# INTRODUCTION TO DIAGNOSTICS REQUIREMENTS FOR ICF

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## 1. INTRODUCTION

During the last ten years considerable progress have been accomplished in all topics related to Inertial Confinement Fusion (ICF): better understanding and modeling of the physical processes, lower cost and reliable drivers, target technology. Of course the development of new or improved diagnostics is of primary importance. Many experiments have been performed on the existing facilities and compared to detailed numerical simulations. Using these sophisticated radiation hydrodynamics codes, it has been demonstrated that the ignition of a small DT filled capsule could be achieved with a 1 to 2 MJ UV laser. So the main objective of the next generation of large ICF facilities, i.e. the National Ignition Facility (NIF)[1] in USA and the Laser Megajoule (LMJ)[2] in France, is the achievement of moderate, i.e. of the order of 10, thermonuclear gain implosions. The gain is defined as the ratio of thermonuclear energy to driver energy.

The diagnostics needed for such ICF experiments is an essential part of these large facilities design. ICF is a several steps process and at each of these steps some critical requirements have to be met to achieve ignition and burn. In spite of the large base of experimental data, uncertainties still remain and parameters such as driver power, beam pointing, etc will have to be adjusted on the way.

After a brief recall of ICF principles and various schemes, we will consider the successive critical points, determine what parameter has to be measured and finally the diagnostics requirements.

## 2. ICF CRITICAL MILESTONES[3]

Nominal ICF capsule is a millimeter scale shell of solid DT contained in a shell of low Z material, called "ablator" and filled with low-density DT gas. In Direct-Drive scheme (DD)[4], the driver power is used to heat the ablator outer surface. In the Indirect-Drive scenario (ID), the capsule is enclosed in a high Z container, also called cavity or

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hohlraum; the driver beams are used to produce an intense X-ray radiation bath inside the cavity. In both cases, the ablator surface is strongly heated, it expands rapidly outward and remaining part of the shell is imploded at high velocity (3 to $4 \times 10^7$ cm/s). As the convergence increases the DT fuel is compressed and heated. Ignition occurs when the central part of the fuel called hot spot has a temperature $T \geq 6$ keV and an areal density $(\rho R) \geq 0.3$ g/cm$^2$.

A small fraction, about one to a few percent, of drive energy is transferred to the fuel but as only a fraction of the DT is heated to ignition conditions, the main part of the fuel being compressed along a low isentrope, it is still possible to achieve high gains.

In another scheme, named "fast ignitor"[5], all the fuel is compressed at low temperature. The hot spot is not generated by the implosion process, but is triggered at the end of the compression by the suprathermal particles generated with an ultra-high intensity short laser pulse[6].

An important characteristic of ICF laser driven experiments is the large range of plasma conditions encountered (figure 1) from the corona conditions where laser beams propagate to the burning fuel.

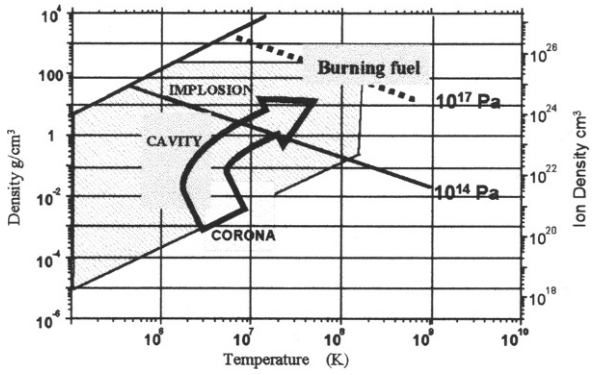


**Figure 1.** density and temperature of ICF plasmas

As the target gain G scales as

$$G \propto \eta \,.\, (\eta . E_d / \alpha^3)^{0.3} \qquad [1]$$

it is important to maximize the coupling efficiency $\eta$. For DD, $\eta$ depends on rate absorbed energy and hydrodynamical efficiency. For ID $\eta$ also depends on X-ray conversion efficiency and X-ray capsule coupling.

