FCI in France
status and perspective

Thierry Massard
Chief scientist CEA  Defense and Security

Guy Schurtz (CELIA), Benoit Canaud (CEA), Laurent Grémillet (CEA), Christine Labaune(CNRS)

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Outline

• ICF in France: a long history of successes

• ICF for energy: a place in the French energy vision?

• LMJ / PETAL a key facility for the IFE in Europe

• How France scientific community participates in HiPER (European program for IFE feasibility demonstration)

• The French strategy

• A world wide forum is necessary for IFE
ICF research in France was initiated at Ecole Polytechnique, in 1964 with the support of CEA-Limeil.

In 40 years, 5 national generations of lasers were commissioned,

- **Rubis laser**:
- **CO2 laser**:
- **Nd laser**: 2 beams-200 J – 600 ps (w, 2w, 4w) (1980)
- **Nd laser**: 6 beams – 600 J -600 ps (w, 2w, 4w) (1985-2002)
- **Ti/Sa**: 100 TW
- **LULI2000**: 2 beams – 2 kJ – 1.5 ns (w, 2w, 3w)

In 1968 the first fusion events are observed.

C6 laser, delivering up to 600 J
Today several critical laser facilities and labs in France

- Ecole Polytechnique {LOA, LULI},
- CELIA (Bordeaux)
- CEA (Bruyères, Saclay and Bordeaux)
- LCD/ENSMA

Lucia : objectif : 100 J – 10 Hz
French Contributors to IFE are coordinated by ILP
Why ICF should go for Energy?

We are facing a huge challenge:

- A global increase in energy demand is inevitable
- Fusion offers critical advantages: no carbon emission, no air pollution, unlimited fuel, intrinsically safe
- IFE in France aims to demonstrate that fusion by lasers is a credible alternate energy source complimentary with magnetic fusion not a competition.
A global response from the nuclear industry: fission and fusion
Bringing IFE on the roadmap for Energy in France

In France the National Coordination for Energy Research (2010)…
• Builds the national roadmap for energy research
• Identifies the necessary breakthrough technologies and the scientific issues
• Promotes transverse collaboration within the various sources
• Promotes the emergence of national champions insuring long time safe and durable supply of energy (AREVA, GDF SUEZ, TOTAL…)
• Proposes scientific programs to ANR
• …In conjunction with the European Energy Research Alliance

IFE groups have applied to participate in ANCRE working groups

Member of the Consortium

Founders: CNRS, CEA, CPU, IFP Energies nouvelles

Associates: ANDRA, BRGM, CDEFI, CEMAGREF, CIRAD, CSTB, IFREMER, INERIS, INRA, INRETS, INRIA, IRD, IRSN, LNE, ONERA ...
Key technologies for a low carbon energy system
By choosing to build the PETAL laser next to the LaserMegaJoule, we open the way to explore a new type of energy. With ITER and PETAL, France is now a world leader for the production of energy by fusion. This is a major program that you are opening here.
PETAL Project objectives

Coupling a petawatt class laser PETAL to quads of LIL or LMJ

1 quad = 30 kJ / ns / 3 \omega

- **Energy**: 3 kJ,
- **Wavelength**: 1053 nm,
- **Pulse duration between 0.5 and 10 picoseconds**,  
- **Intensity on target**: $10^{20}$-$10^{21}$ W/cm²,
- **Intensity contrast (short pulse)**: $10^7$ at -7 ps,
- **Energy contrast (long pulse)**: $10^{-3}$. 

