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The role of experimental science in ICF – examples from X-ray diagnostics and targets

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Abstract. The USA Inertial Confinement Fusion (ICF) Program evolved from the Nuclear Test Program which had restricted shot opportunities for experimentalists to develop sophisticated experimental techniques. In contrast the ICF program in the US was able to increase the shot availability on its large facilities, and develop sophisticated targets and diagnostics to measure and understand the properties of the high energy density plasmas (HEDP) formed. Illustrative aspects of this evolution at Lawrence Livermore National Laboratory (LLNL), with examples of the development of diagnostics and target fabrication are described.

PACS. 52.57.-z Laser inertial confinement – 52.25.Os Emission, absorption, and scattering of electromagnetic radiation – 52.57.Fg Implosion symmetry and hydrodynamic instability (Rayleigh-Taylor, Richtmyer-Meshkov, imprint, etc.) – 52.38.Ph X-ray, gamma-ray, and particle generation – 52.38.-r Laser-plasma interactions

1 Introduction

The ICF program is a major effort in the US with budget far exceeding the US magnetic confinement program [1]. A part of the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program (SSP) it has clear scientific goals and methodology. The goal and objectives of the present day US ICF program is clearly stated [1]. It is to develop laboratory capabilities to create and measure extreme conditions of temperature, pressure, and radiation, including thermonuclear burn conditions, approaching those in a nuclear explosion, and conduct weapons-related research in these environments.

The demonstration of laboratory ignition is the highest priority goal of the ICF Program and a major goal for NNSA. The US ICF program has a strong and open scientific infrastructure, with countless publications and awards from the broad fusion community. A key element of the scientific culture of the US ICF program is the interplay between experiments and theory (design). This is best if there is an abundance of sophisticated experiments and sophisticated design codes.

An abundance of sophisticated experimental capability is a relatively recent development in the ICF program. For many of the early lasers, Janus 100 J, 1 μm, Shiva 10 kJ, 1 μm, Novette 6 kJ, 0.35 μm, the laser itself was the experiment. However the community gradually learned how to build facilities for experimental use. However experiments on HEDP plasmas produced by high intensity lasers are difficult because of the extreme conditions of temperature and pressure, the short time scales (ns) and small-scale lengths (μm). For these reasons it takes many shots to develop the diagnostics for HEDP plasmas so that the diagnostic themselves are not the experiment. And for all of the high energy lasers shots are very limited.

In this paper, a Teller award acceptance lecture, I outline examples of new experimental techniques which I and colleagues in the US and the UK developed, opening new areas of HEDP. The examples from X-ray backlighting development, gated X-ray imaging development, fast electron transport and hydrodynamic instability experiments, are anecdotal and not inclusive. But key to this development was the story of how the shot availability was increased on the Nova laser in the late 1980's, following the model of the much smaller laser at the Central Laser Facility in the UK.

2 Shots, shots and more shots

The Nova laser at Lawrence Livermore National Laboratory (LLNL) has been used for target experiments since 1984. Initial years of the facility the shot rate was modest ~400 shots per year. However to fully use the facility and to grow the diversity of experimental techniques and scientists who could take advantage of high intensity lasers we made a conscious effort to increase the shot rate. The hundreds of processes required to have a successful shot were

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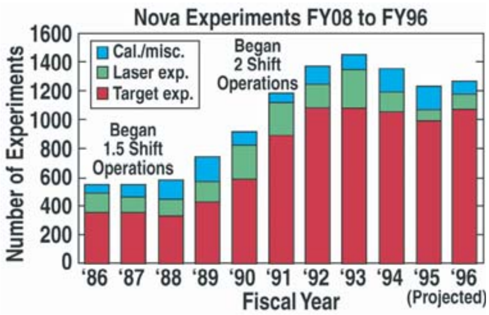

Fig. 1. The number of experiments/year on Nova was increased to provide more capability for the US ICF Program.

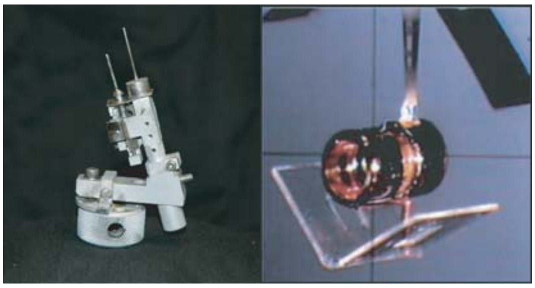
(a) (b)

Fig. 2. (a) The Nova double target point backlighter mount. Backlighter was on the left hand rod with 3 axes of relative adjustment. Post separation ∼6 mm. (b) OMEGA hohlraum with two fixed area backlighter below.

examined, minimized and parallelized as much as possible. Quantitative examination of the shot rate was made and optimized. Operational hours were extended but staggered to allow parallelization of efforts as much as possible. As a result the facility's experimental shot rate has increased every year as shown in Figure 1 reaching a peak of 1430 shots/year in 1993 which has only been exceeded by OMEGA in 2005.

