Studying Ignition Schemes on European Laser Facilities

S. Jacquemot

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A dual European horizon

1 - a very-large-scale laser facility: the Laser MégaJoule

to trustfully demonstrate indirectly-driven laser ignition
at the MJ level

thanks to an improved target design & a series of validating experimental campaigns

2 - an ambitious project: HiPER

towards Inertial Fusion Energy

currently supporting numerical and experimental studies of alternative ignition schemes & innovative technologies
The key partners

- Czech Rep.: FZU/PALS & CTU Prague
- France: CEA, LULI, CELIA & LPGP
- Germany: GSI & MPQ
- United Kingdom: STFC/RAL
- Hungary: KFKI RMKI & Szeged
- Italy: ENEA/Frascati, U. Milano-Bicocca, Roma “La Sapienza” & ILIL Pisa
- Poland: IPPLM
- Portugal: IST/GoLP
- Spain: Ciemat & UPM
The generic laser-target assembly for LMJ ID ICF

- 3 UV laser cones
- High-Z (Au) hohlraum
- Low-Z gas (HHe, <1mg/cc)
- Polyimid e window (Φ~3mm)
- Adequate pulse shaping
- Spherical convergence of accurately timed shock waves
- Isentropic compression & hot spot formation

- Uniformly doped ablator (e.g. CHGe) e~160µm
- Solid fuel shell (cryo. DT) e~100µm
- Gaseous DT 0.3mg/cc

- Drive profile:
  - Laser power (TW): 550TW / 1.8MJ
  - Radiation temperature (eV): 3.5MK
  - Time (ns): 0, 5, 10, 15
Current status of the LMJ facility

up to 240 beams in 60 quads, up to 2 MJ/600TW

building commissioned, 2(/4) laser bays completed, target chamber being equipped
cryo. target assembly under characterization & insertion systems validated

1st experiments end of 2014

J. Ebradt CEA/DAN
Improved target design provides flexibility

* cocktail hohlraum (75%U-25%Au) to improve the hohlraum energetics

* rugby-shaped hohlraum for a significant x-ray drive enhancement

* gradually doped ablator to reduce hydro. risks & control rad. preheating

* 160 laser beams in 2 cones

⇒ 1.2 MJ - 330TW
Laser-Plasma Interaction experiments on the LIL facility give confidence on the effectiveness of the implemented optical smoothing technique to control parametric instabilities.
Rugby-shaped hohlraums allow improving the overall energetics thanks to reduction of the wall surface (and thus of the wall losses) up to +25% expected in LMJ conditions.

Experiments on OMEGA (LLE, US) exhibit a significant increase of the radiative temperature (+16%) leading to a record neutron flux ($1.5 \times 10^{10}$) for a $\text{D}_2$ indirectly-driven implosion @20kJ.
The first 2 shock dynamics has been reproduced on LIL using a LMJ-relevant radiation drive.
Perspectives: Inertial Fusion Energy (IFE)

1. Target factory
   mass production of low-cost targets

2. Target engagement
   high rep. rate injection, tracking & shooting – survivability

3. Driver
   high repetition rate, low cost
good “wallplug” efficiency & availability

4. Fusion scheme
   robust & simple target design
   high gain

5. Fusion chamber
   long lifetime & low activation

6. Steam plant

\[ P_{\text{out}} \approx 0.4 \text{ GW} \Rightarrow \text{driver } \eta_d \approx 20\% @ 20\text{Hz} \Rightarrow \text{target } G \approx 100 \& E_d \approx 600\text{kJ} \]
   (shock ignition)
The HiPER project

to demonstrate high repetition rate operation and solve power-production bottlenecks

26 Eu partners

in a single facility step

PETAL on LMJ:
 a forerunner to address physics issues

C. Edwards STFC, F. Amiranoff LULI, N. Blanchot CEA/CESTA
Preparatory Phase

Physics roadmap

Technology roadmap

Technology Developments & Risk Reduction

Final design & cost analysis

ignition scheme down-select & experimental validation (LMJ/PETAL)

1 & 10 kJ beamlines prototyping

reactor concept design.

