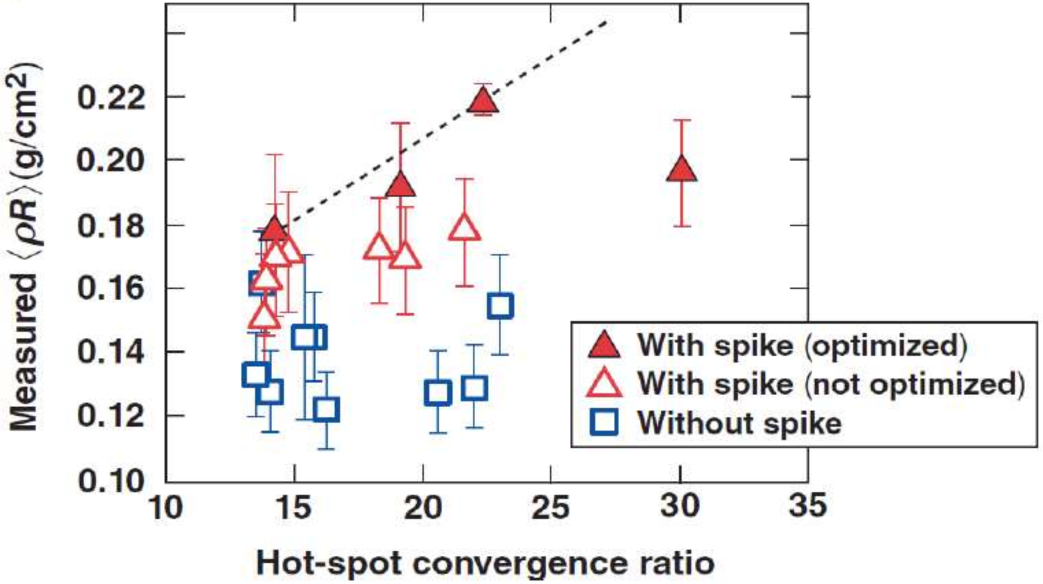
Higher neutron yields and areal densities are measured in shock ignition experiments using thick CH targets



Factor 4 in neutron yield

Neutron yields:
Compare SI and CHS targets,
40 µm CH shells filled with
25 atm D2 gas

Higher Areal density



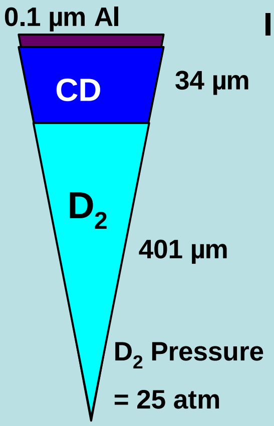
Areal densities:
Compare SI and CHS targets
Varying fill pressures

W. Theobald et al,
Phys Plasmas 15, 056306 (2008)

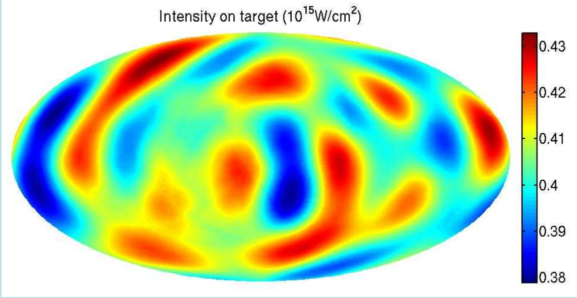
Omega 40+20 beams campaign: shock ignition platform

