



Fusione a confinamento inerziale fondamenti fisici degli esperimenti di ignizione

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Seminario

“Fusione e Fissione Nucleare: stato e prospettive sulle fonti energetiche
nucleari per il futuro”

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- J. J Honrubia (UPMadrid), J. Meyer-ter-Vehn (MPQ)
- HiPER WP9 (target modeling) group

For permission to use figures/viewgraphs:

- Lawrence Livermore National Laboratory (through S. Haan):



Bibliografia

Tutorial sull'argomento del seminario:

- S. Atzeni Plasma Phys. Control. Fusion **51** (2009) 124029

Libri sulla fusione inerziale

- S. Atzeni and J. Meyer-ter-Vehn, *The Physics of Inertial Fusion*, Oxford University Press, 2004 (paperback: 2009)
 - J. D. Lindl: *Inertial Confinement Fusion*, Springer, New York, 1997.
- collezione di articoli (un po' datati) sulla tecnologia della fusione inerziale
- *Energy from Inertial Fusion*, IAEA, Vienna (1995).

collezione di articoli sulle diagnostiche:

- P. E. Stott, A. Wootton, G. Gorini, E. Sindoni and D. Batani (Eds): *Advanced Diagnostics for Magnetic and Inertial Fusion*, Kluwer Academic, New York (2002).
-



Bibliografia (II)

un'interessante review sulla fusione come fonte energetica:

- W. J. Nuttal (Ed.), *Fusion as an Energy Source; Challenges and Opportunities*, Institute of Physics Report, Sept. 2008
(http://www.iop.org/activity/policy/Publications/file_31695.pdf)

Invited talk alle maggiori conferenze su fusione e plasmi:

- EPS Plasma Physics Conference: *Plasma Phys. Controll. Fusion* (Dec. issue)
 - APS Plasma Physics Division: *Phys. Plasmas* (May issue)
 - IAEA Fusion Energy Conference: *Nucl. Fusion*
 - Inertial Fusion Science and Applications
 - Symposium on Fusion Technology: *Fusion Technol.*
-



Summary



- ICF principles
 - essential ingredients
 - key requirements /issues
- Ignition experiments at the NIF
 - laser, target
 - physics basis
 - design vs issues
- Are there alternatives?
 - drive: direct-drive
 - approach to ignition: fast ignition, shock ignition
- The route to the reactor
- Conclusions



Inertial confinement fusion (ICF)

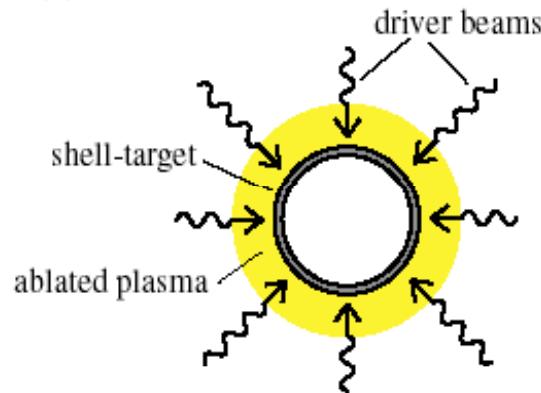


- Fusion reactions
 - from a target containing **a few mg** of DT fuel
 - **compressed** to very high density ($\rho > 1000$ times solid density)
 - and **heated** to very high temperature
 - No external confinement => fuel *confined by its own inertia*
($t = R/c_s$ with c_s the sound speed and
 R linear dimension of the compressed fuel)
=> confinement parameter: nR or ρR
(n : particle density, ρ : mass density)
 - Pulsed process: for energy production
 - burn targets at 1 - 10 Hz
 - (Target gain) * (driver efficiency) ≥ 10
- 150 7%

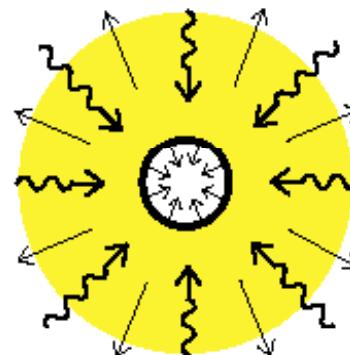
the standard approach: *central ignition*

imploding fuel kinetic energy converted into internal energy and concentrated in the centre of the fuel

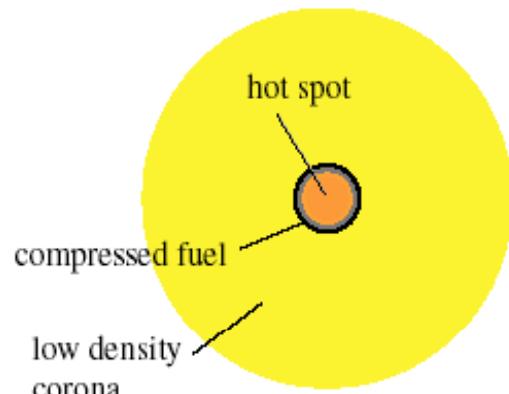
(a) irradiation



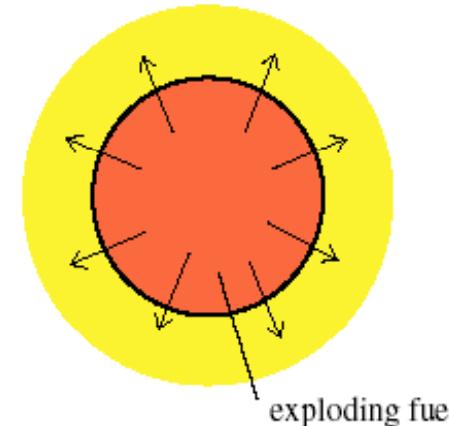
(b) implosion driven by ablation



(c) central ignition



(d) burn and explosion



implosion velocity for ignition:

$$u_{\text{imp}} > 250 - 400 \text{ km/s}$$

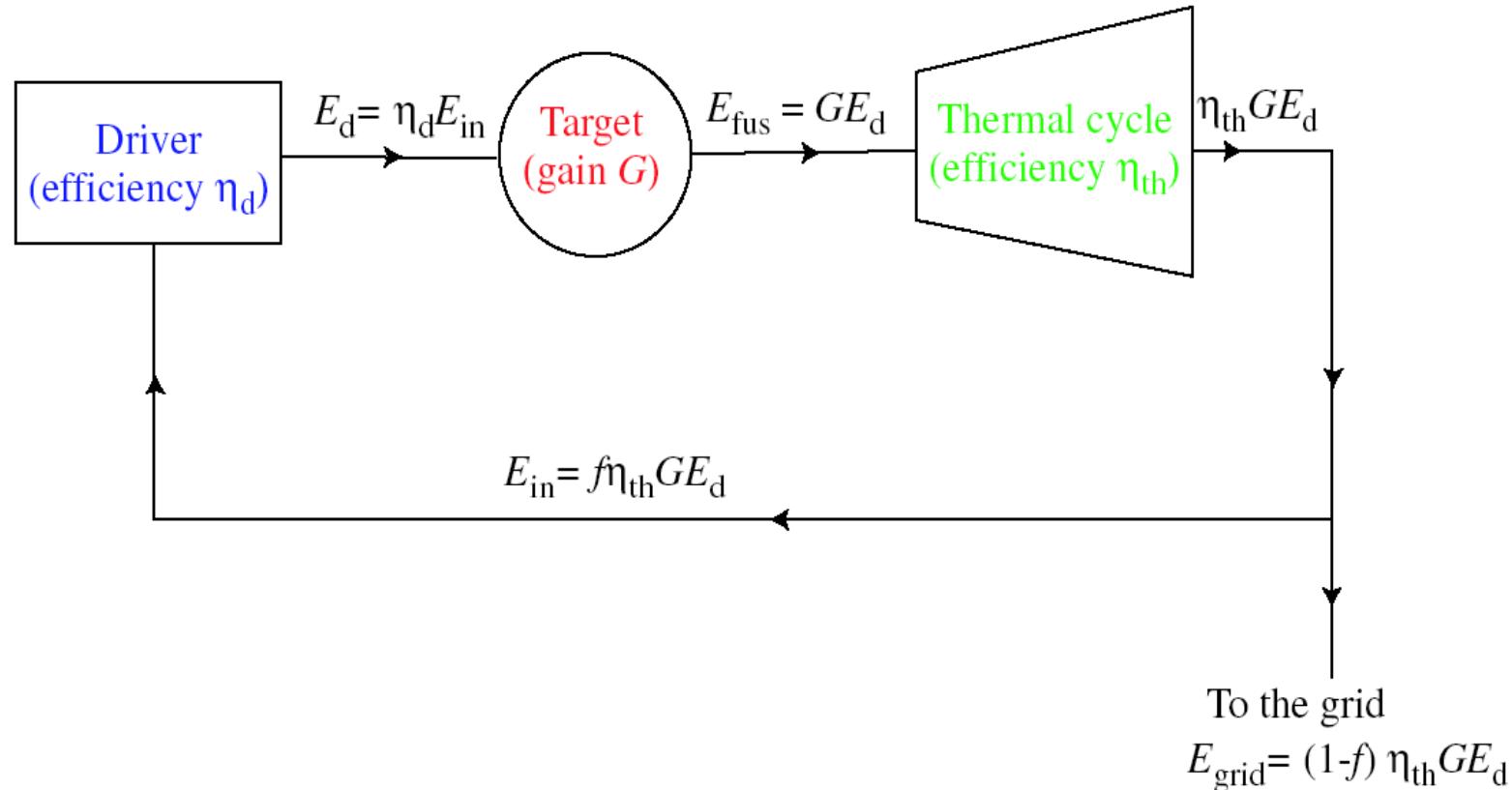
depending of the fuel mass:

$$u_{\text{imp}} \propto m^{-1/8}$$



The reactor cycle: high target energy multiplication (gain) required to overcome cycle inefficiencies

$$G \eta_D > 10$$





The essential physical ingredients of ICF

(homogeneous sphere of DT, radius R , density ρ)

- **COMPRESSION:**

burn fraction $\Phi = \rho R / (\rho R + 7 \text{ g/cm}^2)$

$\Phi > 20\% \implies \rho R > 2 \text{ g/cm}^2$

mass $m = (4\pi/3)\rho R^3 = \text{few mg} \implies \rho > 200 \text{ g/cm}^3$

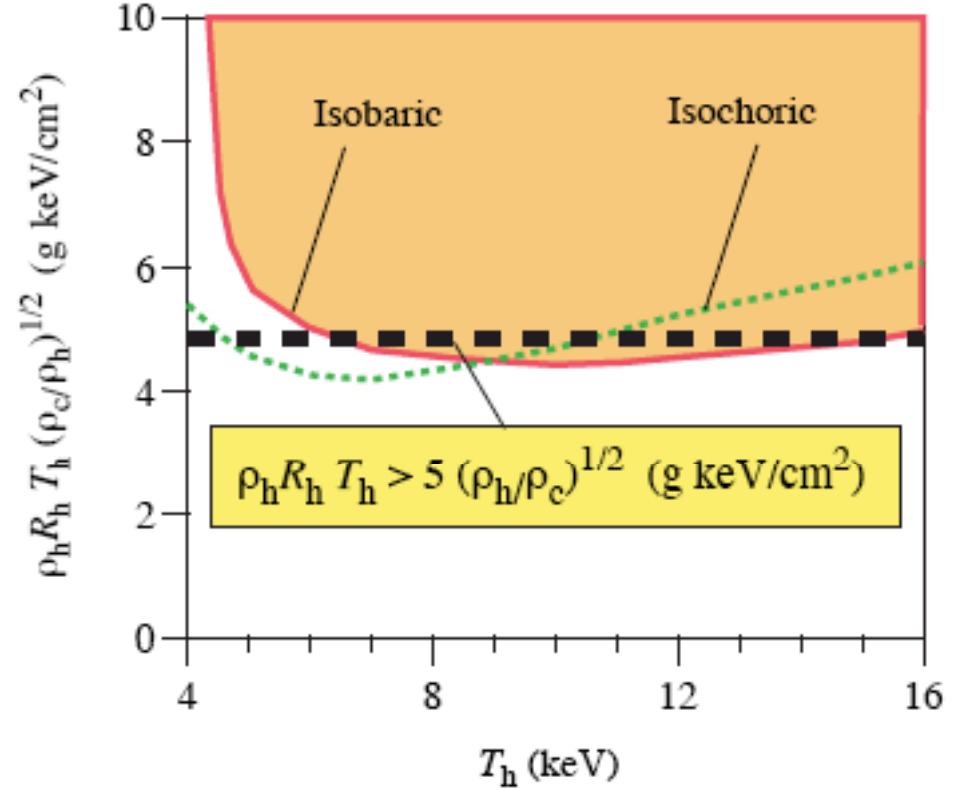
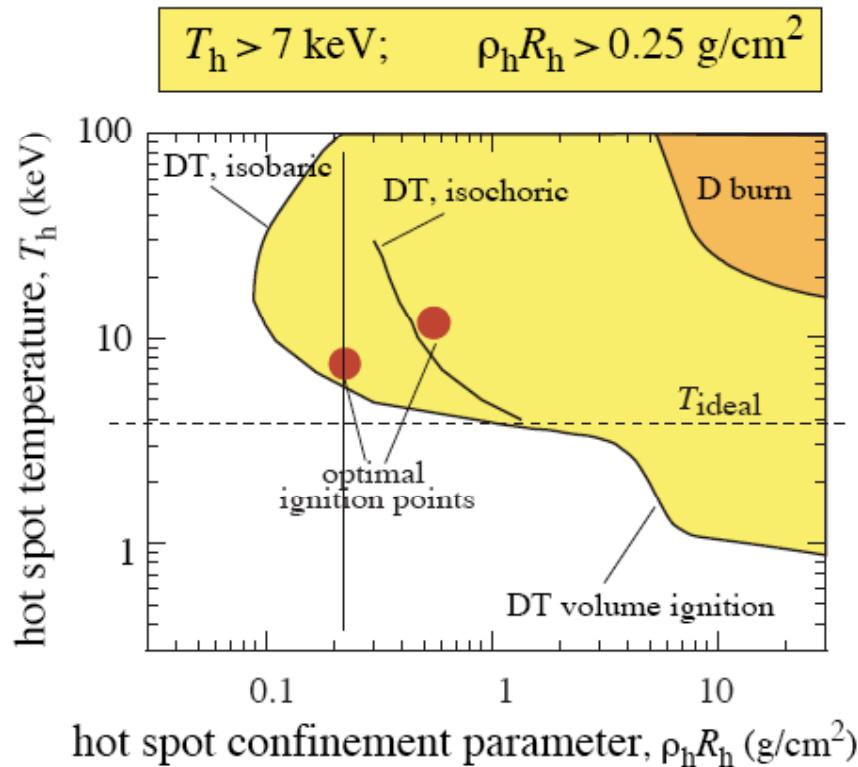
- **HOT SPOT IGNITION**

do not heat the whole fuel to 5 keV

heat to 5 – 10 keV the smallest amount of fuel capable of self heating and triggering a burn wave



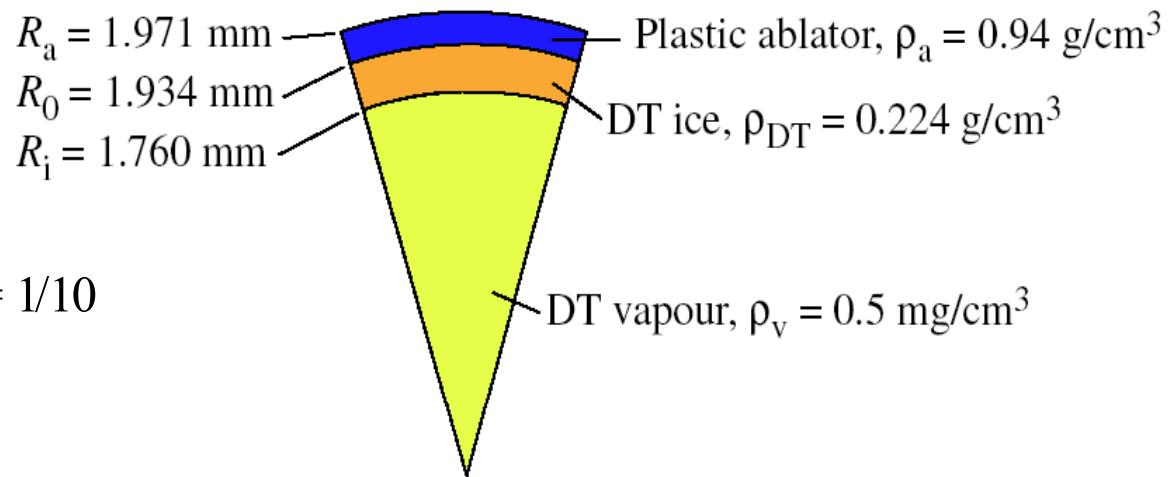
Hot spot ignition condition: Lawson-like and $n\tau T$ (or ρRT) criteria



Hollow shell target, irradiated by a large number of overlapping beams

Target (hollow shell)

- Fuel mass: few mg
- Radius: 1 – 3 mm
- Fuel radius / thickness = 1/10

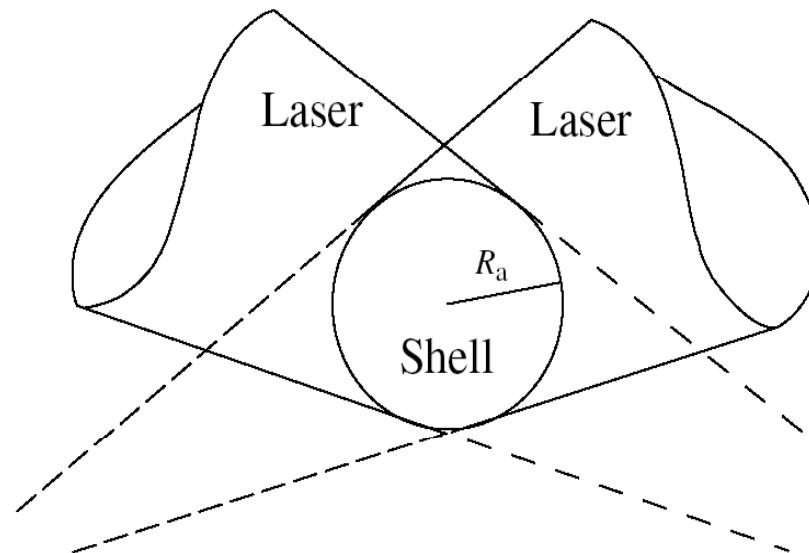


Laser pulse

- Energy: 1 – 5 MJ
- Duration: 10 – 20 ns
- Peak power: 300 – 500 TW
- Peak intensity: 10^{15} W/cm^2
- Wavelength: $(1/4) – (1/3) \mu\text{m}$

Compressed fuel

- Density: 200 – 1000 g/cm^3
- Low average entropy,
but hot-spot with $T = 10 \text{ keV}$