Each of these terms should be addressed separately. In the case of laser driven experiments, due to the high intensity of the beams propagating through the plasma ($10^{14}$ to $10^{15}$ W/cm$^2$), various parametric instabilities may occur[7]. These instabilities are the result of the non-linear coupling between the plasma wave and the laser E.M. wave. As

they may strongly affect the efficiency and the quality of the coupling, this problem requires a specific set of diagnostics[8].

To reduce the driver requirements, the DT should be compressed along a low isentrope and remain nearly Fermi degenerate. The fuel equation of state can be then written as:

$$\varepsilon \text{ (Specific energy J/g)} = 3\text{x}10^5 .\alpha. \rho^{2/3} \text{ (g/cm}^3\text{) with } \alpha \geq 1 \qquad [2].$$

As the thermonuclear gain is proportional to $\alpha^{-1}$, the entropy parameter $\alpha$ has to be carefully controlled. The low entropy compression is realized by a precise shock sequence obtained with an accurate driver pulse shaping (figure 2). The fuel entropy can also be influenced by high energy radiation (photons or particles) generated by the driver plasma interaction and transmitted through the ablator shell.

If the drive flux $\phi$ around the capsule is not perfectly symmetric, the velocity non-uniformity $\delta V/V$ will result in a non-spherical hot spot. Assuming that the deviation $\delta R_f$ must be less than $R_f/4$, $\delta V/V$ will be less than 0.25. $R_f/R_0$, where $R_0$ is the initial capsule radius. As typical values for $R_0/R_f$ are 30 to 40, $\delta V/V$ should be about 1%. Requirements for $\delta\phi/\phi$ are of the same order.

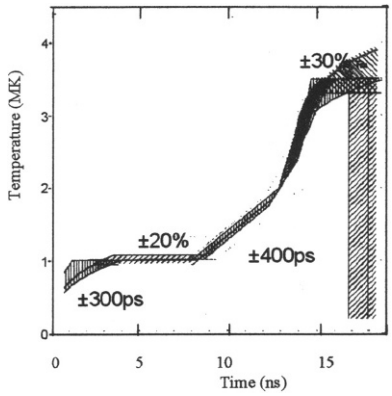


**Figure 2** . Drive temperature for a typical LMJ capsule. A variation in the hatched area results in a 25 % yield reduction.

Beside non-symmetric implosion, irradiation non-uniformities and capsule roughness can seed hydrodynamical instabilities such as Rayleigh-Taylor (RT) instability[9]. During the acceleration phase, the ablation front, where the low density evaporated plasma pushes the high-density shell, is RT unstable. The instability growth may lead to shell breakup. Later, during the slowing down phase, the transition zone between the cold, dense main fuel and the lower density hot spot is also RT unstable. The perturbed interface increases the thermal losses for the hot spot to the surrounding fuel, reducing his ability to trigger ignition.

ICF is based on a two zones fuel configuration: a hot spot containing a small fraction (a few %) of the total mass, satisfying ignition conditions to be able to trigger a thermonuclear burn wave in the main fuel compressed on a low isentrope. In the nominal schema, the hot spot results from the driving pulse shaping and from the low-density gas

inside the capsule. As several phenomena may affect the hot spot generation, measurements should allow the identification of failure mechanism, if any.

## 3. EXPERIMENTAL STRATEGY

First experiments on NIF or LMJ will not use cryogenic DT filled capsule. Experimental programs are being constructed to reach the milestones of §2 with increasing complexity and difficulty. The successive stages are:

- ✓ Control the ability to point and synchronize the beams on the target
- ✓ Measure the energy absorption
- ✓ Adjust the cavity parameters for radiation time history and symmetry
- ✓ Check the implosion velocity
- ✓ Determine the fuel conditions at stagnation
- ✓ Measure the burn wave parameters.