CELIA

40 beams:
2.6 % non-uniformity:
best symmetry

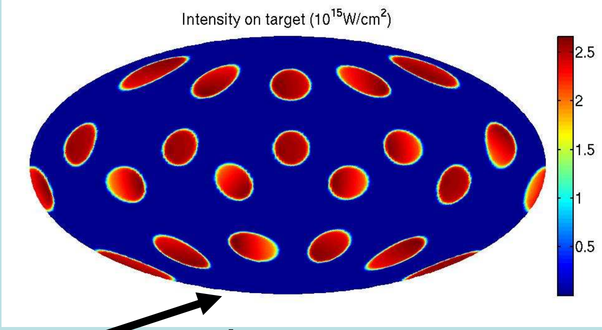


Incident on target after beam repointing



20 beams:
on Dodecaedron vertices:
best symmetry

On critical surface

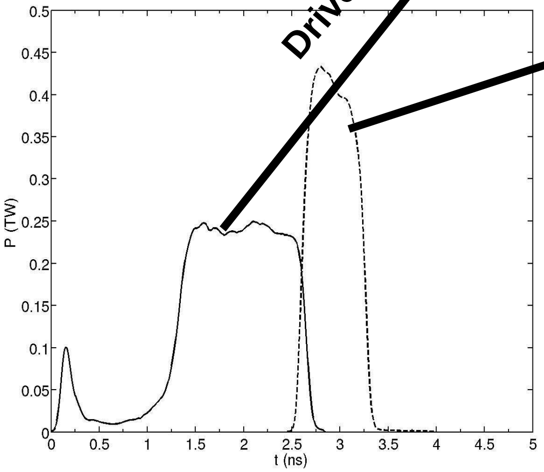


2 rings :

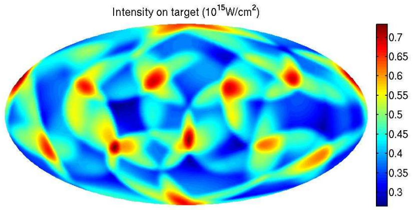
- **5 beams 37.4°**
- **5 beams 79.2°**

Drive: 40 beams

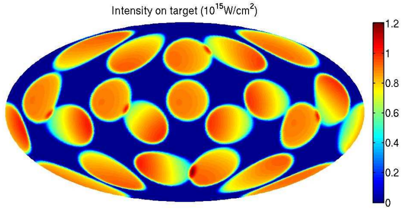
Spike : 20 beams



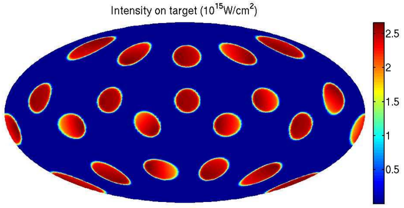
Spike intensities varies by changing the lens defocus