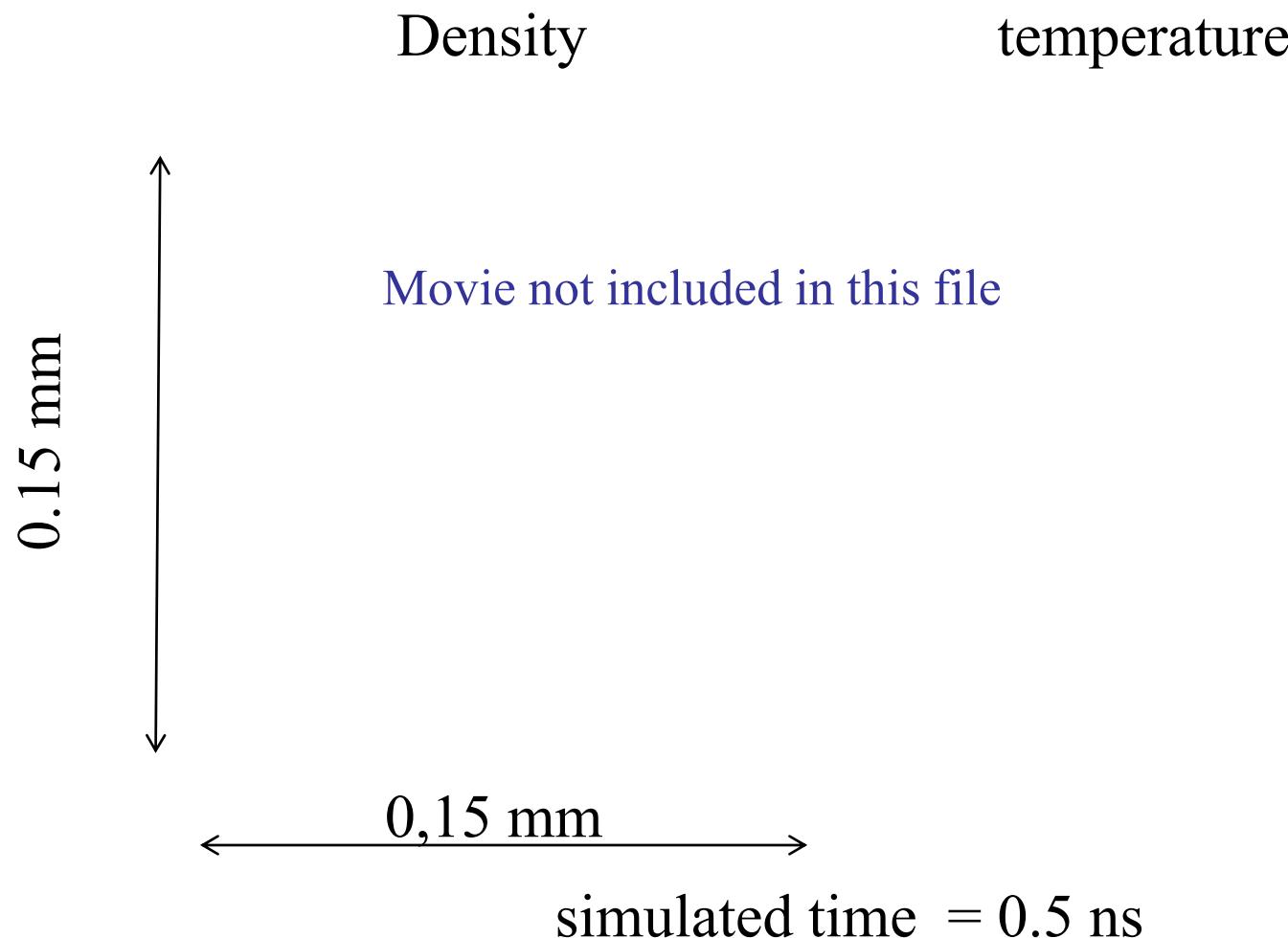
Irradiation, implosion, compression, ignition & burn

(shell with 1.67 mg of DT fuel, irradiated by 1.6 MJ pulse, see later)

Movie not included in this file



Zoom (in space and time): final compression, ignition, burn and explosion





Implosion concentrates energy in space, multiplies pressure, but four key issues

1. couple efficiently driver energy to the target, to achieve adequate imposition velocity
2. use efficiently the coupled energy to compress the fuel
3. mantain nearly spherical symmetry (small, central hot spot to be created)
4. limit dangerous effects of Rayleigh-Taylor instabilities (RTI)

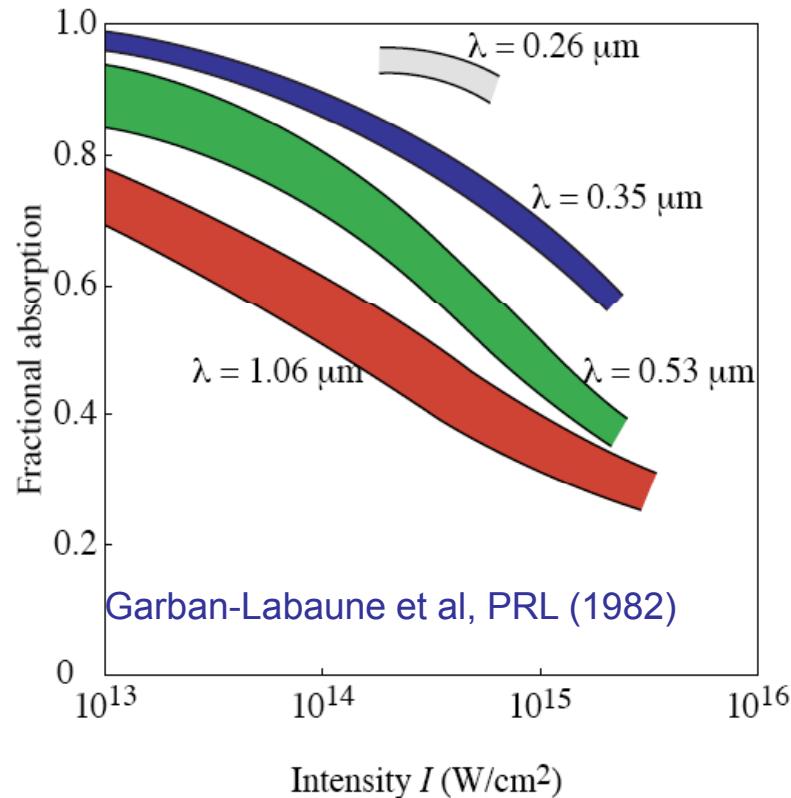




1st issue: coupling laser light

- use short laser wavelength (e.g. $\lambda = 0.35 \mu\text{m}$)
- limit intensity I to 10^{15} W/cm^2
=> use hollow shell target, instead of sphere

good absorption in the collisional regime, at short wavelength



$$p \propto (I/\lambda)^{2/3}$$

$$@ I = 10^{15} \text{ Wcm}^2 \\ \lambda = 0.35 \mu\text{m}$$

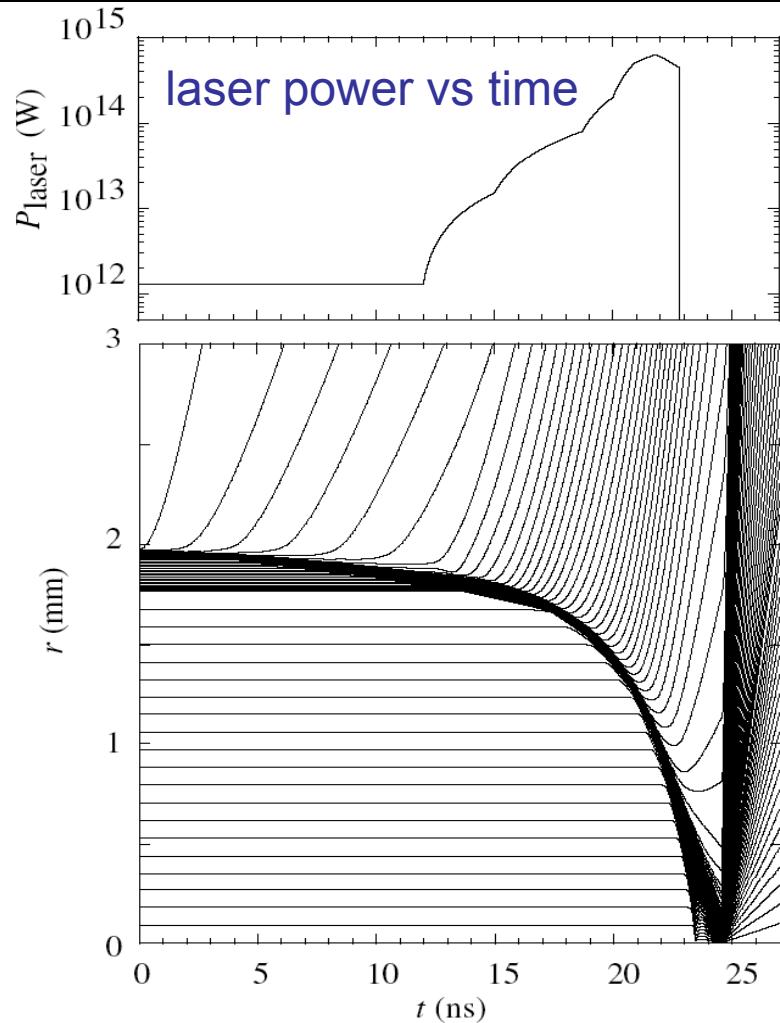
$$\text{pressure } p = 80 \text{ Mbar}$$



2nd issue: compress efficiently

do not heat before compressing =>

- no “preheating” by fast particles, hard X-rays
- tune the pulse, to reach high pressure gradually



“Pulse shaping”

Laser power carefully tuned, to launch a sequence of properly timed shocks, that approximate adiabatic compression

1-D
“Flow chart”

we want $\alpha = p(\rho, T)/p_{\text{Fermi}}(\rho)$ as small as possible



3rd issue: symmetry: irradiate as uniformly as possible

long scale shape of compressed fuel depend
on driving pressure non uniformity

$$\frac{\Delta R}{R} = \frac{\Delta u_{\text{imp}}}{u_{\text{imp}}} = \frac{\Delta p}{p} \cong \frac{2}{3} \frac{\Delta I}{I}$$

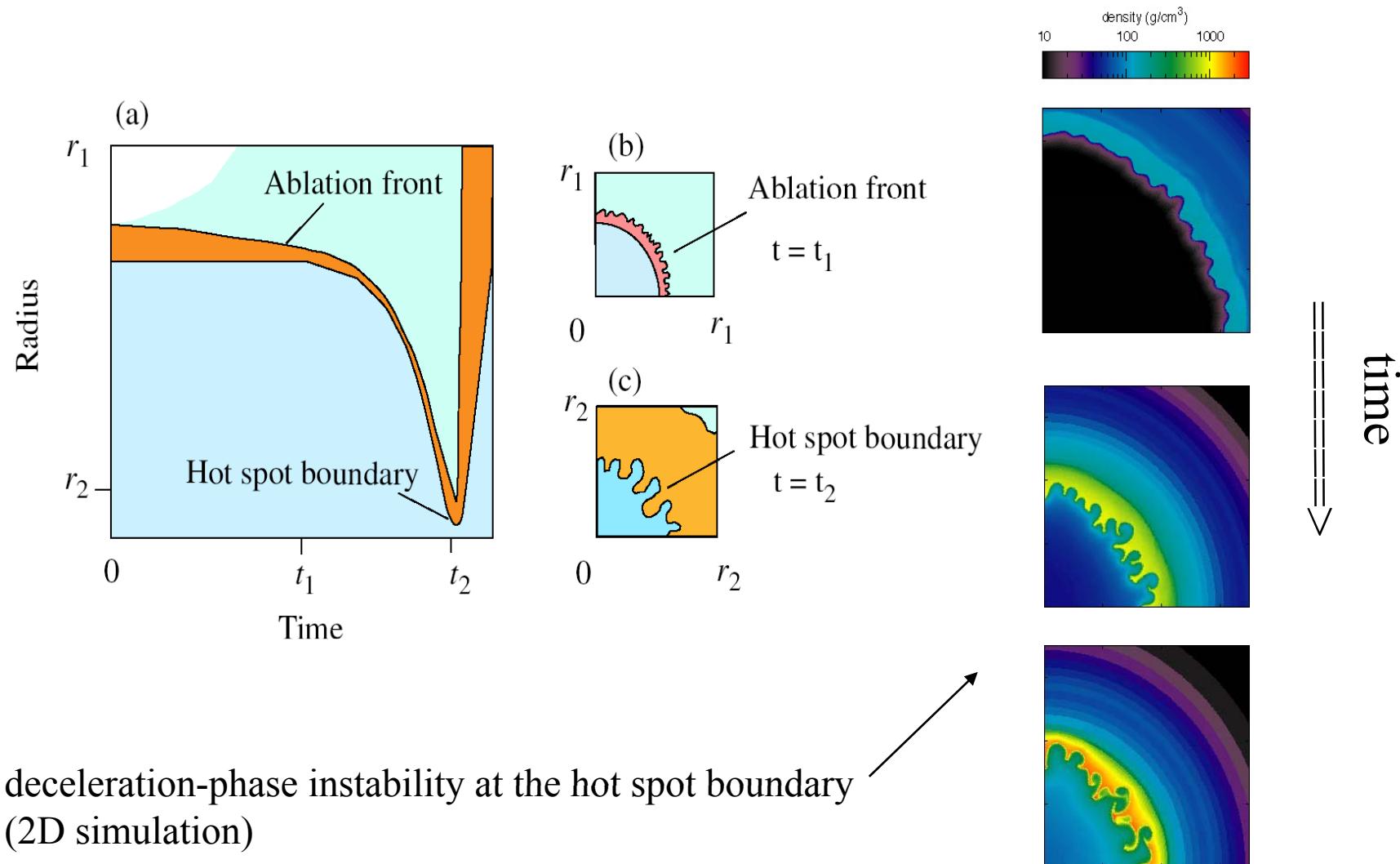
we want hot spot relative deformation $\Delta R_h/R_h \ll 1$

but R_h is typically 1/30 of the initial radius

$\implies \Delta I/I \ll 1/20$; \implies we request $\Delta I/I < 1\%$



4th issue: Rayleigh-Taylor instability unavoidable in inertial fusion



Movie not included in this file



4th issue: limit Rayleigh-Taylor instability (RTI)

RTI unavoidable.

To reduce effects

- limit seeds:
 - target defects,
 - short-scale irradiation non-uniformity
- choose less unstable regime (increase ablation velocity)
- limit implosion velocity (trade-off with ignition energy)

Rayleigh-Taylor instability hinders hot spot formation and ignition
(multimode perturbation with rms amplitude at the end of the coasting stage = 1.5 μm)

Ion temperature (eV) map evolution

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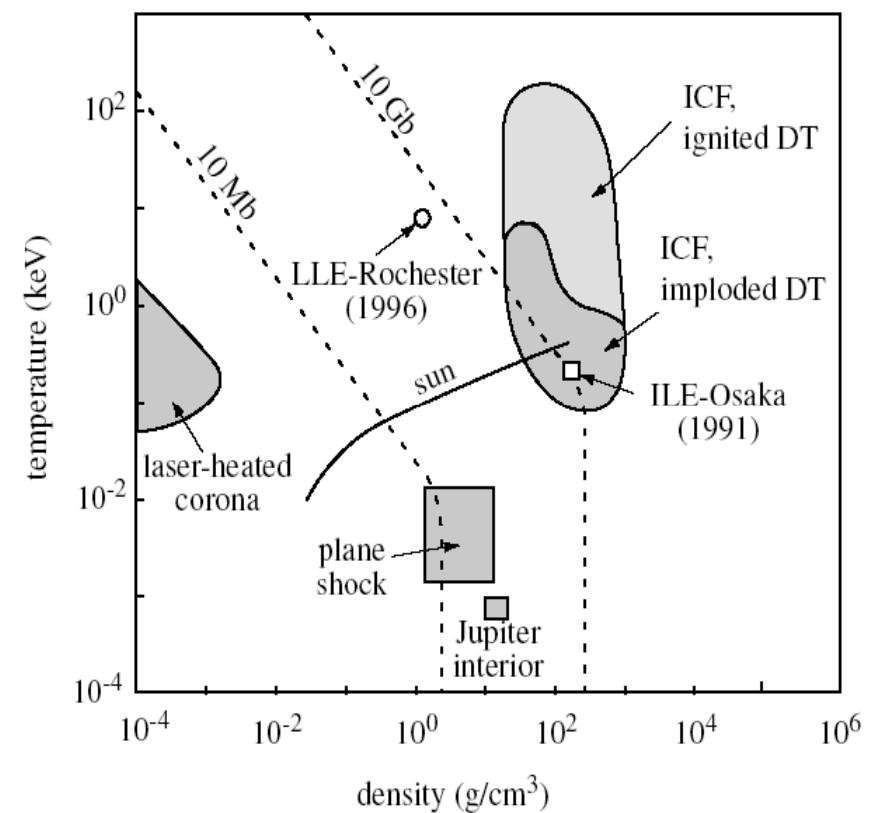
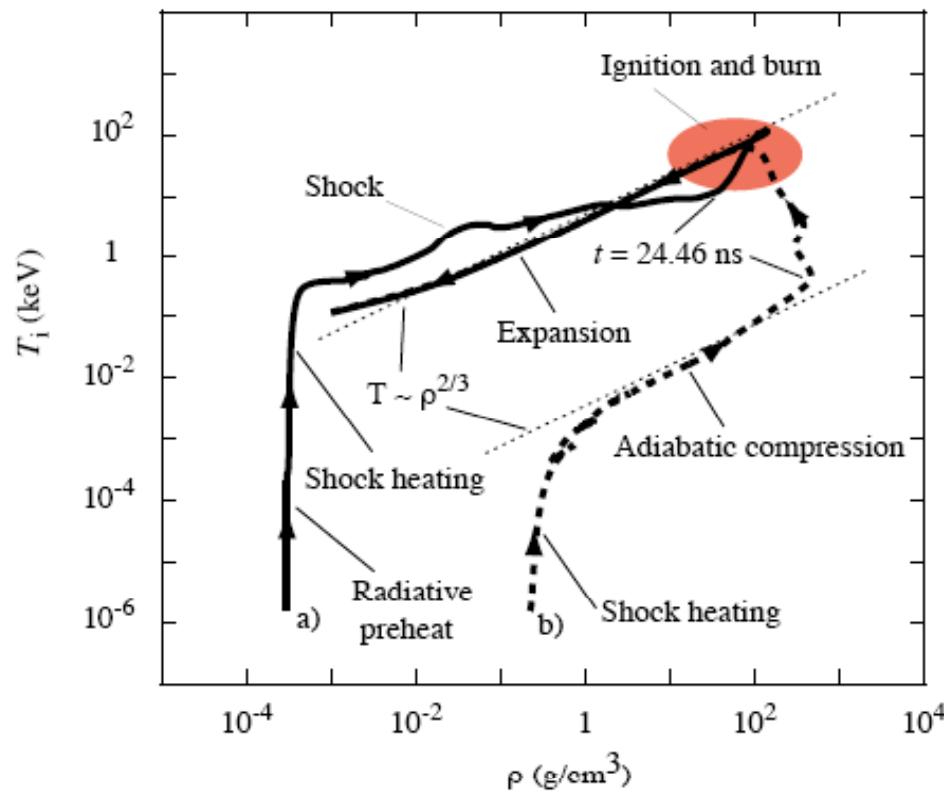
A too large initial corrugation
amplified by RTI, makes hot spot formation impossible