Each step requires a specific set of diagnostics.

The measurements required during the first stages, i.e. before ignition experiments, do not need the nominal cryogenic DT capsule and sometimes will even be impossible with such a capsule. These measurements involve surrogate capsules, which mimic or emphasize some aspects of the nominal capsule behavior. When such a capsule is to be used, the diagnostics requirements are established in close connection with capsule requirements. Examples of surrogate capsules are gas filled shell, shell with tracers, low density foam ball...

## 4. DIAGNOSTICS REQUIREMENTS

### 4.1 Laser plasma coupling

This item is specific to laser driven experiments and is important for both Direct[10] or Indirect Drive[11] scheme. When the laser beams propagate through the evaporated plasma to the critical density or through the plasma filling the cavity to the wall, parametric instabilities, Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS), in particular, could be significant. Laser-plasma instabilities can scatter a fraction of driver energy out of the plasma, reducing the coupling efficiency. Previous experiments have shown that the time evolution of the backscattered light is generally quite different from the time evolution of the incident power (figure 3). It is important to measure separately the time dependence of SRS and SBS because:

- The time dependence of the pressure driving the capsule implosion is tied to absorbed and not to incident power
- The detailed knowledge of the instability's effects may help to identify an improvement.

Most of the SBS and SRS energy is backscattered toward or near the focusing optics. Some optics is required to collect the reflected light and to inject it into spectrometers coupled to streak camera[12]. The light scattered outside the focusing optics can be measured with an array of filtered fast diodes.

Another prejudicial effect of the plasma instabilities is the generation of suprathermal electrons with temperatures in the range $T_h \sim$ a few 10's to a few 100's keV. These

electrons can preheat the DT increasing the fuel entropy (parameter $\alpha$ ). The temperature and the number of fast electrons are routinely measured by recording the bremsstrahlung spectra of these electrons as they move through the target material. Measurement are performed with a set of Fast Scintillators coupled to PM tubes and high-pass filters or fluorescence filters.

Thomson scattering (TS) is a classical technique in plasma science, but it was used only recently on large facilities as Nova[13] or Phebus to characterize ICF plasmas ($n_e$ up to $3x10^{21}$ $cm^{-3}$, Te, Ti, Z, velocity). TS was also used to analyze the characteristics of electron or ion acoustic wave associated with the parametric plasma instabilities[14]. The possibility to accommodate TS to NIF or LMJ is still to be analyzed (S.H. Glenzer, in this proceedings) as it would require a few kJ probe beam at 0.26 μm wavelength.

### 4.2 Cavity (hohlraum) physics

This item is specific to Indirect Drive experiments but concerns all drivers. The driver beams deposit their energy at the wall of the cavity or in converters placed inside the cavity. A fraction of absorbed energy is converted to X-rays. These X-rays are confined by the cavity wall, producing a nearly Planckian and nearly uniform radiation environment around the capsule. The radiation field is conveniently expressed as a brightness temperature $T_r$.

As $T_r$ time history determines the shock sequence required to compress the fuel on a low isentrope, it should be precisely measured (typical values are: $\Delta T_r/T_r$ of the order of 1 %, with less than 100ps time resolution). Many measurements have been already performed to establish the relation between the absorbed driver power and the drive temperature[15].

Broad band X-ray spectrometers are used to infer X-ray intensity escaping from a hole in the cavity wall. They are either based on a transmission grating[16] or on an array of fast diodes[17]. $\Delta T_r/T_r$ of the order of 2 % are routinely achieved. But as the cavity is heated high Z plasma from the wall may obscure the line of sight, reducing the observation hole diameter. To improve the overall precision a companion diagnostic is needed, i.e. a Soft x-ray Imager working at several photon energies (about 300 eV to 1200 eV)[18]. Other techniques exploit the strong dependence on the drive temperature of the radiation wave or of the shock generated in a well-characterized sample.