power-to-grid demonstration in ~ 2040
Alternative ignition schemes allow reducing laser energy requirements

fast ignition & shock ignition both rely on decoupling direct drive target compression from ignition, using - as an external match - either a laser-accelerated fast particle beam or a strong shock
An optimized irradiation configuration, using only 48 laser beams, has been found. 2D multimode simulations show that the target ignites despite capsule deformation due to illumination non-uniformities. Reasonable power imbalance and pointing error can be borne if focal spot carefully optimized.
2D hydro, PIC & transport simulations allow following fast ignition for an asymmetric illumination and investigating influence of the electron beam divergence increase of the ignition energy threshold by a factor $\sim 1/[1-\theta_r/\Delta\theta_0]$
First experiments at RAL on electron transport in pre-compressed matter provide valuable information to benchmark numerical codes.

- Compression: 4x50J / 1ns
- Fast electron generation: 5 x 10^18 W/cm²
- Gold shield: proton energy too low
- Simulated: good agreement with numerical simulations (MC code)
- Proton radiography: good agreement with numerical simulations (transmission)
- X-ray radiography: detection of fast electrons in compressed matter

HOPG spectrometer:
- Ni-Kα
- Cu-Kα
- Ni-Kβ
- Cu-Kβ

% of electrons passing through the whole cylinder

Cu-Kα imager (side & rear): 100 µm
2D hybrid simulations show importance of resistivity gradients

Very good agreement between experiment and simulations

before stagnation: due to resistivity gradients, magnetic fields collimate the fast electron beam
at stagnation: the shock converging to the center, the resistivity gradients disappear & the electron beam is no longer collimated

F. Perez LULI, A. Debayle UPM
Shock ignition leads to higher gain and lower energy threshold for a non-isobaric fuel assembly

...risks due to hydrodynamic and parametric instabilities can be minimized thanks to homothetic scaling of the HiPER target...
Experiments have already started to investigate LPI and shock formation at PALS & LULI2000.

“spike”
I \sim 10^{15} \text{ W/cm}^2

1\text{st shock}
I \sim 5 \times 10^{13} \text{ W/cm}^2

backscattered light (SBS, SRS)
time-resolved
The European DPSSL program

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<td>Germany</td>
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<td>Czech Republic</td>
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<td>&amp; 6J @ 100Hz</td>
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Summary

Current experiments and target design improvements give confidence in demonstrating indirectly-driven ignition at ~1 MJ on NIF and then LMJ.

It will be a major step towards determining the feasibility of ICF as an energy source.

In the framework of the EURATOM keep-in-touch & the HiPER programs Europe has launched coordinated studies to:
(i) choose the most suitable ignition scheme, thanks to innovative experiments and 2D numerical simulations,
(ii) improve DPSSL driver and target technologies.

with the support of LASERLAB-Europe for transnational access to laser facilities
Additional tricks could be employed to further reduce LPI risks and increase safety margins: $2\omega$ operation or plasma-induced beam smoothing.

LULI2000

LIL

S. Depierreux CEA/DIF, C. Labaune LULI

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Fast electron transport has been studied on LULI2000 in well-characterized pre-plasmas

Electrons are less divergent in steep-gradient plasmas (at high laser contrast)

P. Norreys STFC, S. Baton LULI et al.
Realistic PIC simulations address one of the key issues for this scheme: parametric instabilities

- spike intensity above threshold
- SRS & SBS growth observed, but:
  - transient SBS
  - absolute local \( (n_c/4-n_c/16) \) SRS associated with cavitation
- strong laser energy absorption

absorbed energy transported by 30 keV electrons to the ablation zone
- high amplitude shock wave generated in the dense shell

\[ T_{\text{cold}} = 6 \text{ kev} \]
\[ T_{\text{hot}} = 29 \text{ kev} \]
PALS experiments on shock formation in well-characterized pre-plasma conditions (x-ray deflectometry & spectroscopy)

1keV plasma creation 2 $10^{13}$ W/cm$^2$, $\omega$ (1.3µm)

shock generation 5 $10^{15}$ W/cm$^2$, $3\omega$ (0.44µm)

next (2011): characterize hot electrons

SRS < 5%