Ion temperature (eV) map evolution

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ICF involves extreme values of temperature, density and pressure

same conditions as at the center of the sun
already achieved 18 years ago



Inertial confinement fusion

A variety of basic physics processes and of space- and time-scales

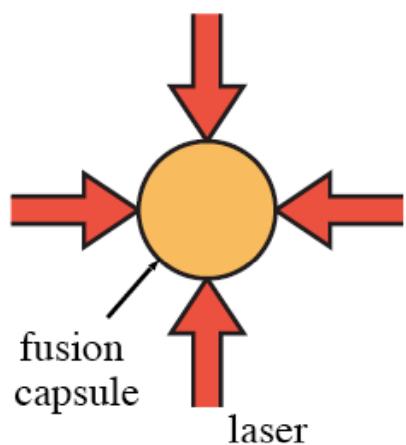
- Laser – matter (plasma) [or particle-beam – plasma] interaction
 - Plasma physics (including non-ideal plasma, partially degenerate plasma, partial ionization)
 - Phase transitions (from cryogenic matter to hot plasma)
 - Transport processes
-
- Radiative transfer
 - Fusion reactions and product (charged products and neutrons) transport
-
- Mass density: $10^{-6} – 10^3 \text{ g/cm}^3$
 - Temperature: $10 – 3 \times 10^9 \text{ K}$
- Time scales:**
- Implosion: few – 30 ns
 - Ignition: few – 100 ps
 - Fluid instabilities: 0.1 – 1 ns
- Space scales:**
- Target size: few mm
 - Compressed fuel: 0.1 mm
 - Density scale-lengths: down to 1 μm
 - Fluid modes: down to μm
 - Plasma instabilities: Debye length, skin depth



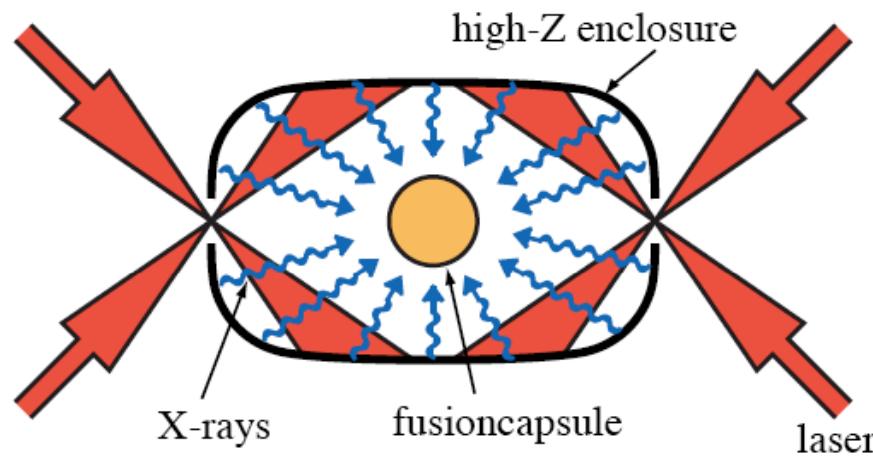
direct drive and indirect drive

In indirect drive, the fuel containing capsule is irradiated by thermal X-rays (200-300 eV), generated and confined in a cavity (a hohlraum).

a) direct-drive



b) indirect drive





Why indirect-drive?



Pros:

- long scale **irradiation uniformity** weakly dependent on beam disposition
- **smooth radiation field** on short scales
- **RTI less violent than in direct drive**,
due to much higher ablation velocity (linear growth rate $\gamma = (ak)^{1/2} - k u_{abl}$,
with a: acceleration, k mode number, u_{abl} ablation velocity = areal mass
ablation rate/density)

Con: lower coupling efficiency

(laser => X-rays => capsule, with loss to generate the radiating plasma, loss from the hole, loss of X in the hohlraum wall)



NOVA (LLNL),
il più potente laser degli
anni '80

(impulsi fino a 50 kJ)



Diagnostiche (I)

plasmi da studiare:

$$\rho \approx 1\text{-}1000 \text{ g cm}^{-3}$$

$$T = 0.01 - 20 \text{ keV}$$

$$L = \mu\text{m} - \text{mm}$$

risoluzione necessaria

- $\Delta x = \mu\text{m}$
- $\Delta t = \text{ps}$

misure di densità, temperatura, “forma”, posizione,
parametro di confinamento



Diagnostiche (II)

- spettroscopia ottica e X
 - backlighting ottico => streak
 - backlighting X => streak
 - scattering Thomson
 - emissione di neutroni e imaging neutronico
 - imaging con protoni veloci (emessi da altro laser-plasma)
-



Fisica: problemi e risultati (I)

- assorbimento, pressione ablativa, velocità di imposizione:
OK, limitando l'intensità del laser ($\leq 10^{15} \text{ W/cm}^2$)
e operando a $\lambda \leq 0.35 \mu\text{m}$
 - raggiunte le velocità e pressioni necessarie
 - simmetria: controllo possibile, con accurato posizionamento dei fasci
 - stabilità: con opportune scelte progettuali si può limitare la crescita dell'instabilità di Rayleigh-Taylor, RTI (previsto dalla teoria, confermato da simulazioni, poi verificato sperimentalmente); è comunque necessario limitare drasticamente la disomogeneità e le irregolarità superficiali dei bersagli
-



Fisica: problemi e risultati (II)

- performance record (con laser a impulsi da 50 kJ):
 - densità: $1000 \times$ densità solido
 - resa neutronica in accordo con previsioni di codici che includono mescolamento indotto da RTI.
 - pressione di ablazione > 100 Mbar
- qualche incertezza ancora su possibili effetti negativi delle instabilità parametriche (scattering Brillouin, Raman) che comunque si debbono evitare
- Si riuscirà a limitare il mescolamento indotto da RTI?
 - $\rho R = 0.2 \text{ g/cm}^2 \implies$ per arrivare ai valori richiesti per l'ignizione è necessario aumentare l'energia laser di un fattore 10-30



Prossimo passo: IGNIZIONE: su quali basi?

- I risultati sperimentali sommariamente citati
 - Le simulazioni numeriche (che riproducono gli attuali esperimenti con buona precisione) e consentono di progettare in modo “affidabile” nuovi esperimenti
 - La consapevolezza che, su scala maggiore, lo schema funziona
 - La disponibilità di tecnologia laser, di strumentazione, etc.
-



Ready to test ignition (NIF, LMJ)

(for reviews: Lindl, *PoP* 1995; Lindl et al, *PoP* 2003;
for more recent results: May issues of *PoP*, 2004-2009)



- understanding and ability to control all four above issues demonstrated
(expts at NOVA, OMEGA)
 - required drive temperature, pressure demonstrated
 - simulations predict experiments (when RTI mix is included)
[still some uncertainties from laser-plasma interactions, RTI mix]
 - diagnostics suitable for nuclear environment, large ρR developed
 - design based not only on extrapolation, but also on interpolation
(@low energy: data from lasers; @ large energy: from explosions)
 - cryogenic targets developed
-

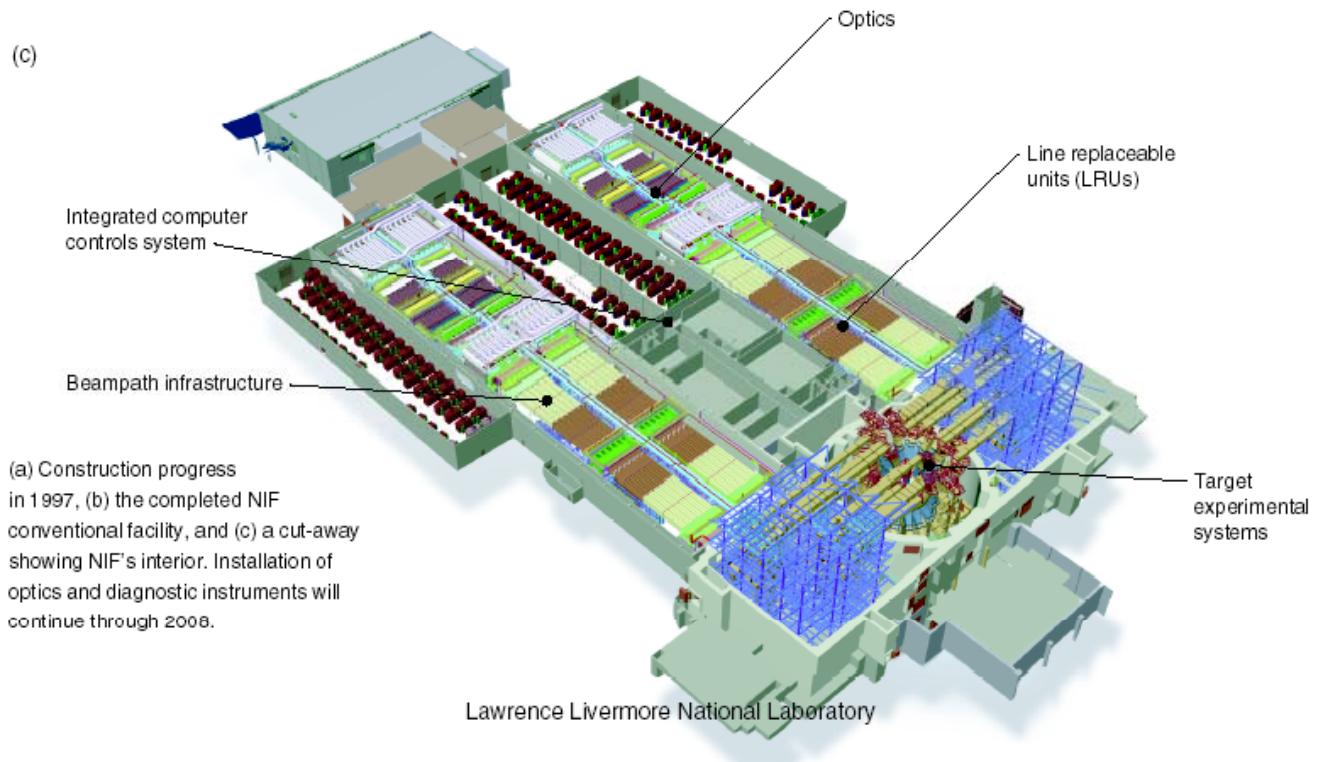
National Ignition Facility, NIF (LLNL, USA)

- laser a vetro:Nd, con triplicazione di frequenza
 - energia totale per impulso: 1.8 MJ ($\lambda = 0.35 \mu\text{m}$)
 - potenza di picco: 500 TW
 - 192 fasci, focalizzabili con errore $< 50 \mu\text{m}$
 - potenza (di ciascun *bundle* di fasci) programmabile nel tempo (range dinamico 1:100);
 - funziona un pò meglio delle specifiche di progetto!
(review NIC-JASON, La Jolla, 14-16 gennaio 2009)
 - costruita fra il 1998 e il 2009; oggi operativa al 50% della potenza; opererà a piena potenza dall'estate 2010
 - costo: 4 G\$; finanziata dal Defence Program del DoE (ora dalla NNSA del DoE)
-



(from LLNL website)

NIF laser



NIF: un laser da 2 MJ per la fusione, costruito presso il Lawrence Livermore National Laboratory

filmato dal sito del LLNL, realizzato durante la costruzione (conclusa nel febbraio 2009)

Movie not included in this file

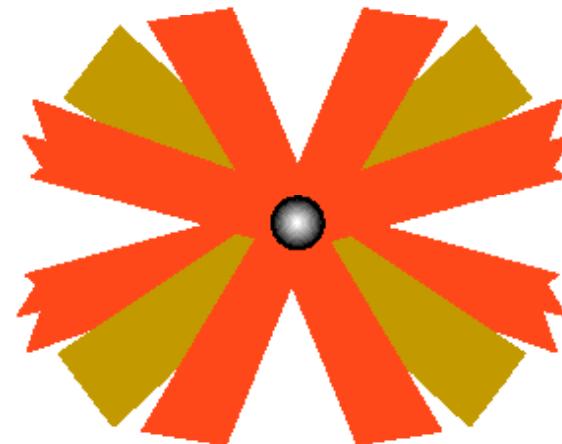
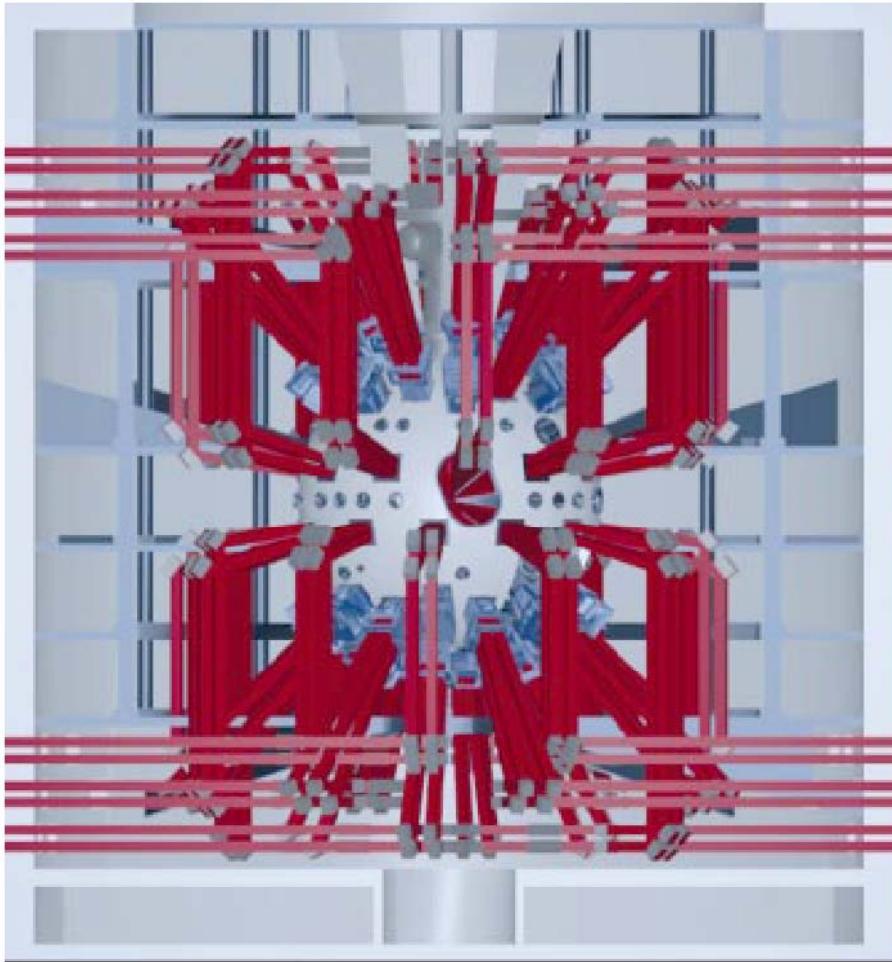
NIF: schema del laser

filmato dal sito del LLNI

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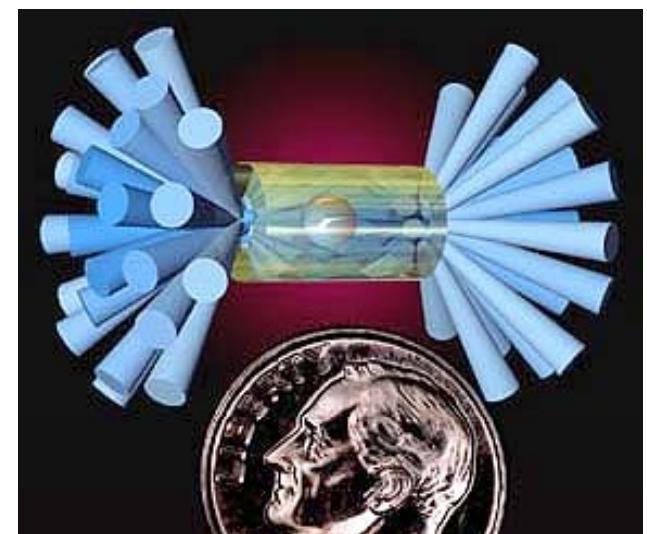
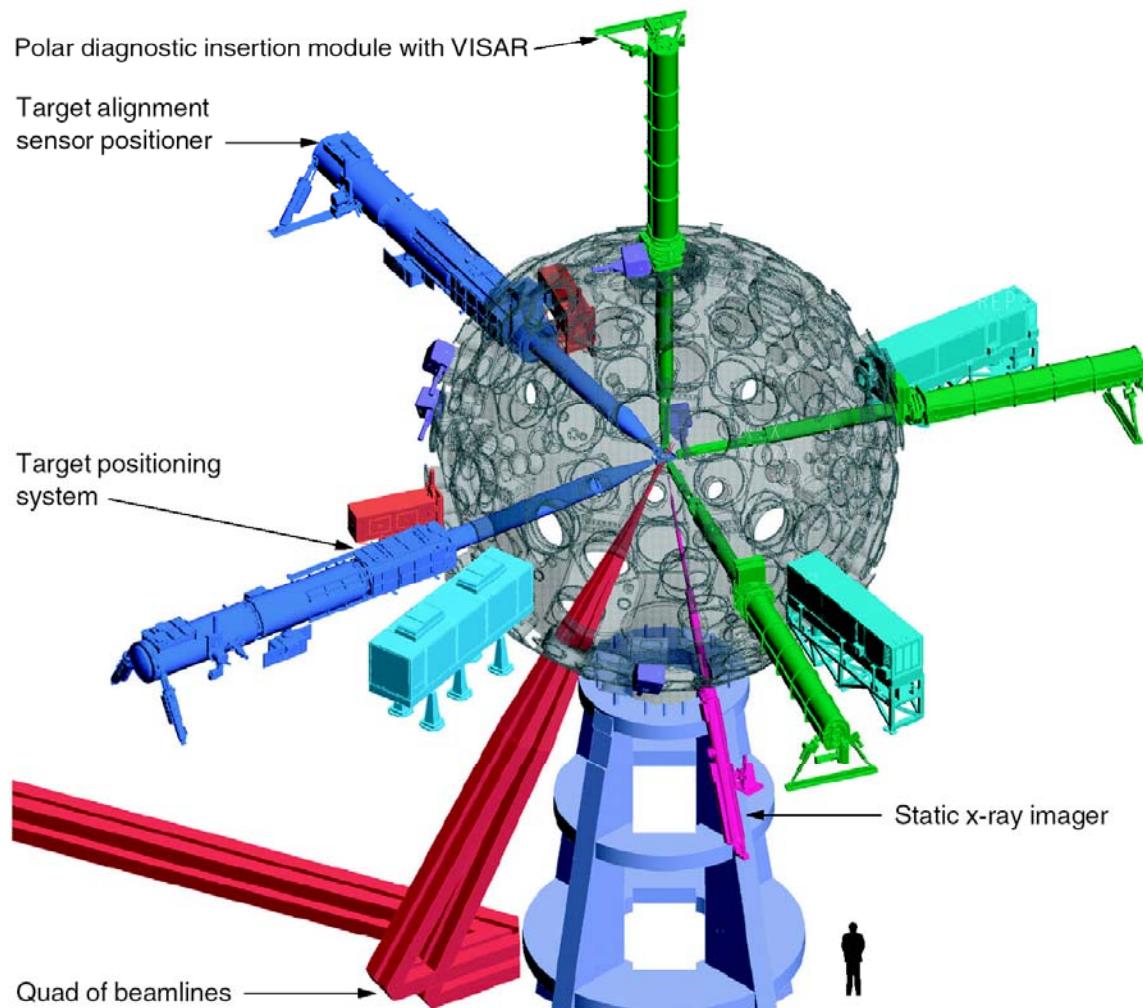
NIF: camera di reazione (diametro: 10 m)

dal sito del LLNL:





Camera di reazione, qualche diagnostica e bersaglio



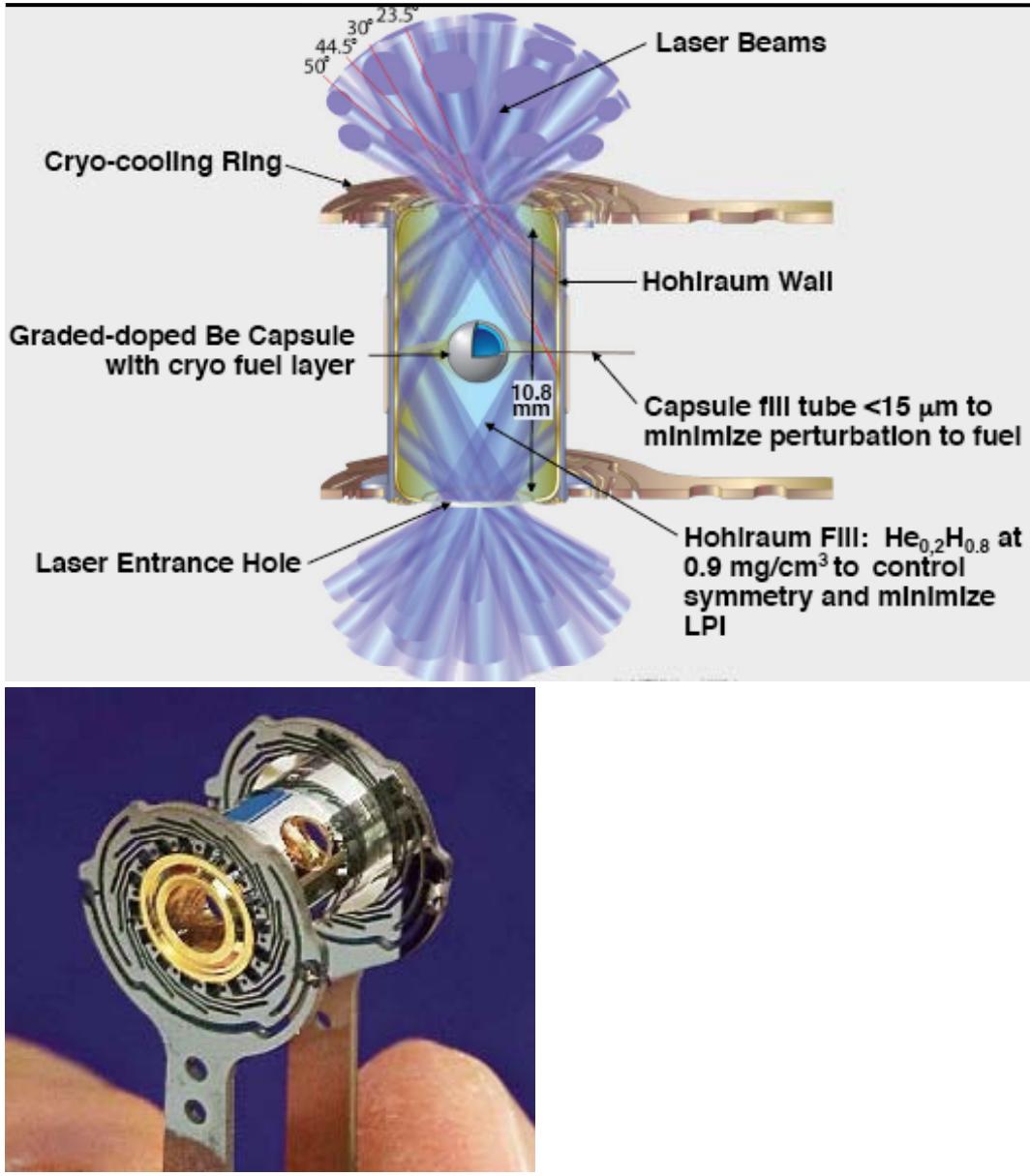
NIF main goal: demonstrating ignition, propagating burn and gain > 10

- indirect drive
- point design [see S. Haan *et al.*, *PoP* **12**, 056316 (2005)]
 - pulse energy: 1.13 MJ
 - radiation temperature: 285 eV
 - implosion velocity: 380 km/s
 - isentrope parameter $\alpha = 1.46$
 - yield: 15 MJ

Next: hohlraum, capsule, pulse:

design vs four main issues discussed above

NIF hohlraum coupling & symmetry



symmetry control:

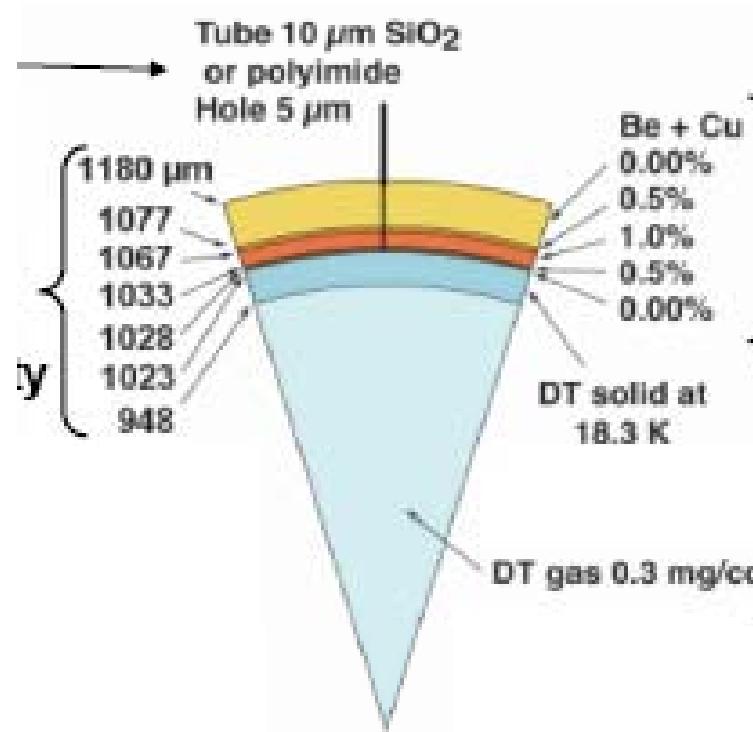
- beam orientation
- beam pointing
- hohlraum aspect ratio
- hohlraum fill

beam coupling: choice of materials

entropy control: cryogenic fuel

courtesy of LLNL

NIF capsule & pulse efficiency, entropy control, stability



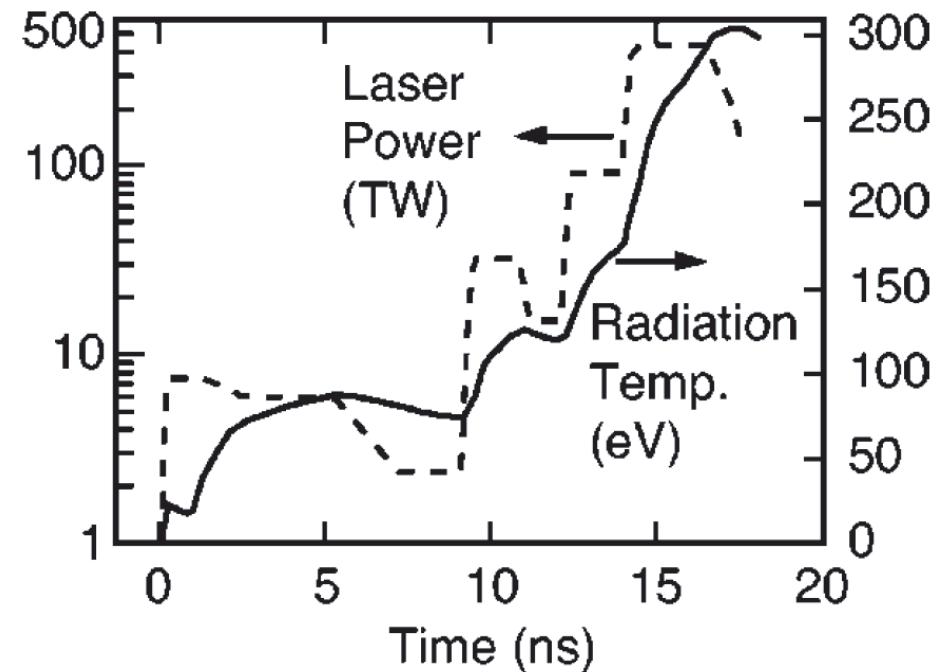
Be ablator: efficient absorber

Cu graded doping: to avoid preheat
to decrease instability

ultra-smooth surfaces: to minimize RTI seeds

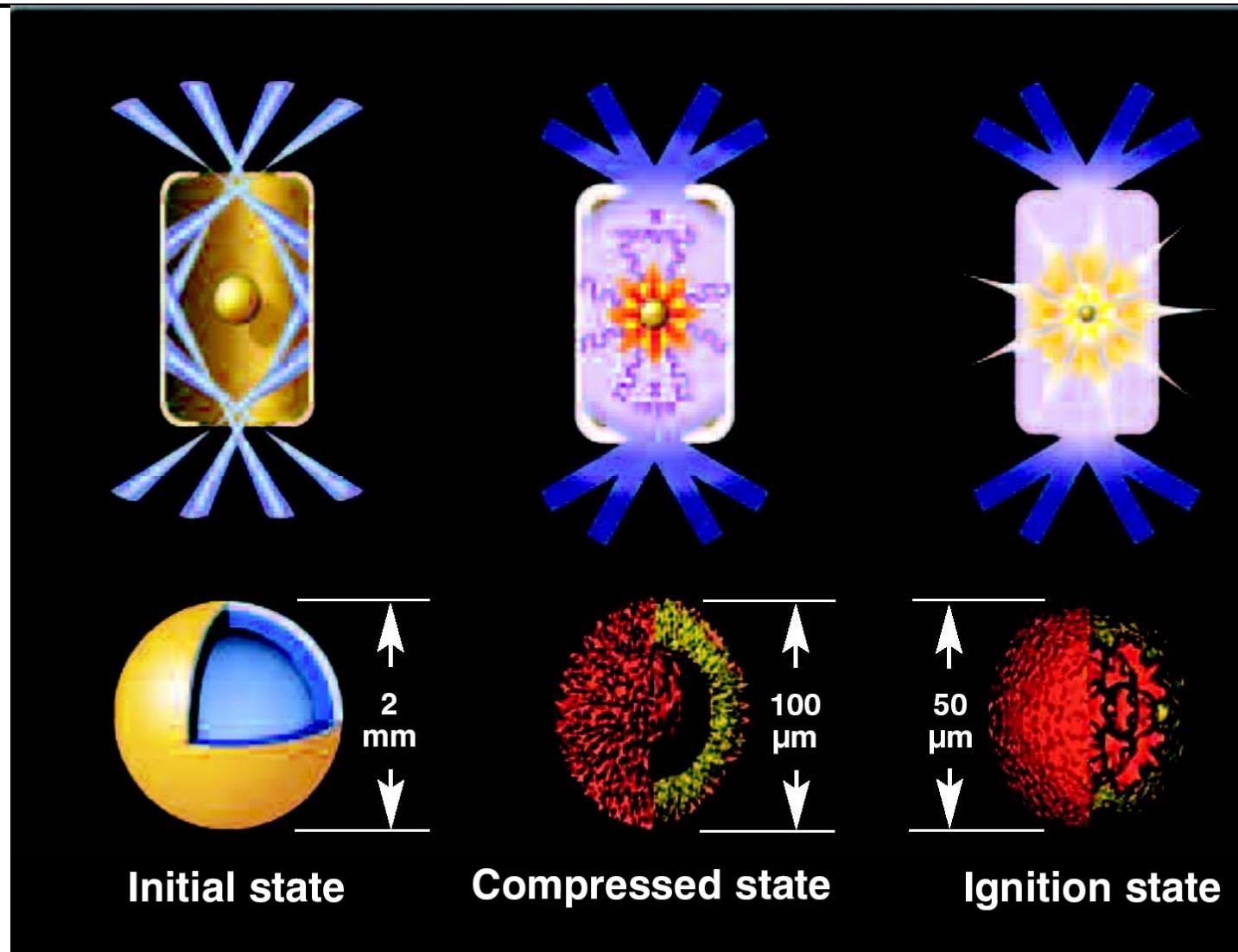
S. Haan *et al.*, PoP **12**, 056316 (2005)

pulse shaping to:
achieve $p > 100$ Mbar,
keeping entropy low



3D simulation of a NIF ignition experiment

S. Haan et al., *NF* 44, S171 (2004), courtesy of LLNL

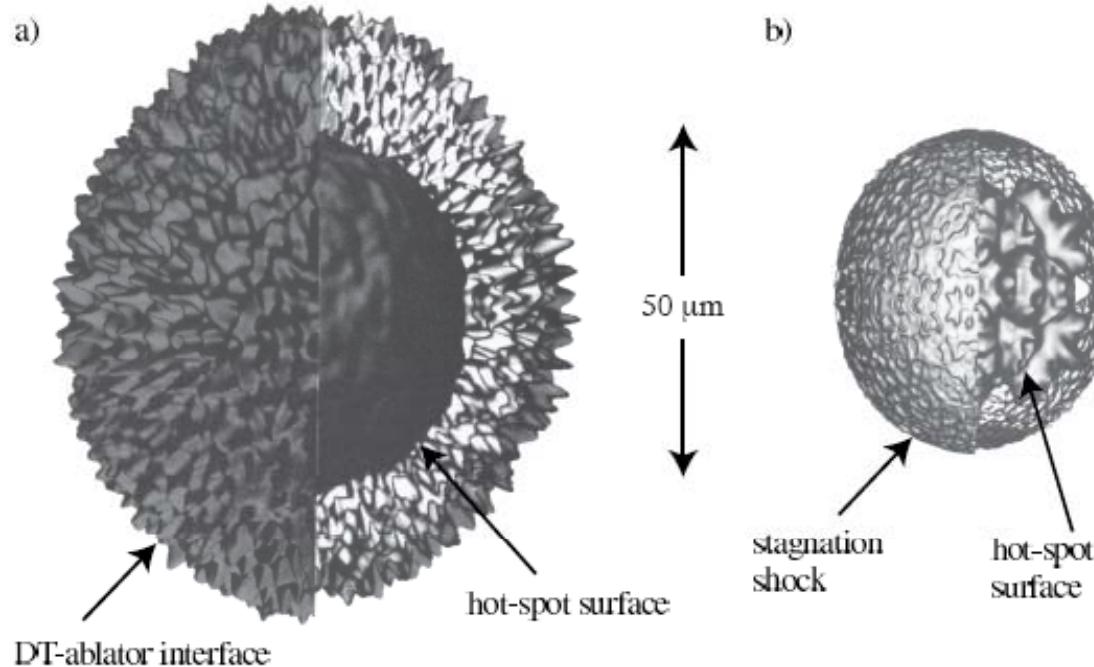


3D simulation of a NIF ignition experiment

S. Haan et al., *NF* 44, S171 (2004), courtesy of LLNL

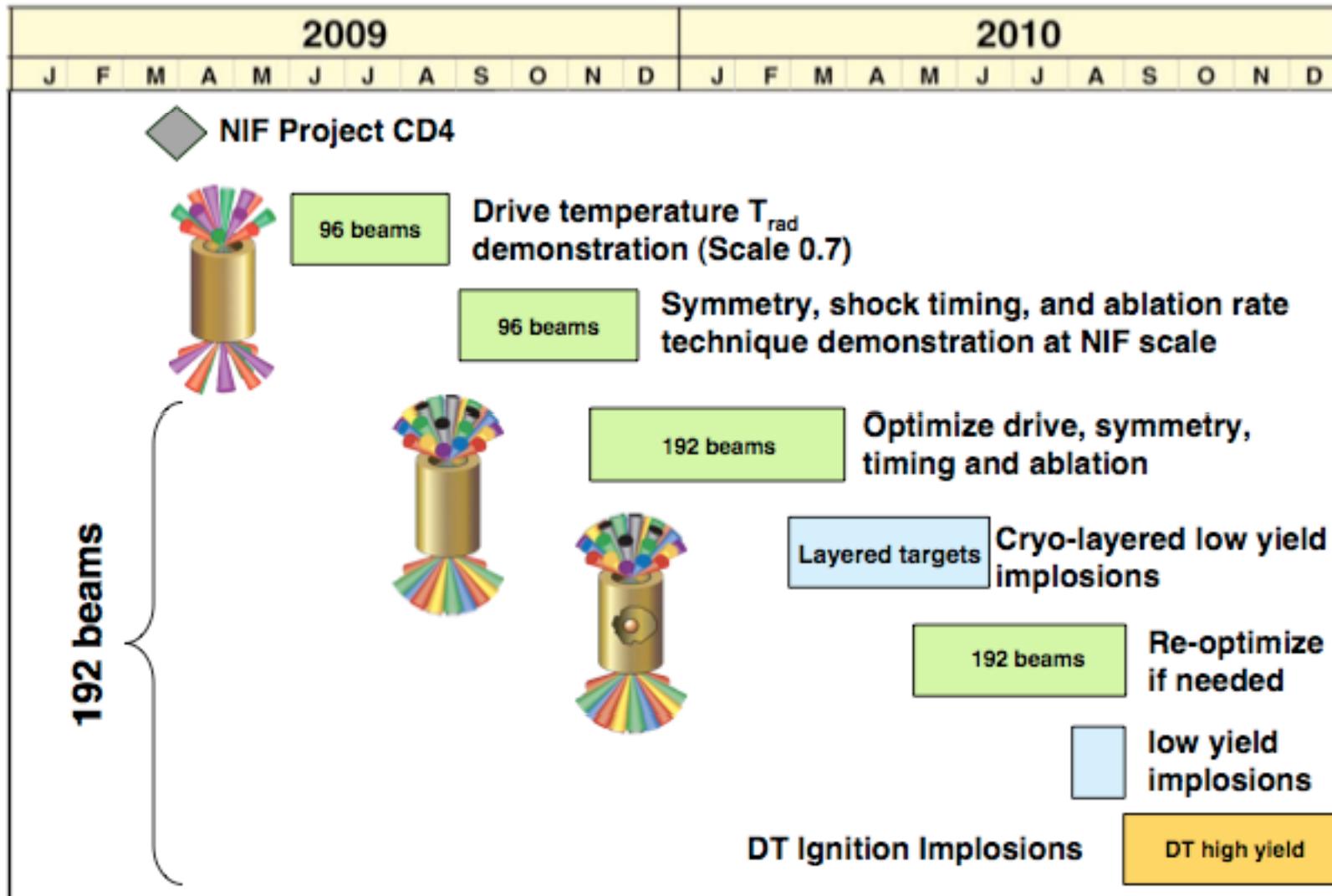
60 g/cm³ surfaces
140 ps before ignition