The radiation field produced in a laser-heated hohlraum is not perfectly Planckian and reflects the wall material atomic structure. The M-band radiation of wall material at a few keV can penetrate deep in shell and increase of fuel entropy. So the amount of energy radiated in the range 2 to 5 keV has to be measured and an absolutely calibrated, time resolved, $\lambda/\Delta\lambda \sim 300$ spectrograph should also be available.

As ICF cavities never reach a complete equilibrium, the radiation environment around the capsule evolves in time. In ID scheme driver beams (and laser entrance holes) positions generate low order ($l < 10$, if the intensity distribution is expressed in terms of spherical harmonic functions $Y_{lm}$) asymmetries at the capsule surface. The intensity pattern around the capsule can partially be controlled by changing the target geometry or the relative power of the beam cones[19]. Drive symmetry measurements are well essential to optimize the irradiation geometry. One possibility is to image the compressed shell at stagnation[20]. Although quite valuable, this kind of measurement integrates the time

evolution of the non-uniformity making the analysis much more difficult. Several time resolving techniques using X-ray imaging and surrogate capsules have been developed[21,22,23]. The comparison of these methods is beyond the scope of the present paper, but is important to notice a lot of work is still to be done. As a matter of fact, for example the NIF specifications on flux asymmetry are 1% for $a_2/a_0$, and 0.25 % for $a_8/a_0$. If we assume azimuthal symmetry, the flux is expressed as $\Sigma\ a_l(t)P_l(\Theta)$ ($P_l$ = Legender polynomial). It translate to $a_8 < 2\mu m$, so high spatial resolutions are required.

### 4.3 Implosion phase

Numerical simulations and models indicate that, for a given driving pressure, the ignition energy scale as[24] $E_{ign} \propto \alpha^{1.88}.V^{-5.89}$ with V= final implosion velocity and $\alpha$ = fuel entropy parameter during the implosion. If the coupling between the capsule and the driver is correct, most of the energy transferred to fuel appears, at the end of the implosion phase, as shell kinetic energy. Therefore, the measurement of the final implosion velocity V is also an essential over-all control of the coupling efficiency. On the other hand, $\alpha$ higher than expected is the signature of fuel heating by suprathermal particles or, more likely, an inappropriate pulse shaping.

Rather than V, the beginning of the stagnation phase can be measured. The end of the acceleration phase is marked by the collapse of the strong shock generated in the DT gas by the shell motion (commonly named "bang time"). At that time, the gas temperature increases sharply generating X-ray and neutrons emissions. Typically, the bang time is measured with an X-ray streak camera and temporal resolution less than 30ps, satisfying NIF/LMJ requirements.

The entropy parameter is not directly accessible. It has been proposed to measure the shell thickness $\Delta R$ by X-ray radiography ($\Delta R$ is proportional to $\alpha^{-0.6}$). The measurement would require a backlighting source at 6 to 8 keV and a high spatial and temporal resolution X-ray imager (typically less than 2μm and 10ps).

Concerning the problem of hydrodynamical instabilities during the acceleration phase, although experiments using spherical corrugated shell have already been performed[25], the analysis of instability growth will probably be performed in cylindrical[26] or planar geometry[27]. The measurements will require X-ray radiography capabilities with high spatial resolution (<10 μm) X-ray imaging at a few keV.