Defocus 3.5 mm
<I> ~ 0.5x10^{15} W /cm^2

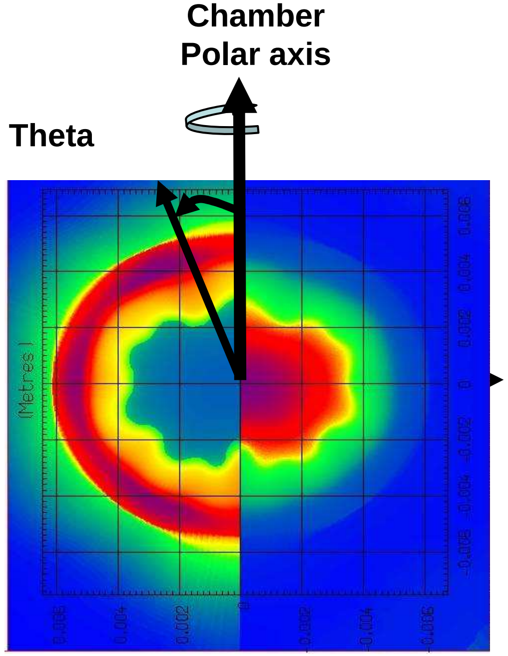


Defocus 1.5 mm
I ~ 1x10^{15} W /cm^2

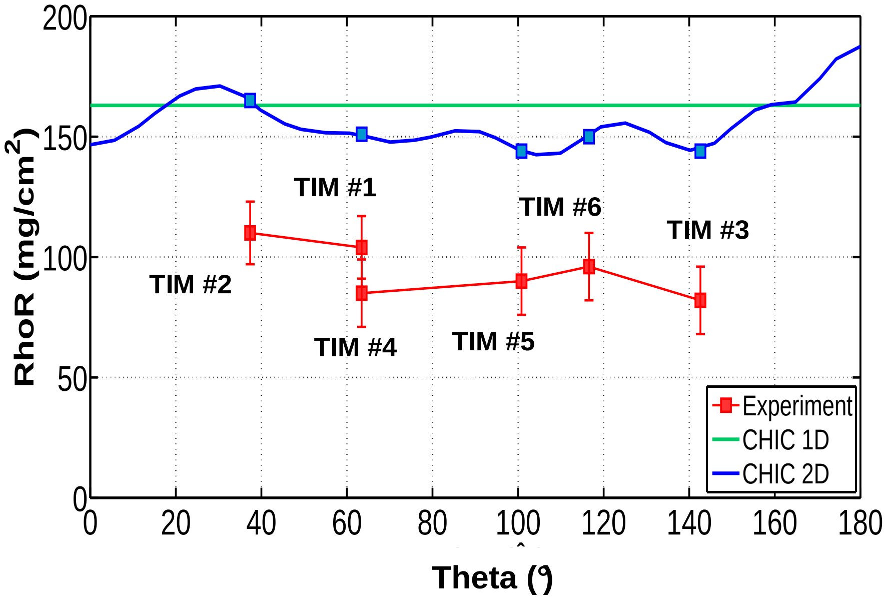


Defocus 0.77 mm
I ~ 2.5 10^{15} W /cm^2

2D CHIC simulations reproduce rougly the measured modulation of the areal density



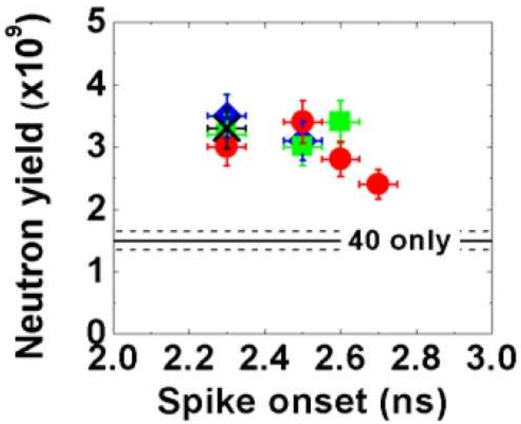
At stagnation



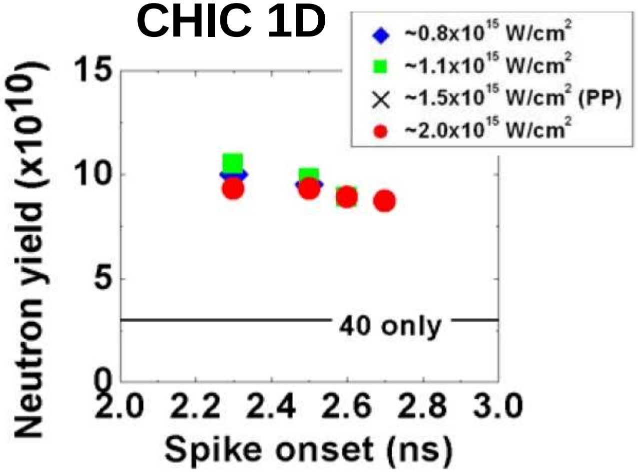
- 2D CHIC simulation is ρR ~50 mg/cm^2 Higher (Peak ρR)
- ρR variation with theta agrees with simulations