400 g/cm³ surfaces
at ignition



The National Ignition Campaign is focused on preparing for the first ignition experiments in 2010

NIC
The National Ignition Campaign



courtesy of LLNL



How does energy for ignition scale? Any room for ignition at smaller energy?

$$E_{laser} = \frac{E_{\text{central ignition}}}{\eta} M$$

- η : overall coupling efficiency=
absorption * X-conversion * transfer to capsule *
hydrodynamic efficiency

low, to reduce risks associated to asymmetries; can be improved (see, eg
L. Suter et al., *PoP* 2000)
 - M = (large) safety margin > 2

to reduce risks due to RTI induced mixing; could be reduced after
successful ignition
-

MJ energy required on NIF to reduce risks

- $E_{\text{fuel-1D}}^{\text{central ignition}} \propto \alpha^{1.8} u_i^{-5.9} p^{-0.8}$

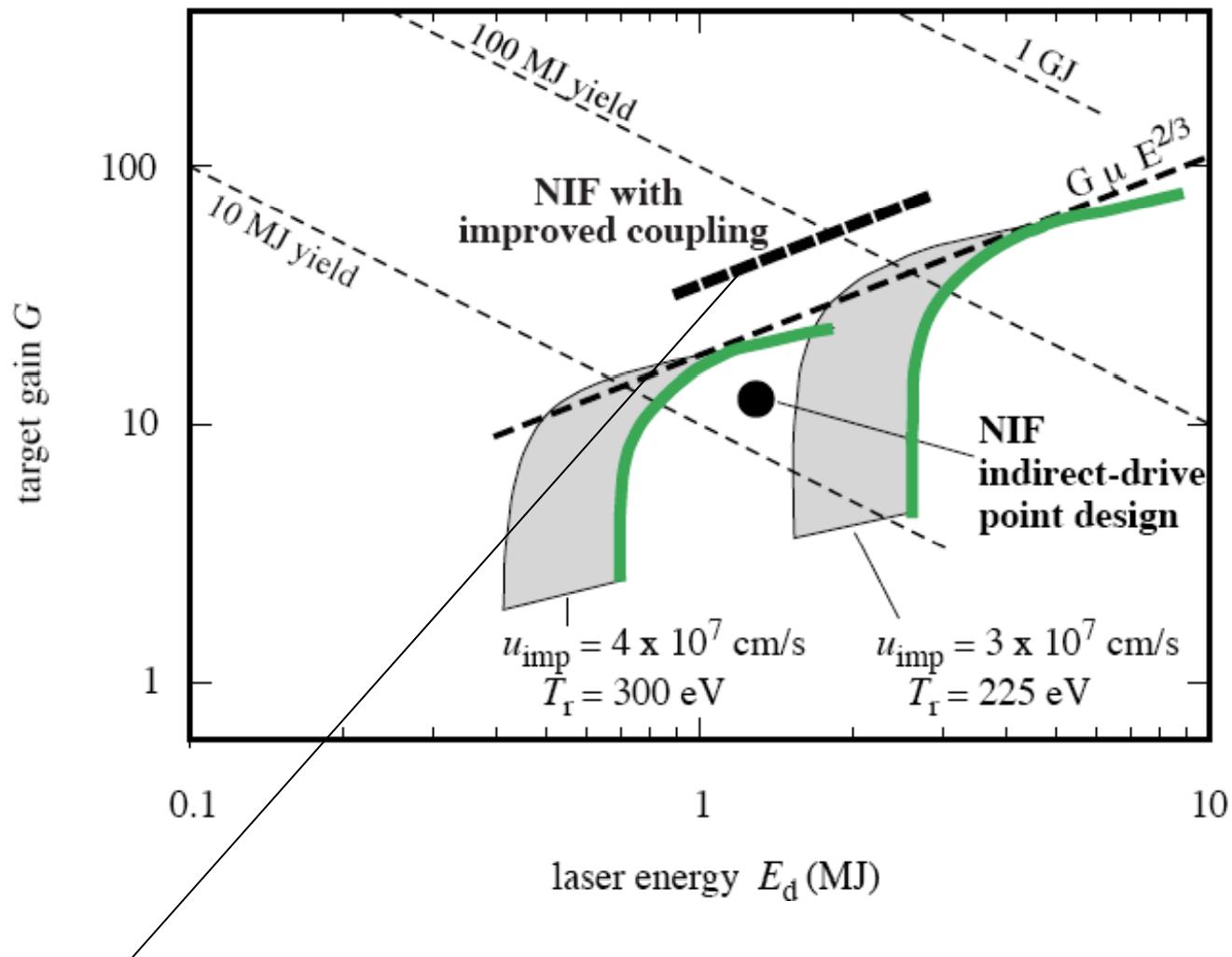
with α = isentrope parameter, little room for improvement

u_i = implosion velocity, limited to reduce RTI risks; small increase leads to major reduction of energy

p = ablation pressure,
limited to reduce laser-plasma instability risks

The NIF & LMJ original approach

Risk reduction ==> large pulse energy ==> low gain



Significant improvements may be possible, see Suter *et al.*, PoP 2000

Ignition at smaller laser energy ?

Higher gain?

Simpler targets?

NIF-LMJ designed 15 years ago; since then

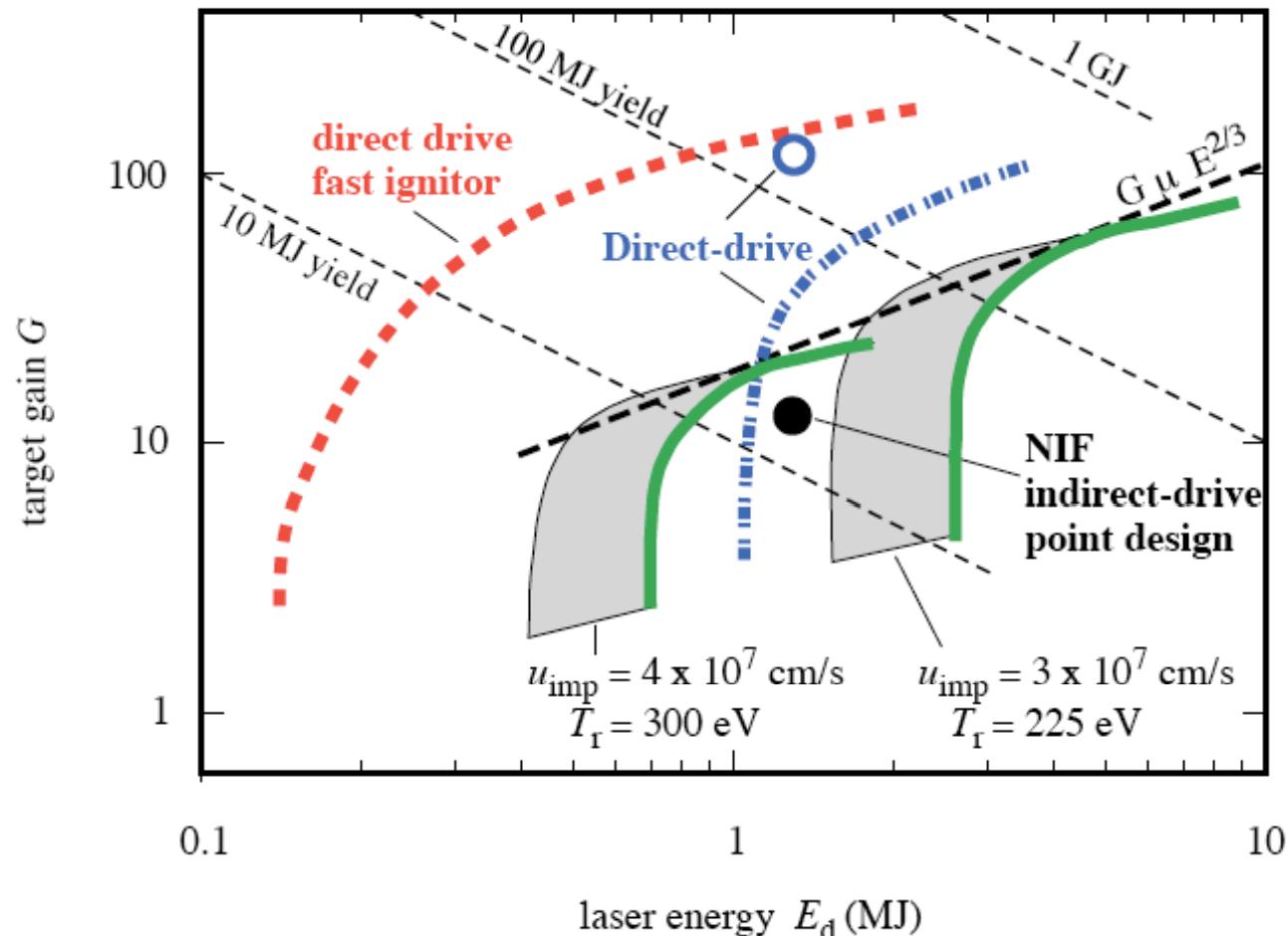
- laser progress:
 - smooth beams
 - ultraintense lasers
 - pulse shaping
- new ignition schemes (fast ignition, shock ignition)
- improved understanding of RTI

==>

- New options for direct-drive
and/or
 - Alternate approaches to ignition
-



Other schemes have potentials for higher gain





What's new for direct drive?

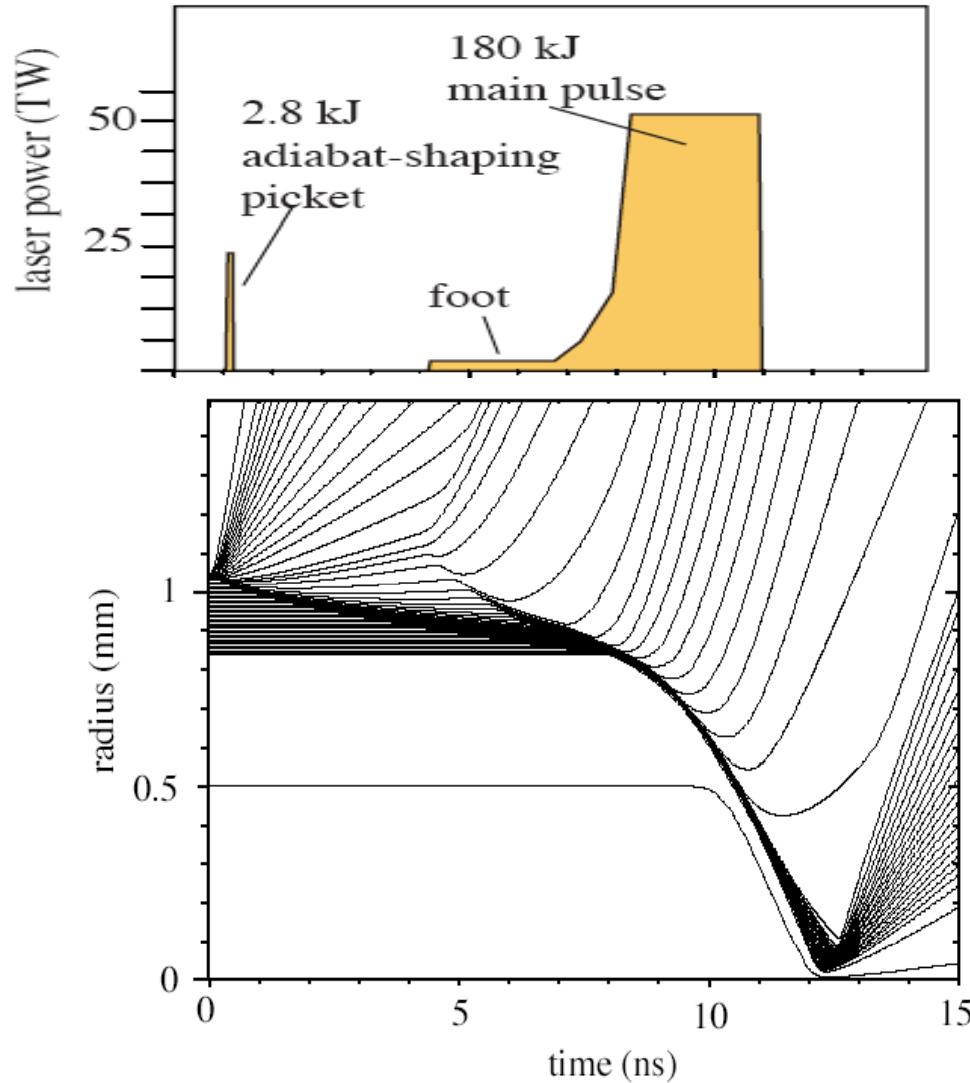
- beam smoothing techniques routinely implemented ==> RTI seeds reduced
- lasers with large number of beams manageable ==> symmetry
- understanding of ablative RTI (theory, simulations, expt.)
$$\gamma = (ak)^{1/2} - \beta k u_{abl},$$
with β dependent on flow and materials ==> choice of ablator materials
- adiabat shaping techniques (Bodner 2000, Anderson & Betti 2004, Goncharov et al 2003)
set to high entropy (lower density) the outer part of the shell
⇒ higher u_{abl} ==> less RTI,
while keeping very low the entropy of the inner fuel

==> direct drive target designs for both NIF and LMJ
(eg: McCrory et al.; Canaud et al.)

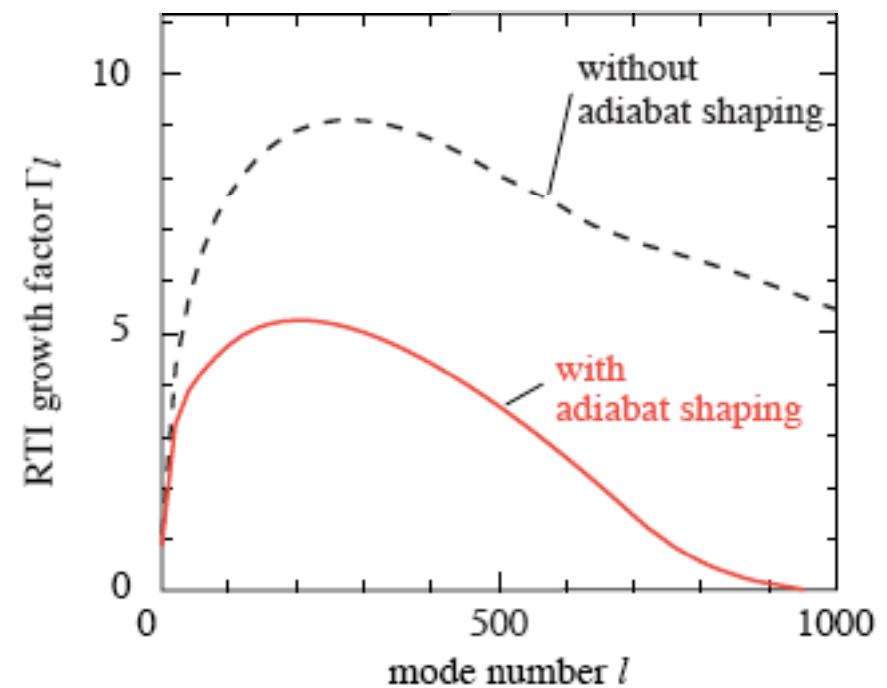
==> high gain direct drive targets proposed (eg, Bodner *et al.*, PoP 2000)



Adiabat shaping drastically reduces RTI growth ==> great opportunity for direct drive



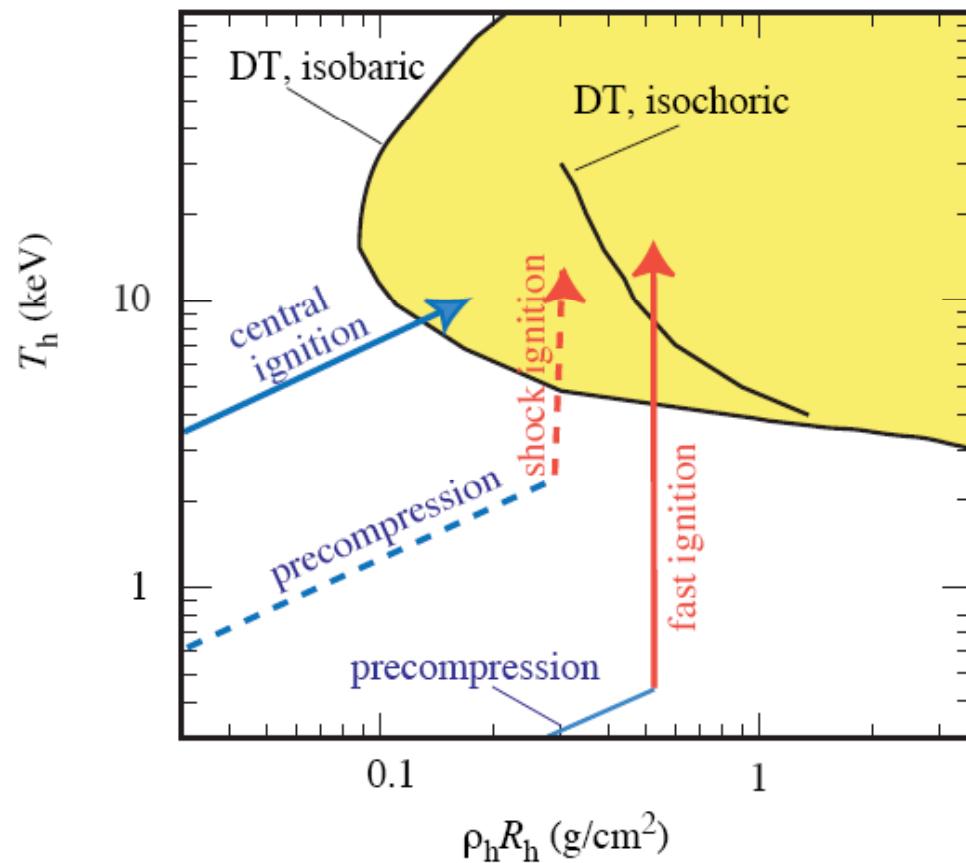
Atzeni, Schiavi, Bellei 2007,
confirmed by Olazabal et al
(private commun., yesterday)



adiabat shaping RX2 technique
(Anderson & Betti, 2004)