### 4.4 Fuel assembly

The capsule hydrodynamics during the stagnation phase will be analyzed in several situations: surrogate capsules ($D_2$ filled, low DT mass, tracer...), deliberately under driven cryogenic DT capsule and nominal capsules that fail to ignite. The parameters to be measured are given in Table 1 in conjunction with some proposed diagnostics[28]. Many of these measurements have been carried out on smaller scale capsules (with laser energy up to 40 kJ), to infer the core and pusher final conditions. Some of the diagnostics could meet the requirements for MJ scale capsules with minimal R&D (yield measurements, ions temperature...). Others need significant improvements, for example, the measurement of size and shape of the burning zone. In recent experiments on Omega laser, neutron imaging with penumbral imaging achieved about 20μm spatial resolution,

getting 5 μm resolution requires more work (detector, aperture, data processing). Lastly, some presently used techniques are limited to small-scale capsules, but similar method can be extrapolated. For example fuel areal density has been measured by secondary neutron emission (Reaction in Flight) in $D_2$ filled balloons, but the measurement is limited to $\rho R < 0.1$ g/cm$^2$. For MJ DT filled capsules, $\rho R$ measurement will be possible via tertiary secondary neutron emission.

**Table 1 .** Measurements for fuel assembly characterization

| Parameter | Diagnostic | Range for MJ experiments | Precision |
|---|---|---|---|
| Number of reactions Y | Activation measurements | $10^6$ to $10^{17}$ | 10 % |
| Emission time | X-ray or γ detector [29] + Streak camera | 10 to 20 ns | 100 ps |
| Emission duration | idem | < 300 ps | 10 ps |
| **Hot spot** | | | |
| Ion Temperature Ti | * Neutron spectrograph / Time of flight<br>* X-ray spectroscopy | 4 to 15 keV | 5 % |
| Density ρ | * X-ray spectroscopy [30]:<br>* Tracer Stark broadening | 50 to 200 g/cm$^3$ | 10 % |
| Areal density ρR | Reactions in Flight[31,32]:<br>* Neutron spectrograph/Time of flight<br>* Proton spectrograph<br>Radiochemistry[33] | < 0.5 g/cm$^2$ | 10 % |
| Radius and shape | - Neutron Penumbral Imaging[34]<br>- X-ray imaging (10 to 15 keV) | 15 to 100 μm | 5 μm |
| **Main Fuel** | | | |
| Areal Density ρΔR | 1/Reactions in Flight:<br>* Neutron spectrograph / Time of flight<br>* Proton spectrograph<br>2/Radiochemistry<br>3/X-ray spectroscopy absorption measurement | < 1.5 g/cm$^2$ | 10 % |
| Density ρ | | 1500 g/cm$^3$ | 10 % |
| Integrity | X-ray imaging[35] | | 5 μm |

### 4.5 Ignition and burn

The phase devoted to the study of burning capsules requires less measurements than the previous ones. The first reason is that if ignition is achieved, it implies nominal hot spot conditions. The second is that when the main fuel burns, it conceals the hot spot emissions. Finally, if capsules operate not very far from ignition threshold, it could not tolerate measurements inducing some perturbations such as tracers, observation windows ... The core measurement for burning capsules is the burn efficiency by the reactions number, the emission time and duration, the ion temperature and the total areal density with a neutron spectrograph. The related diagnostics are the same than in previous step, only the ranges differ.

## 5. CONCLUSIONS

The measurements requirements for moderate thermonuclear gain ICF experiments have been analyzed considering the critical yardsticks. Solutions have been proposed to

meet most of these requirements and the diagnostics have been successfully tested on existing facilities. R &D are still needed for some of them to reach the specified spatial or temporal resolutions. Some measurements involve specific surrogate capsules or geometry: the transposition to the nominal capsule has to be further analyzed.

It is important to stress that most of these measurements requires absolutely calibrated diagnostics and that they will have to work in a perturbed environment for high yield experiments[36].