Neutron Yield mesurement and CHIC simulations

Measures



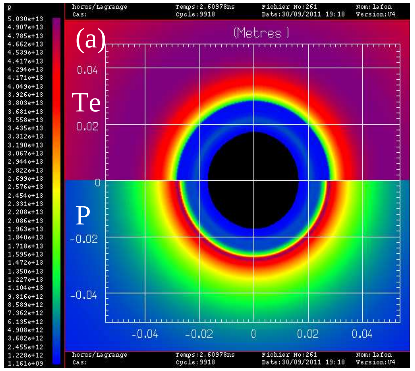
CHIC 1D



The neutron yield is insensitive to spike intensity

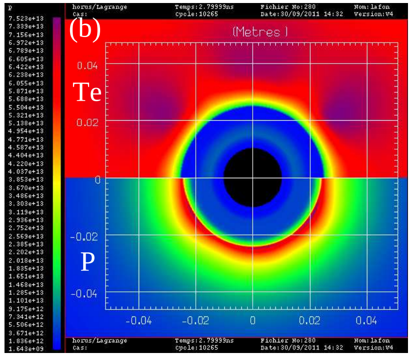
For all spike intensities the pressure remain fairly symmetric and constant then the neutron yield too

CHIC 2D

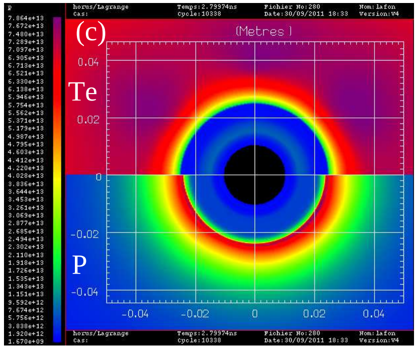


40 beams only

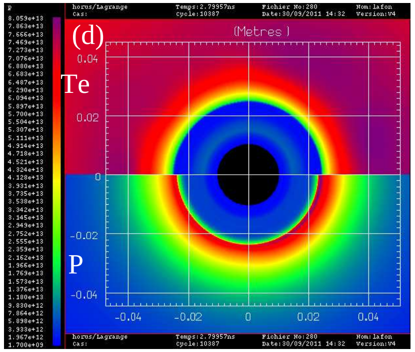
P=50 Mbar



I_s ~ 2.5x10^{15} W /cm^2



I_s ~ 1x10^{15} W /cm^2

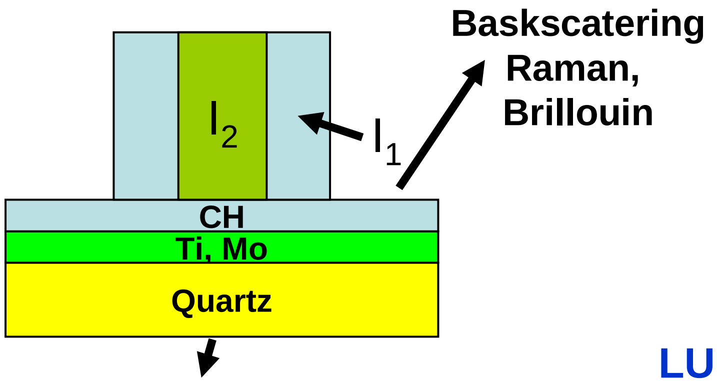


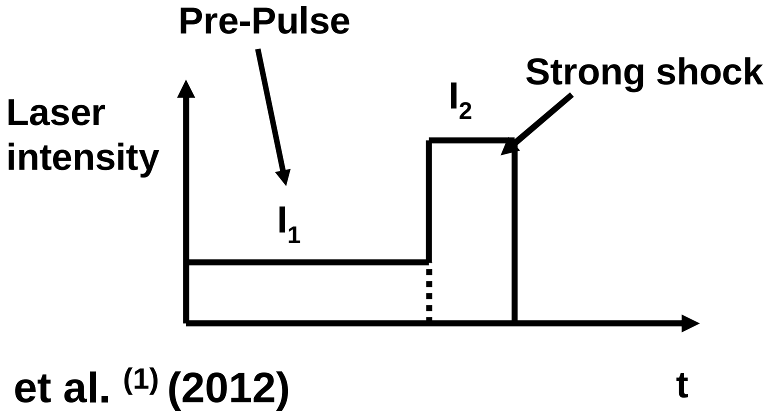
I_s = 0.5x10^{15} W /cm^2

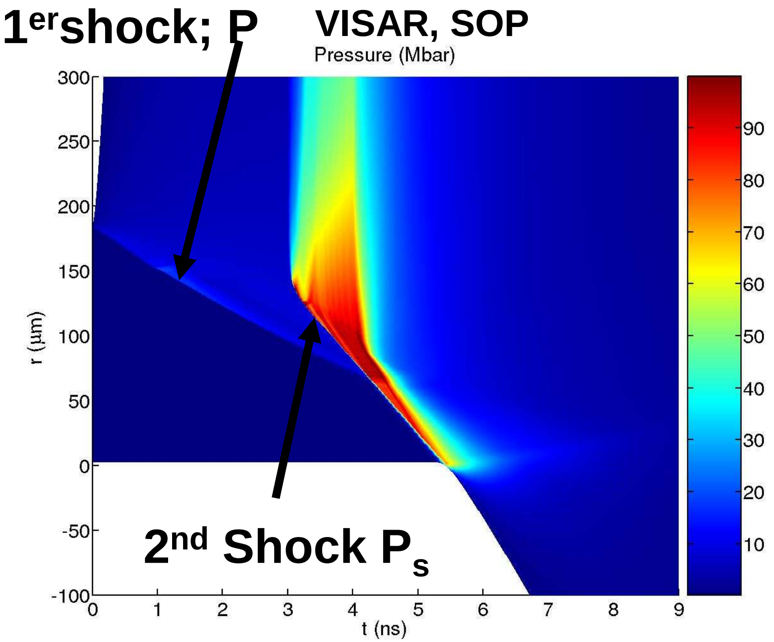
40+20 beams at spike onset

P=75 Mbar whatever the spike intensity

Planar Strong Shock experiment in long plasma corona







LULI: S. Baton et al. (1) (2012)
I_1=7x10^{13} W/cm^2 : I_2=10^{15} W/cm^2 : 2 ω
P_s=40 Mbar, Large 2D effects, Reflectivity < 15% (filamentation ?)

PALS: D. Batani et al. (2) (2010-11) (stepped target)
I_1=2x10^{13} W/cm^2 : I_2=10^{16} W/cm^2 :
P_s~90 Mbar, Large 2D effects, reflectivity < 5% (filamentation ?) 30-50 keV hot e 3 ω

OMEGA: M. Hohenberger et al(3) (2012)
I_1=2x10^{14} W/cm^2 : 3 ω , I_2=1.2x10^{15} W/cm^2 : 3 ω
P_s=70 Mbar, Low 2D effects, Reflectivity < 7 % (SBS+SRS)
1.8% of laser energy in 70 keV hot e

Experimental difficulties to achieve P_s > 300 Mbar i.e. intensities larger than 5x10^{15} W/cm^2 (at 3ω)

(1) S. Baton et al. PRL **108**, 195001 (2012) (2) D. Batani et al. PPCF 53 124140 (2011), (3)M. Hohenberger et al. Submitted to PRL

Conclusions

- Important progress has been made in the few last years

But several physical issue need to be resolve to validate shock ignition

- How to High ablation pressure P > 300 Mbar ?
  - What is the role of the Parametric instability ?
  - How the hot electron contribute to the pressure ?
- How to keep the hot spot integrity ?
  - What is the role of the shock on the RTI ?
- Converging shock physics study: collision, rebound, amplification, stability, symmetry …
- How to achieve shock ignition on LMJ ?
  - Target design, adiabat shaping, PDD study …
- Need experimental data relevant for shock ignition physics