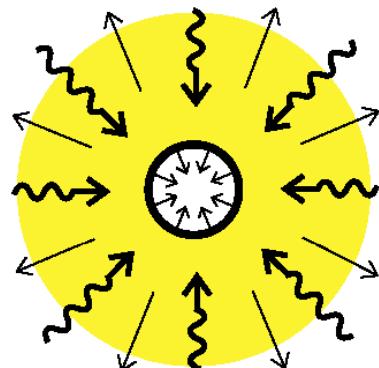
Alternative routes to ignition: separate compression & heating



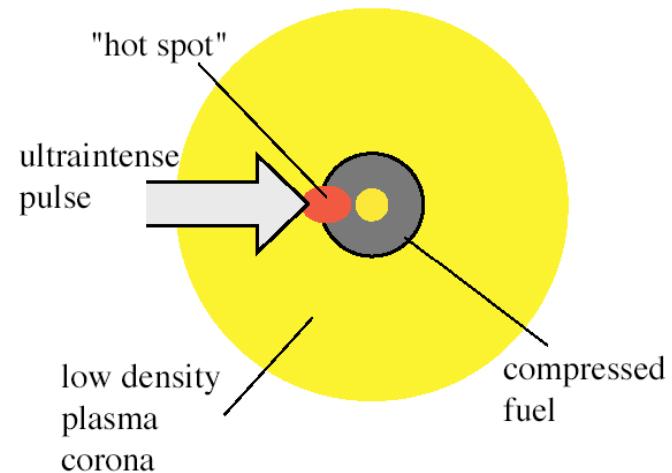


Fast ignitor

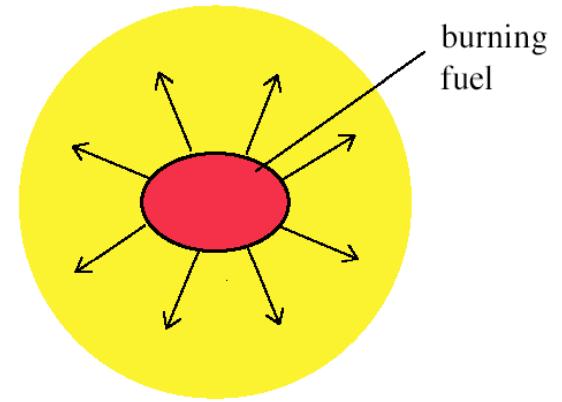
(a) and (b)
symmetric irradiation
and implosion



(c) hot spot generation by
an ultraintense pulse



(d) burn



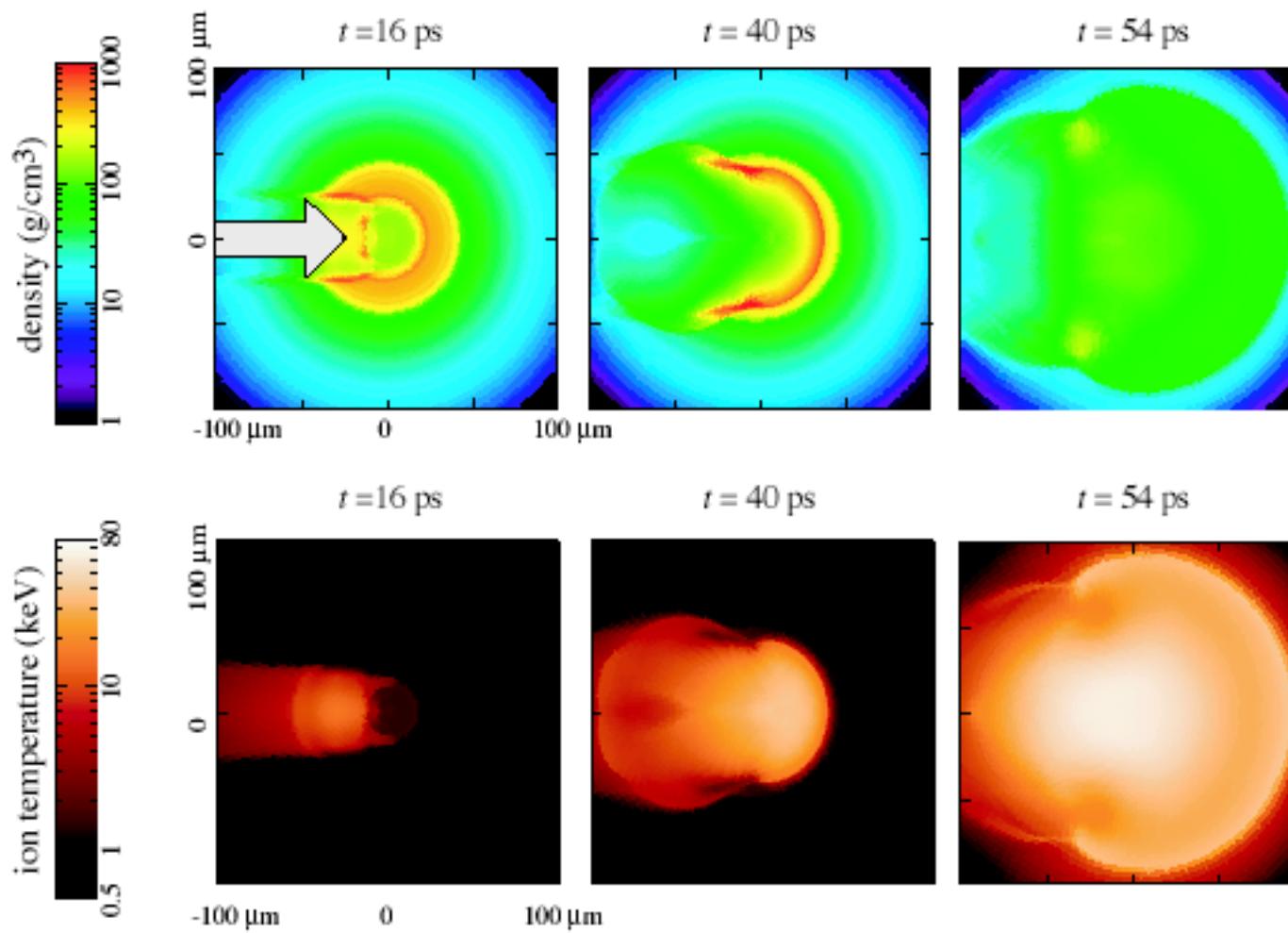
- Scheme: M. Tabak et al., Phys. Plasmas 1, 1626 (1994).
- Ignition mechanism: S. Atzeni, Jpn. J. Appl. Phys. 34, 1980 (1995)
- Ignition requirements: S. Atzeni, Phys. Plasmas 6, 3316 (1999);
S. Atzeni and M. Tabak, Plasma Phys. Controll. Fusion 47, B769 (2005)



Fast ignition

induced by a beam of 1.5 MeV electrons,
delivering 25 kJ, in 16 ps, onto a spot of radius = 20 μm .

Fusion yield: 13 MJ.





The potentials of fast ignitors

No central hot spot

==> relaxed implosion symmetry
and stability requirements

Lower density (=> lower implosion velocity)

==> relaxed stability requirements
==> higher energy gain

because the fuel at ignition is isochoric; we do not
spend energy to compress the outer fuel to balance
inner pressure

(see Rosen, 1984; Atzeni 1995, 1999)



The advantages of fast ignition paid by the need for an ultra-intense (& efficiently coupled) driver

optimal parameters for density $\rho = 300 \text{ g/cm}^3$

delivered energy	18 kJ
spot radius	20 μm
pulse duration	20 ps
delivered pulse power	0.9 PW
delivered pulse intensity	$7.2 \times 10^{19} \text{ W/cm}^2$

CPA lasers can meet such requirements

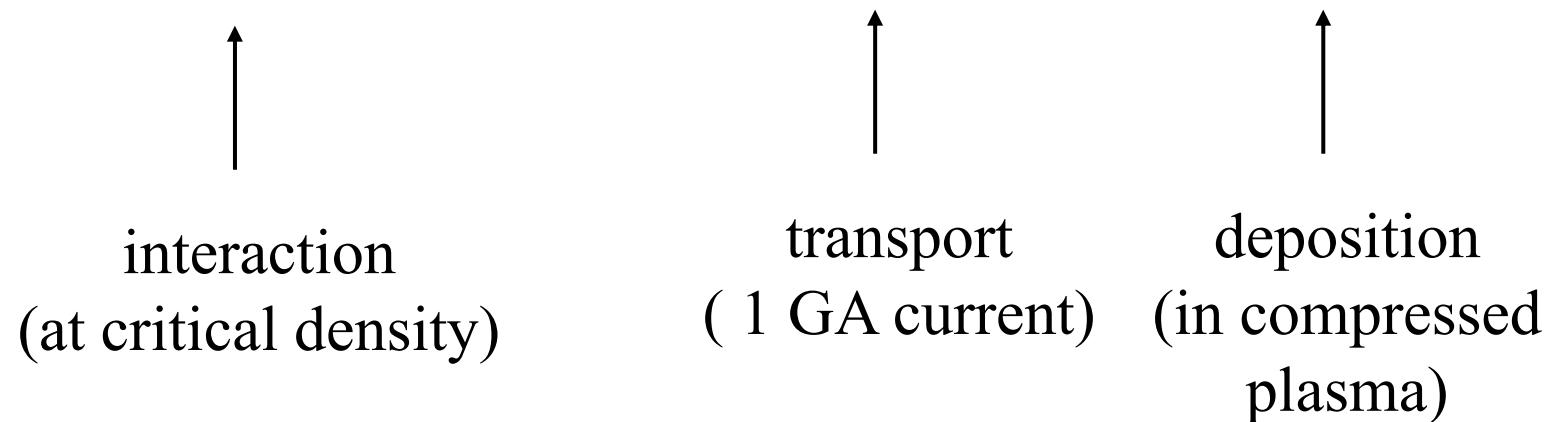
$$E \propto \rho^{-1.85}; \quad r \propto \rho^{-0.97}; \quad t \propto \rho^{-0.85}; \quad W \propto \rho^{-1}; \quad I \propto \rho^{0.95}$$



Standard fast ignition: how is energy transported to the fuel? Nonlinear, relativistic plasma physics involved

we have to rely on large extrapolations

Ultraintense laser ==> hot electrons (few MeV) ==> hot-spot creation

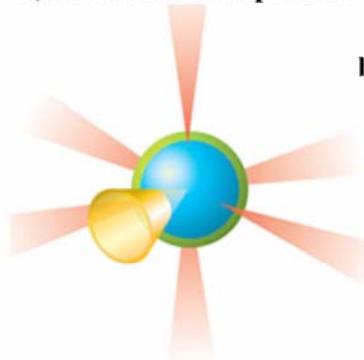


other issue: matching hot electron range energy with hot spot;
a lot of current debate



Cone-guiding: a possible solution to shorten the path from critical surface to compressed fuel

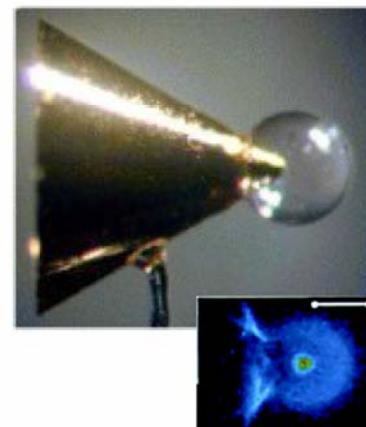
a) direct-drive compression



b) cone-guided ignition beam



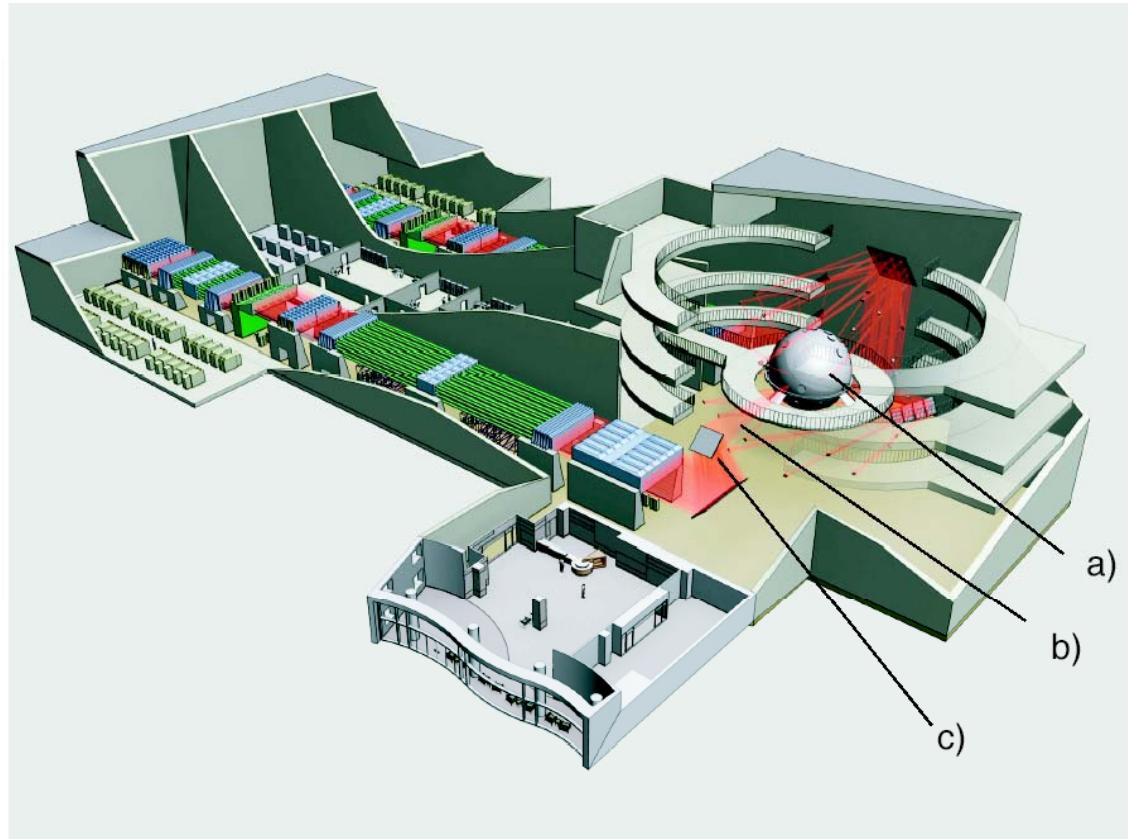
2001 ILE experiment
(Kodama et al., Nature)



works at small energy (Kodama et al Nature 2001, 2002)
can be scaled? pointing?
compatible with strong compression?
materials mixing?
cone tip design?
====> experiments programmed at FIREX and OMEGA-EP

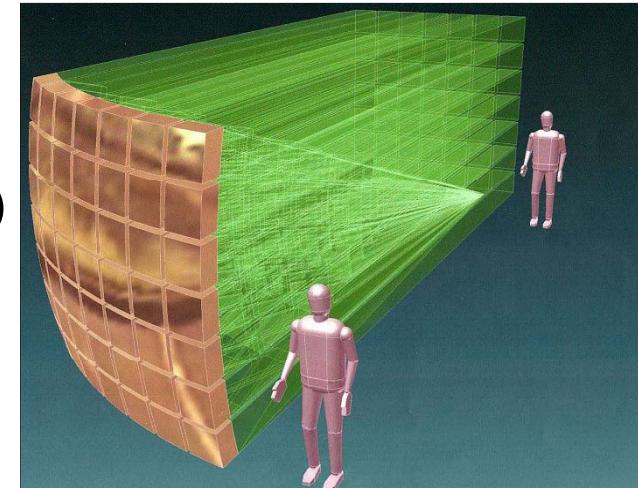


testing fast ignition at
minimum energy



artist's view

70kJ, 10psec, 1 ω , 2 ω or 3 ω



a)



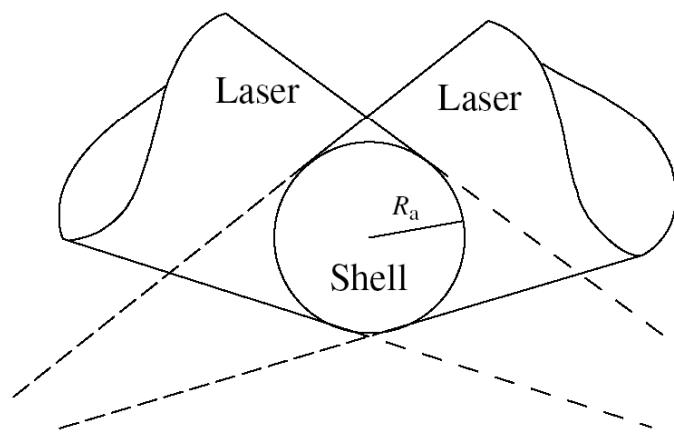
200-300kJ, 5nsec, 3 ω

Baseline capsule

$R_a = 1.044 \text{ mm}$

$R_i = 0.833 \text{ mm}$

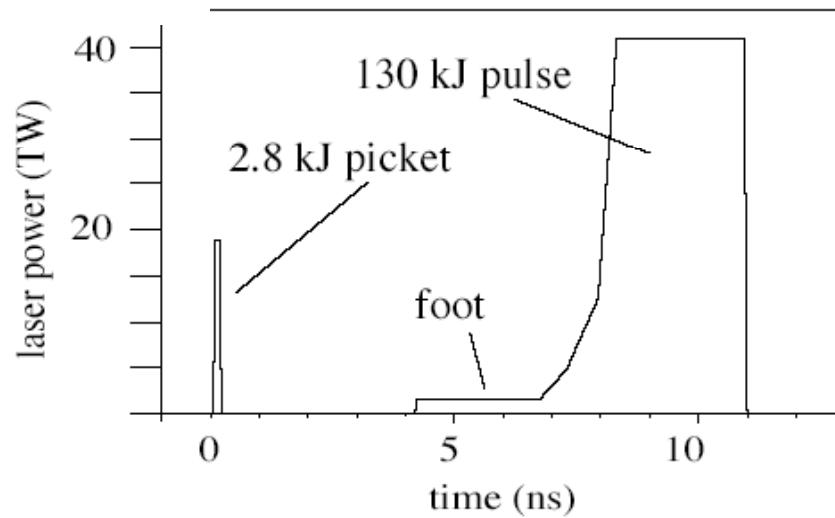
DT vapour
 $(\rho_v = 0.1 \text{ mg/cm}^3)$