[Images and logos of organizations]
Former planned configuration: PETAL-LIL Coupling
Front-end, amplifier prototype, spatial filter vessel
Compression stages on the LIL facility

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New configuration : PETAL-LMJ Coupling
PETAL beamline thru the LMJ building

Amplifier Section in the South-East laser bay
Compression and focusing stages

Arrivée du faisceau (ET1)

Focalisation stage

Beam Transport

Diagnostics

2nd Compression stage (under vacuum)

1st compression stage (on air)
The LMJ-PETAL will address a wide range of applications

**crucial issues for the European IFE project HiPER**

- **Inertial Fusion Energy**
- **Astrophysics**
- **Societal issues**

- **Warm dense matter**
- **Theoretical physics**
- **Particle acceleration from high power, multi ps pulse**
- **Transport of relativistic electron beams in plasmas**
- **Optimization of laser to electron converter**
- **High energy hydro expts + high resolution diagnostics**

**Thierry Massard**

**Direction scientifique**
LMJ-PETAL is on the track to Fusion Energy

**Input from Omega EP + FIREX**

**PETAL**
- Address design issues of fast ignition:
  - electron sources
  - Transport and fuel heating
  - target design
  - High Resolution diagnostics of DD implosions

**LMJ**
- 2/3 LMJ
  - Radiation Driven Implosions (ID) Validate
  - Ignition Physics
  - Hydrodynamics
  - PDD SI implosion with G~10 gives Proof of principle of SI

**Full LMJ**
- Direct Drive Implosions + Shock Ignition demonstrate G=100

**HIPER design**

**IFE DEMONSTRATION**

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The IFE French Strategy

- As a EU requirement, we keep a clear separation between IFE and “sensitive” weapon science (non-proliferation)
  - No use of Weapon codes in the European programs
  - No benchmarking of physics code with weapons code
  - Not in favor of indirect drive capsule option in the European program for sensitivity issues.
  - French-UK guide for good practices in laser exp. approved

- Initial Design point in accordance with LMJ capability
  - Shock ignition nominal
  - Fast ignition option is investigated (PETAL)

- Optimal design goes towards:
  - Lower laser Energy ($<1$MJ)
  - Higher Target gain ($>100$)

In order to aim a positive favorable energy balance.
The major milestone on the HiPER road map is demonstration on NIF/LMJ

**Physics milestones**
- Part validation expts
  - RAL Luli Alisé PALS
- PETAL expts
  - Omega EP expts
- PDD demo on NIF

**Design steps**
- Preliminary specs
- **Validated physics**
- Validated design

**Validation**
- NiF commissioning
- LMJ commissioning
- LMJ ignites

**Construction**
- Shock Ignition on NIF/LMJ
- Detailed specs
- Decision for construction
Shock ignition becomes the baseline scheme for direct-drive fusion.

$(\alpha=2, v=400\text{km/s})$-Direct-drive marginally igniting target can be shock ignited with high gain.

Shock Ignition: ignite from a converging shock launched from a final spike in the laser pulse

Conventional drive:
- does double duty
- 1 Compress
- 2 Ignite

Low velocity drive:
- safe implosion
- higher fuel mass
- higher gain

Requires a ~200 TW spike to launch the ignitor shock

Same benefit as Fast Ignition but:
- classical LMJ like laser technology
- Simple spherical targets
- Hydro modelling
Direct-Drive Shock-Ignition is still possible with 30 quads.

- 120 beams grouped in 30 quadruplets

\[ \begin{align*}
E_{\text{max}} &= 0.9 \text{ MJ} \\
P_{\text{max}} &= 300 \text{ TW} \\
\lambda &= 0.351 \mu\text{m}
\end{align*} \]

Direct-drive fuel assembly is still done with beams at 49° and 59°5 WITHOUT PDD (*). => the angle @ 59°5 (French specificity) allows a good laser-target coupling efficiency but with reduced fuel assembly energy (≤600 kJ).

Shock ignition should be achieved with beams at 33.2° but with a little available laser power (≤100 TW) => thermonuclear gain < 50, risky.