**References**


[1] M.D. Campbell and W.J. Hogan, Plasma Phys. Controlled Fusion **41**, B39 (1999).
[2] M. André, M. Novaro and D. Schirmann, Chocs **13**, 73 (1995).
[3] J.D. Lindl, Phys. Plasmas **2**, 3933 (1995).
[4] S.E. Bodner et al., Phys. Plasmas **5**, 1901 (1998).
[5] M. Tabak et al., Phys. Plasmas **1**, 1626 (1994).; R. Kodama et al., Phys. Plasmas **8**, 2268 (2001).
[6] K.A. Tanaka et al., Phys. Plasmas **7**, 2014 (2000).
[7] W.L. Kruer , *The Physics of Laser Plasma Interaction* (Addison-Wesley, New-York, 1988)
[8] M. Pergament (these proceedings)
[9] S. Chandrasekhar, Hydrodynamic and Hydromagnetic Stability (Oxford University Press, London, 1961).
[10] S.P. Regan et al., Phys. Plasmas **6**, 2072 (1999).
[11] S.H. Glenzer et al., Phys. Plasmas **7**, 2585 (2000) ; J.C. Fernandez et al., Phys. Plasmas **4**, 1849 (1997).
[12] B.J. MacGowan et al., Phys. Plasmas **3**, 2029 (1996).
[13] S.H. Glenzer et al., Phys. Plasmas **6**, 2117 (1999).
[14] C. Labaune et al., Phys. Rev. Lett. **75**, 248 (1995) ; S. Depierreux et al., Phys. Rev. Lett. **84**, 2869 (2000).
[15] R. Sigel et al., Phys. Rev. Lett. **65**, 578 (1990) ; H. Nishimura et al., Phys. Rev. A **44**, 8323 (1991) ; R. Kauffman et al., Rev. Sci. Instrum. **66**, 678 (1995) ; C. Bayer et al., 23rd ECLIM, St John's College, Oxford, England (1994) ; C. Decker et al., Phys. Rev. Lett. **79**, 1491 (1997) ; R.J. Leeper et al., Nuclear Fusion, **39**, 1283 (1999).
[16] G.A. Chandler et al., Rev. Sci. Instrum. **70**, 561 (1999).
[17] J-L. Bourgade et al., Rev. Sci. Instrum. **72**, 1173 (2001).
[18] K.L. Baker et al., Phys. Plasmas **7**, 681 (2000).
[19] S.W. Haan et al., Phys. Plasmas **2**, 2480 (1995).
[20] A.A. Hauer et al., Phys. Plasmas **2**, 2488 (1995).
[21] N.D.Delamater et al, Phys. Rev.E **53**, 5240 (1996).
[22] P.Amendt et al, Phys. Plasmas **4**, 1862 (1997).
[23] S.M.Pollaine et al, Phys. Plasmas **8**, 2357 (2001).
[24] M.C. Herrmann et al., Phys. Plasmas **8**, 2296 (2001).
[25] C. Cherfils et al., Phys. Rev. Lett. **83**, 5507 (1999).
[26] J.M. Scott et al., Rev. Sci. Instrum. **72**, 643 (2001).
[27] B.A. Remington et al., Phys. Fluids B**4**, 967 (1992) ; J.P. Knauer et al., Phys. Plasmas **7**, 338 (2000).
[28] T.J. Murphy et al., Rev. Sci. Instrum.**72**, 773 (2001).
[29] R.R Berggren et al., Rev. Sci. Instrum. **72**, 873 (2001).
[30] B. Yaakobi et al., Phys. Plasmas **4**, 3021 (1997) ; C.J. Keane et al., Phys. Rev. Lett. **72**, 3029 (1994).
[31] E.G. Gamalii et al., JETP Lett. **21**, 70 (1975) ; H. Azechi et al., Laser Part. Beams **9**, 119 (1991).
[32] R.D. Petrasso et al., Phys. Rev. Lett. **77**, 2718 (1996)
[33] E.M. Campbell et al., J. Appl. Phys. **51**, 6062 (1980).
[34] G.L. Morgan et al., Rev. Sci. Instrum. **72**, 865 (2001) ; J-P. Garconnet et al., Laser Part. Beams **17**, 563 (1994).
[35] B. Yaakobi et al., Phys. Plasmas **7**, 3727 (2000).
[36] J-L. Bourgade (these proceedings).