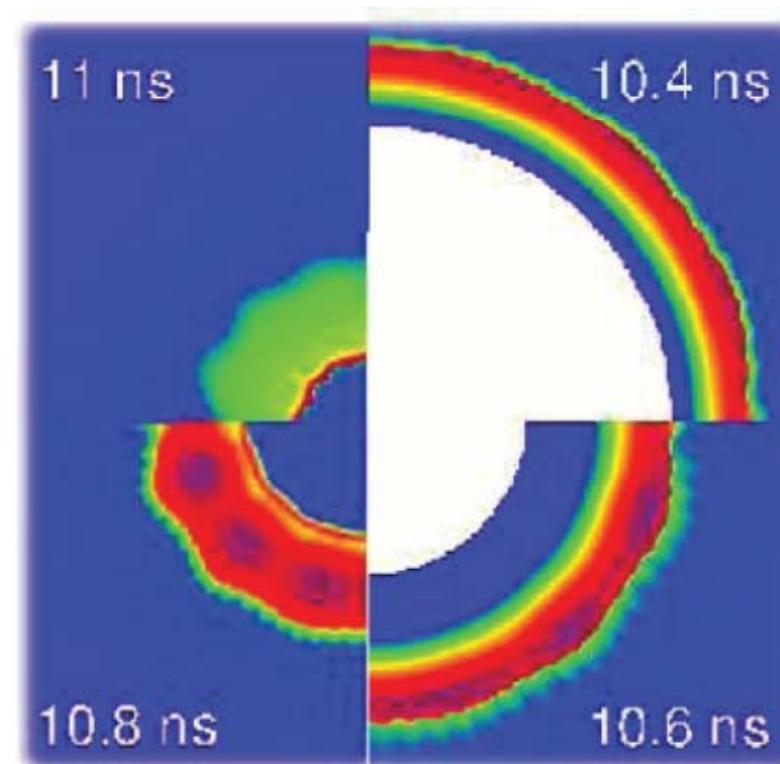
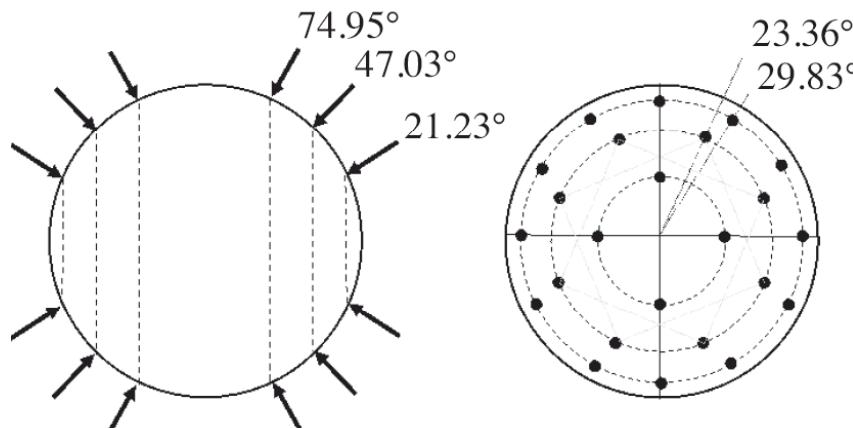
compression laser pulse

- wavelength = $0.35 \mu\text{m}$
- focussing optics f/18
- energy = 130-180 kJ
- absorbed energy = 90-120 kJ

b)

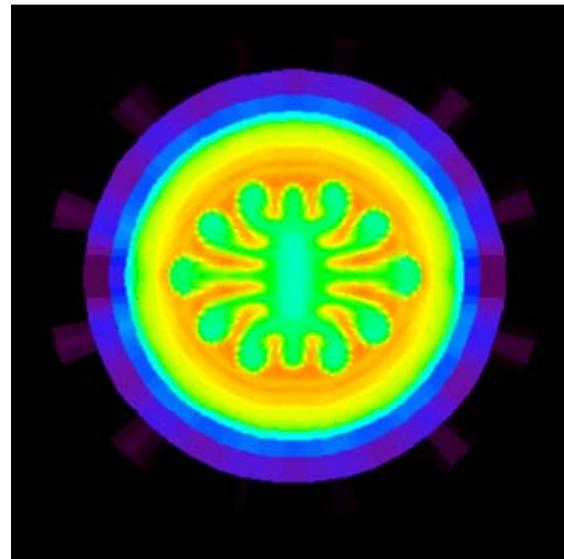
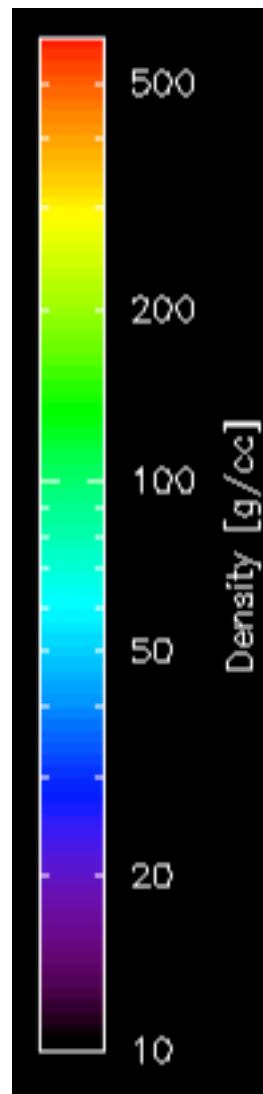


Symmetry is still an issue



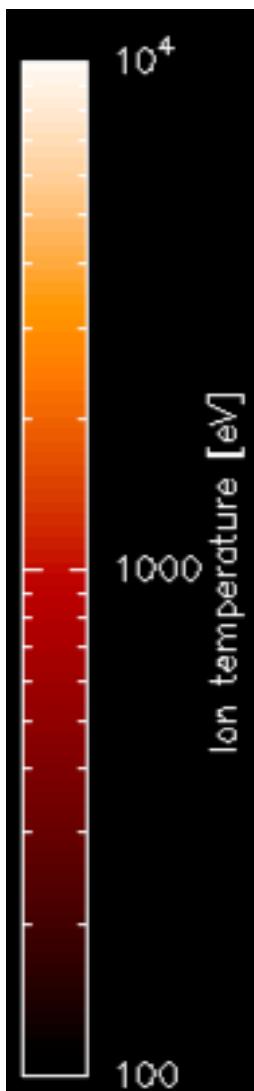
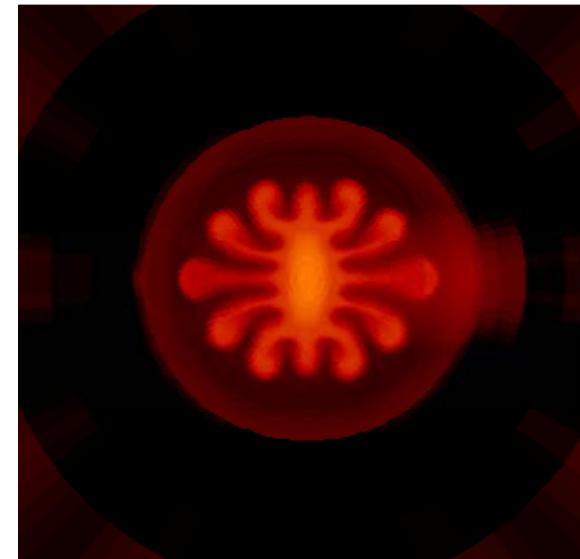
L. Hallo et al., 2009

$t = 11.450 \text{ ns}$; 1 ps after start of ignition pulse

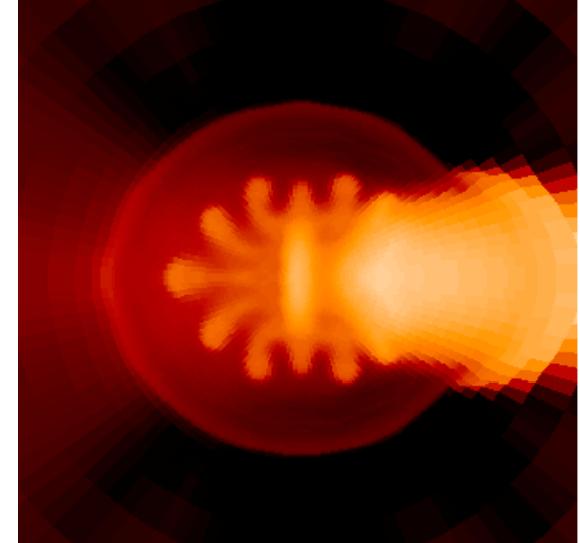
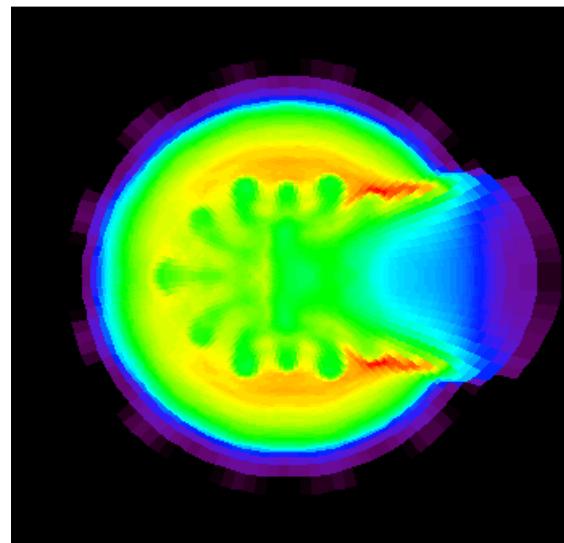


-100

100 μm



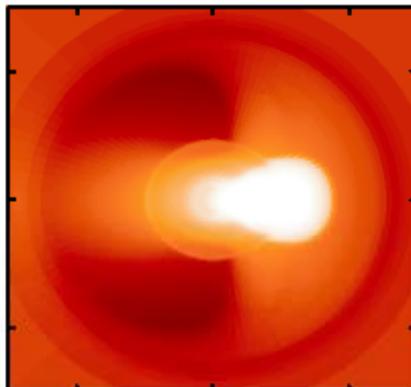
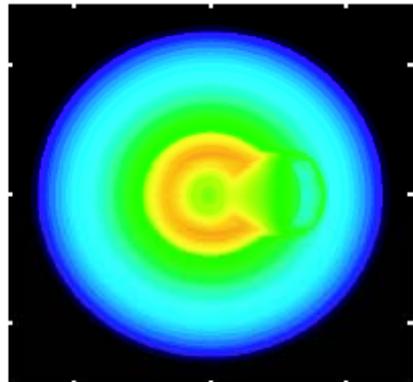
at the end of the ignition pulse



SA & AS

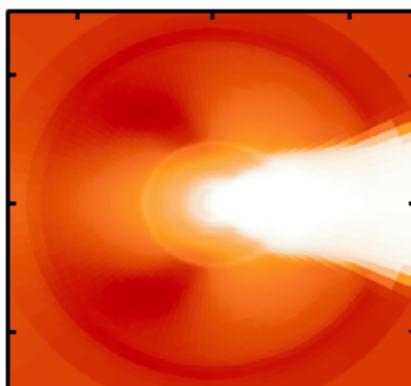
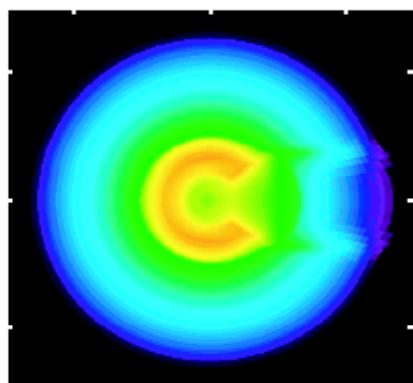
HiPER baseline target - e-beam ignition, with e-beam Coulomb scattering

Maps at the end of the optimal beam pulse for ignition



1-D Maxwellian, $\langle E_e \rangle = 1.5$ MeV
cylindrical beam, **source at $z = 70$ μm**
Gaussian pulse, $r_{\text{HM}} = 14$ μm , $t_{\text{FWHM}} = 15$ ps
with scattering

beam energy $E_{\text{ig}} = 38$ kJ



1-D Maxwellian, $\langle E_e \rangle = 1.5$ MeV
cylindrical beam, **source at $z = 150$ μm**
Gaussian pulse, $r_{\text{HM}} = 13$ μm , $t_{\text{FWHM}} = 16.7$ ps
with scattering

beam energy $E_{\text{ig}} = 47$ kJ

0 150 μm

ρ (g/cm^3)

1 10 100 1000

T_e (eV)

1 10 100 1k 10k

(SA et al, PoP 2008)

Conclusion on fast ignition:

Great potential, but a number of issues

- Energy conversion efficiency into igniting beam
- Temperature scaling of fast electrons
- Transport of fast electron beam in hot dense plasma

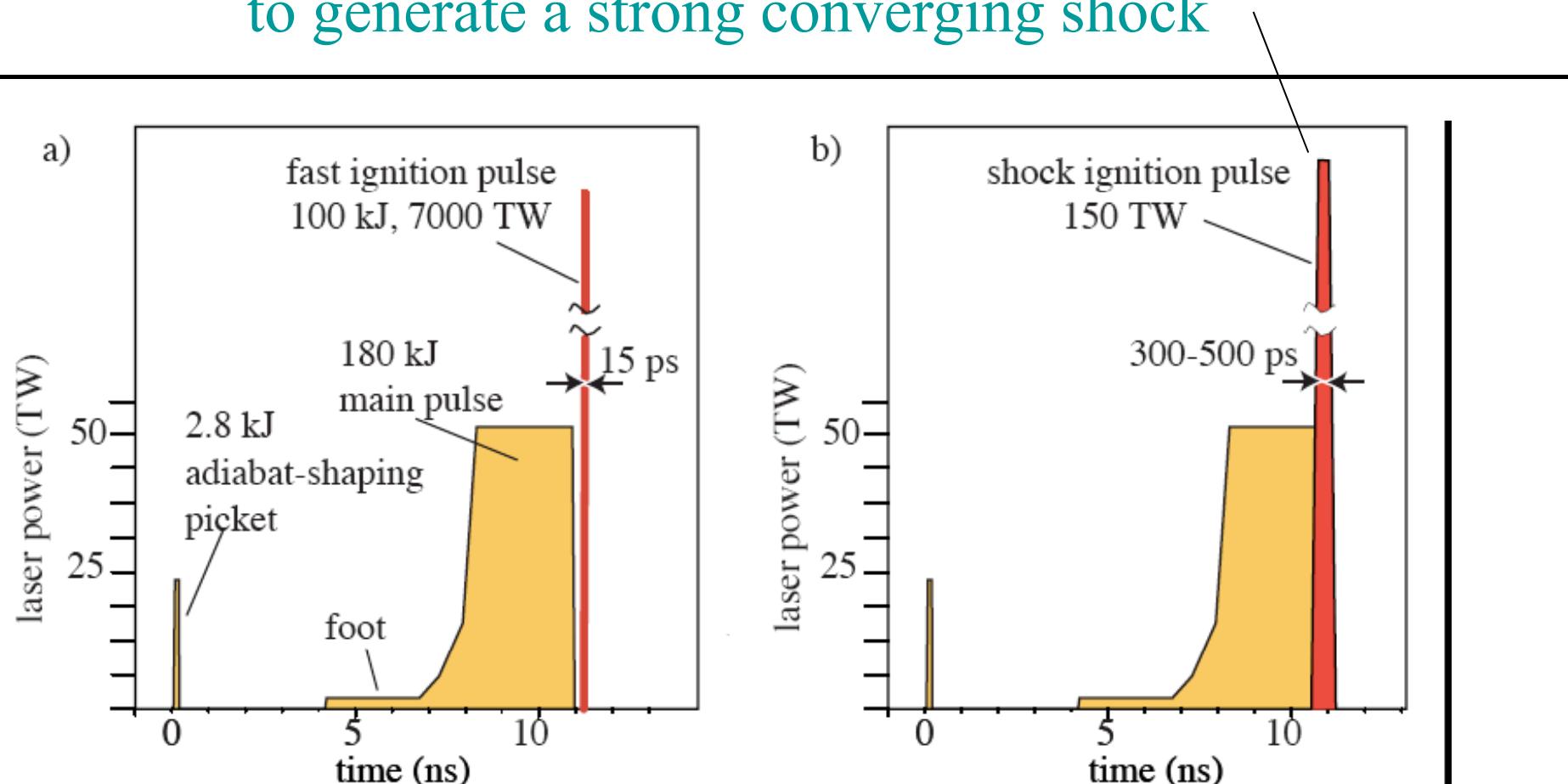
**Anything intermediate between
central ignition and fast ignition?**

Shock ignition

(Betti et al., 2007; Theobald et al, 2008; Ribeyre et al. 2009)

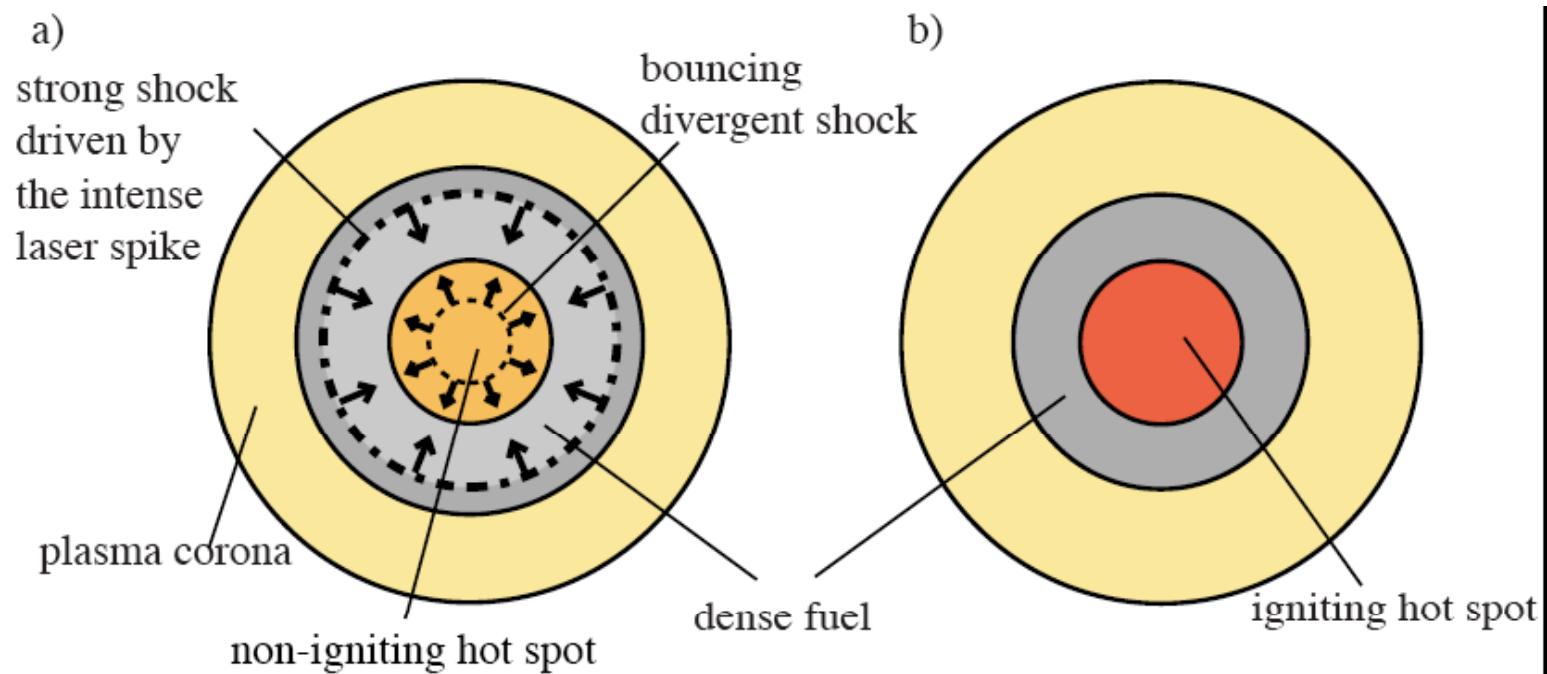
Shock ignition:

intense laser pulse towards the end of the implosion
to generate a strong converging shock