A robust target has been designed for SI demonstration on LMJ

Low aspect ratio + Picket: Improves Target Stability

=> max IFAR ~ 32

- Al coating: Target protection from IR and prepulse
- CH ablator: Higher Absorption

### Parameters

<table>
<thead>
<tr>
<th>Compression</th>
<th>Implosion velocity</th>
<th>Fuel assembly</th>
<th>Shock</th>
<th>Absorption</th>
<th>Yield $t_s=12.6\text{ns}$</th>
<th>Gain</th>
<th>Ignition window</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 TW</td>
<td>240 km/s ($\eta_h\sim5%$)</td>
<td>750 g/cc 1.7 g/cm$^2$</td>
<td>220 TW</td>
<td>72 %</td>
<td>35 MJ</td>
<td>95</td>
<td>300 ps</td>
</tr>
</tbody>
</table>

28 µm

Fat target

Mass: 0.67 mg, AR~3.2

898 µm

870 µm

670 µm

Al (15 nm)

CH

DT cryo

DT gas
No obvious show stopper has been identified so far.

Raman Hot electrons

Rayleigh Taylor Instability at Stagnation

Compression only

Shock + Ignition
Direct-Drive fusion demonstration on LMJ will follow the number of available laser beams

1. Full LMJ (240 beams, 60 quads) => very high gain > 100, WITHOUT PDD.
2. 50 quad-configuration => high gain (50 < G < 100), WITHOUT PDD.
3. 40 quad-configuration => small gain (G < 20), PDD required.
4. 30 quad-configuration => moderate gain (G < 50), WITHOUT PDD.
5. 20 quad-configuration => no gain.

Conclusions on SI ignition option

• As FAST IGNITION, SHOCK IGNITION allows to ignite ICF targets imploded at low velocities (~60% of self ignition velocity)
  – More fuel may be as assembled at same energy
  – Large safety margins may be taken to secure the implosion
  – No show stopper identified yet

• Unlike FI, Shock Ignition does not require specific lasers nor complicated cone-in-a-shell targets
  – Compression and Ignition use same technology
  – SI physics is laser driven hydrodynamics

• Robust ignition designs with G~100 are proposed at 500 kJ, 300 TW
  – Gain G~50 achievable at 320 kJ, 220 TW
  – This is 1/3 of LMJ capabilities
  – May be fielded in the mid term using X-Ray drive final optics
  – Success of Shock Ignition campaigns on LMJ will open the route for IFE

• International collaboration is needed
  – Omega experiments + PDD design for NIF
  – Physics and numerical modelling : LPI, electron kinetics, ablator physics
  – High Rep DPSSL high energy lasers
  – Fusion materials
  – Target handling and manufacturing
IFE Engine design

• We need to have a strong conceptual design of a utility before we can decide to build it
• HiPER will make heavy use of the HPC Simulation capabilities to simulate all the possible concepts of engine (DD, SI, FI, ID)
• European teams will have a very large access to HPC through the European Agency PRACE
• The first petaflops computer to be delivered in 2011 will be in Bruyères le Chatel very similar to TERA100 already operating at CEA-DAM
An International forum for IFE?

- Emerging champions with high level laser facilities:
  - USA
  - Europe
  - Japan
  - Others?

- We need to SHARE and EXCHANGE our experience

- We need to share User-Community Facilities

- Ignition demonstration at NIF could be the right time to announce the launch of the International Forum for IFE which would prepare a global roadmap for inertial fusion for energy
Conclusions and summary

1. France has a strong community in ICF and good laser facilities

2. ICF for Energy (IFE) is emerging as a potential option for the French road map on energy (ANCRE). We are currently looking for new program from the Ministry of research and the Ministry of Industry in charge of Energy.

3. LMJ-PETAL to be a top facility for IFE research involving multi-use capability (X-ray drive, direct drive for FI, direct drive for SI)

4. LMJ-PETAL will be opened for the IFE community for direct drive experiments (FA, SI) according to EU recommendations

5. Institute for Laser and Plasma in carrying the IFE project and is strongly involved in the European HiPER project

6. We propose to create an international forum on IFE to share the strategy