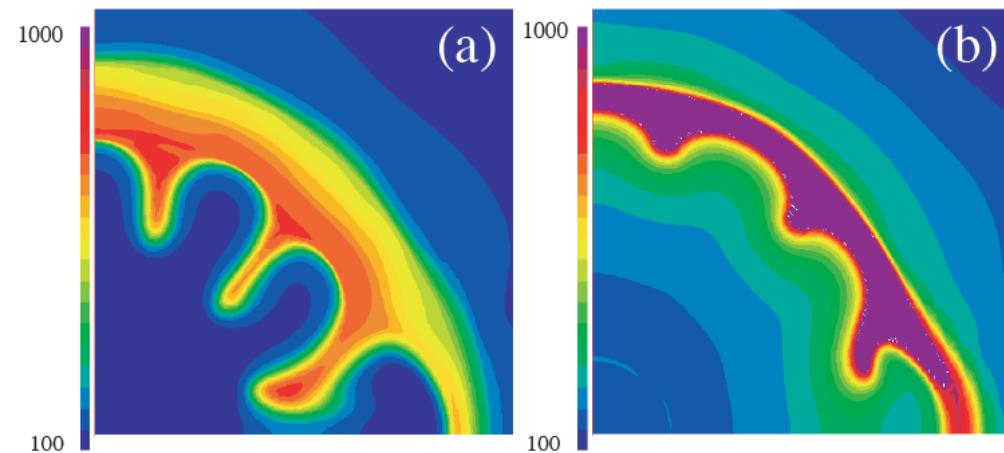
pulse for the HiPER target (Ribeyre et al.,
PPCF 2009 - CELIA, Bordeaux)

Shock ignition as shock-assisted central ignition(*)

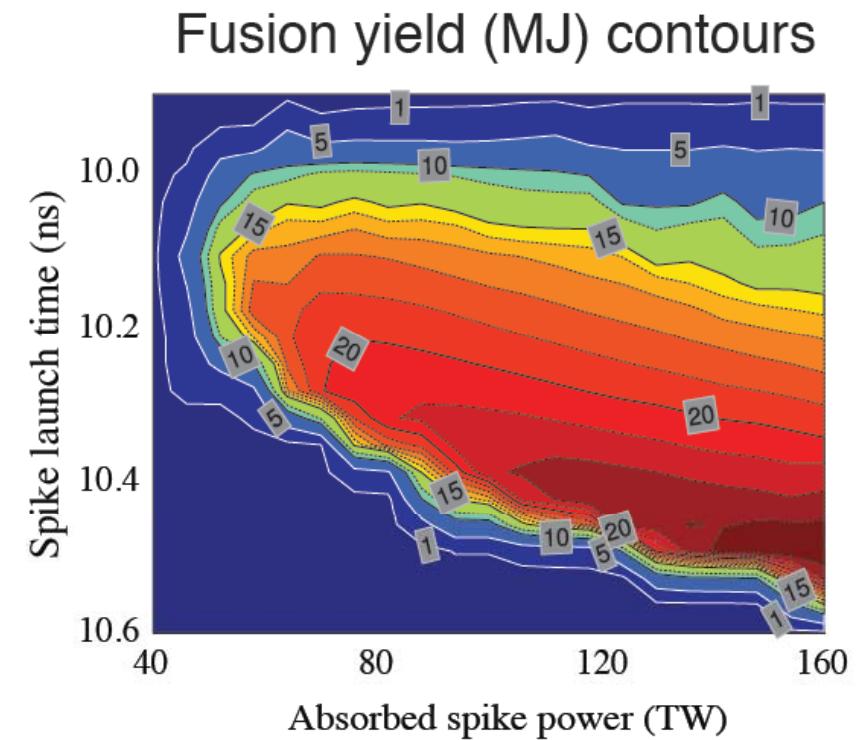


(*) thanks to G. Schurtz and X. Ribeyre

the shock seems to reduce RTI growth!



a large window for ignition



Conclusion on shock ignition:

Great potential, deserves serious investigation (@ LNJ, @ NIF?)

- implosion less critical than standard central ignition
- robust & classical (hydro) ignition process
- does not require two different lasers
- principle tested at OMEGA (Theobald et al, 2008)
- can be tested at NIF, LMJ

Issues:

- intense laser interaction and laser-plasma instabilities
 - shock interaction with short scale RTI perturbation
-



Towards the reactor?

A very long path

we have to increase

- driver efficiency x 10
- driver rep rate x 10000
- target gain x 5 – 10

And to decrease target cost by a factor 1000

However, potential solutions exists and are being studied
(Diode pumped solid-state lasers)



Dall'ignizione al reattore Una strada lunghissima, ma già avviata

Esperimenti di ignizione (NIF):

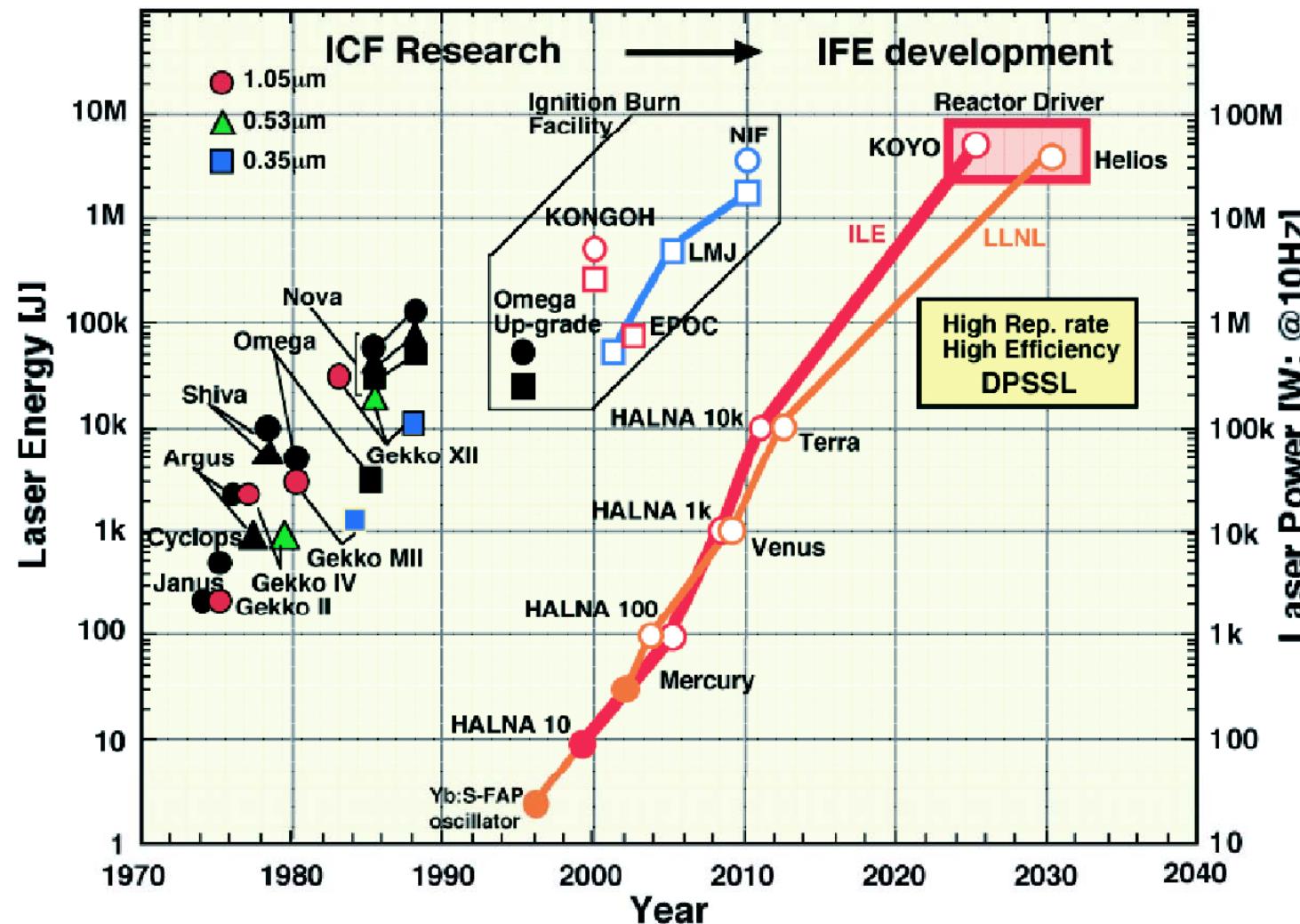
Obiettivo: ignizione, con moltiplicazione $G > 10$,
impiegando laser con rendimento dell'1%
che effettuano pochi spari al giorno,
usando bersagli che costano più di 1000 \$ ciascuno

Reattore:

Necessari: moltiplicazione $G > 100$,
impiegando driver con rendimento del 10%
che effettuano 5 spari al secondo,
usando bersagli che costano meno di 1 \$ ciascuno!

crescita della potenza dei laser per la fusione

S Nakai and K Mima

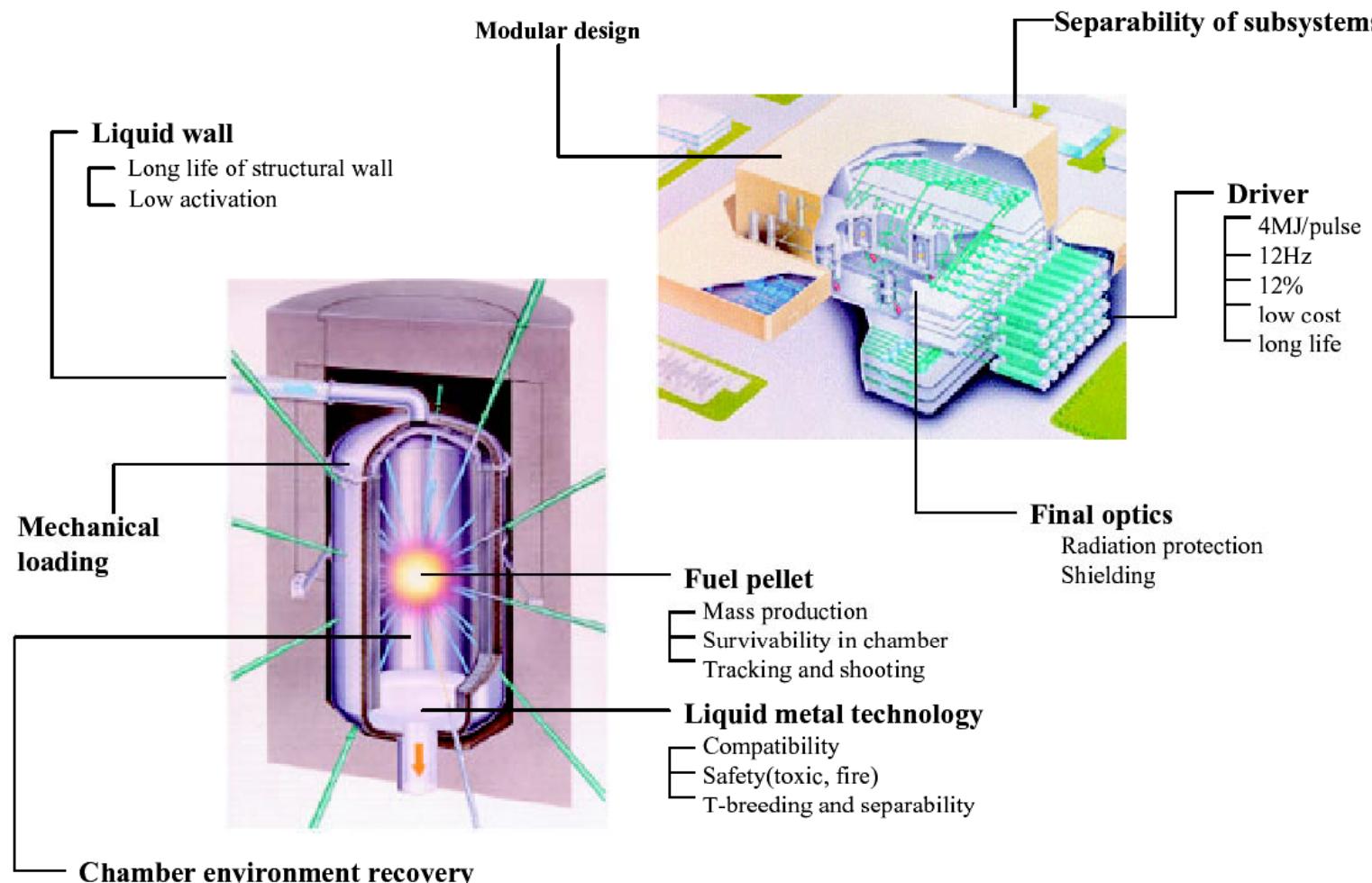


Uno dei molti concetti di reattore

Sono in corso azioni di ricerca e sviluppo su tutti i componenti

346

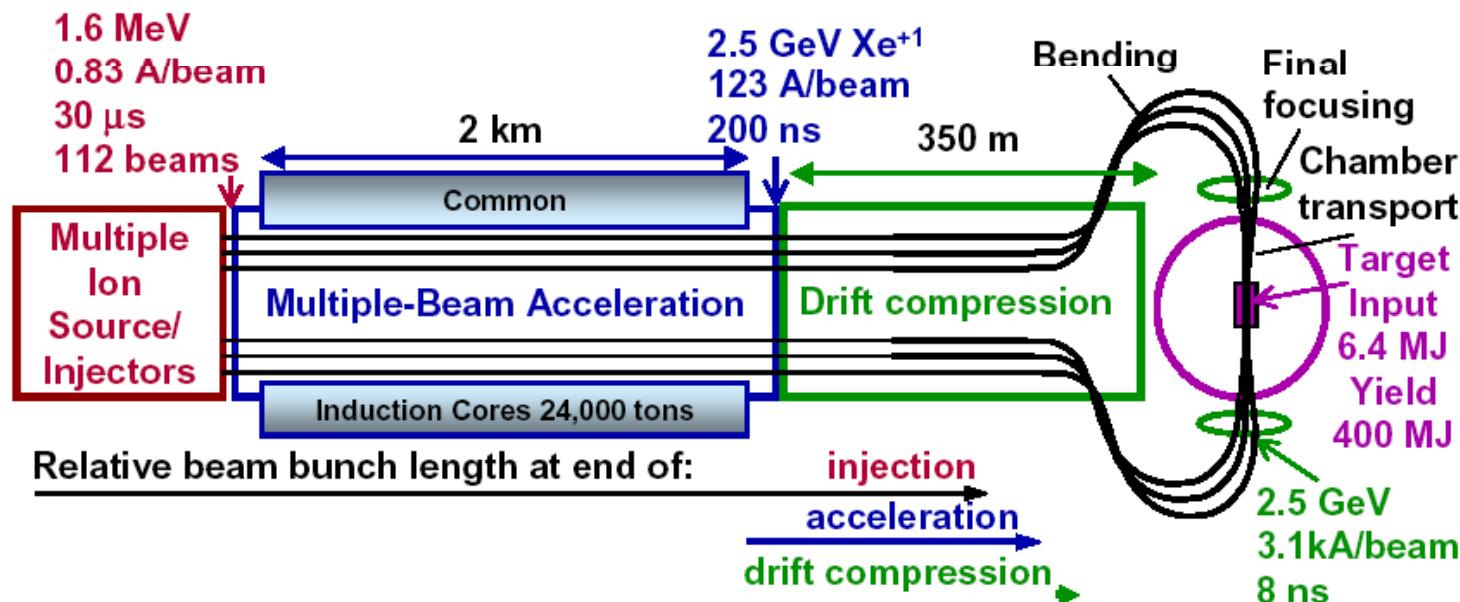
S Nakai and K Mima





Fusione inerziale indotta da ioni pesanti

Reference 6.4 MJ, 112-beam, quad-focused driver



Bunch length compression is integral part of HIF concept

Driver efficiency ~ 45% → very low recirculating power fraction



Fusione inerziale e fusione magnetica

I pro della fusione inerziale:

- fenomeni di base compresi e simulabili senza modelli ad-hoc (almeno per lo schema classico)
- separazione fisica dei componenti del reattore
- possibilità di prima parete fluida
- impiego dei laser anche per esperimenti non fusionistici
- Ricadute industriali che possono attrarre investimenti privati (possibili ROI > 1 entro pochi anni!)

Contro

- grande “distanza” ignizione-reattore
 - Finora ad alcuni anni fa poca collaborazione internazionale (programmi militari, classificazione). La situazione sta rapidamente cambiando (progetto HiPER in Europa, collaborazione fra gruppi europei e NIF, ...)
-



Applicazioni dei laser a impulsi “ultraintensi”

Con laser a impulsi intensi:
nella materia irraggiata, valori record di
pressione ($>$ milioni di atm)
densità (600 x materia solida)
campo elettrico (1000 000 000 000 V/m)
campo magnetico (100 000 000 gauss)

Astrofisica in laboratorio
Campi magnetici ultraintensi
Accelerazione di particelle
Chimica al “femtosecondo”
Reazioni nucleari
Laser a raggi X
Lavorazioni di precisione, applicazioni mediche



Conclusions (on ICF)

The physics basis for ignition is understood and “controlled”
Predictive capability

With 40 years of intense research all main issues addressed

Impressive technical progress (laser, target, diagnostics)

Anyhow, the ignition campaign is an experiments,
as such enters a new domain (*terra incognita*)

If ignition is achievement: scientific milestone and boost to IFE

ICF/IFE physics is rich and vital; potential interesting, but little
developed alternative schemes
physicists ready to contribute to next steps