However a high information rate requires more than a high shot rate. Small user facilities such as the Rutherford Laboratory do block scheduling of several weeks to one investigator who brings his own diagnostics up. On the larger facilities this is not an efficient process. It most efficient to keep diagnostics on the chamber and operate them routinely by facility technicians. For diagnostics to operate properly they must be pointed in the right direction and timed. Pointing and timing requirements are demanding with plasmas whose size is measured in tens of microns and existence of at most 10 ns and as short as 1 ps. Keeping diagnostics working given the drifts in time and space of timing systems and mechanical structure is demanding requiring robust engineering and a quality management system to ensure a continual improvement in the reliability and effectiveness of the diagnostics. At Nova and most recently on OMEGA the user satisfaction of shots is well in the 90%. In contrast to some smaller facilities, the diagnostics on Nova were engineered to be routinely run on any shot by facility staff. This involved professional engineering standards being applied to the diagnostics. The paradigm of several Ph.D. level scientists working for many weeks to get their principal diagnostic installed for their series of experiments, and after an intense campaign of experiments removing their diagnostic, has been avoided. In the long run, this is an efficient use of resources.

For flexibility, all of the X-ray imagers and X-ray spectrometers that operate close to the target were made to be interchangeable into one of six standardized vacuum load lock and manipulator devices, known as a SIM (six inch manipulator). In excess of twenty diagnostics were mounted on the carts that fit into the SIMS. This standardization allows key diagnostics to be moved from one location on the target chamber to another location over a period of about 1 h, so that the configuration of target diagnostics could be rapidly changed for different experimental campaigns typically every 2–4 shots. This orderly procedure for the diagnostics ensured that this is not a limiting process in the turn around time for shots.

3 The development of X-ray backlighting for ICF

It is well-known that the absorption a probe beam of photons can be used to measure the optical depth of a medium by $I(t) = I_0 e^{-\tau}$, and thus the properties of a plasma. Experimentally the backlighter must be differentiated from self emission from the plasma implying that the backlighter must be brighter in the spectral region of interest than the plasma being probed. A laser-produced plasma can often satisfy this requirement by changing the intensity of irradiation and by choosing the atomic number Z of the backlighting target.

In the field of ICF this technique was pioneered at the Central Laser Facility [2] albeit on a relatively small laser. On the 30 kJ Nova at LLNL we gradually adopted and improved this technique. Nova and OMEGA are lasers primarily designed for implosion, without an extra beam for backlighting. This requires one or more of the implosion beams to be taken off the main target and focused on the backlighting target(s). Moreover Nova only had one target positioner. Working with Roy Powell of AWE we designed a single based target mount with had an adjustable position backlight target holder as shown in Figure 2a.

Experiments on Nova in collaboration with AWE on hydrodynamic instabilities and opacity started in 1987 [3]. Initially point projection backlighting was used as a synchronous short pulse could be used to irradiate a "point" source. Figure 2a shows the separate alignment required for the point backlighter. The point backlighter had to then be accurately placed at the tight focus of the backlighter beam, a complicated alignment process pushing the limits of the alignment system on Nova at the time. The back lighter target was a cocktail material to get a broadband X-ray emission source mixing bands of emission from several elements. A similar concept is now used for the wall material of a hohlraum to get a high average X-ray opacity of a wall to impede radiation flow [4].

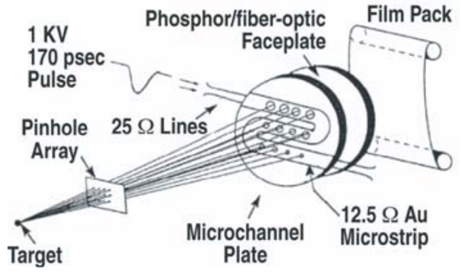

Fig. 3. The concept of applying a pulse voltage to a microchannelplate with a gold micro-strip transmission line coated onto it.

With the advent of gated imaging systems on Nova the easier technique of area imaging was used extensively for hydrodynamic growth rate experiments. Area gated imaging progressed slowly because a reliable gated imaging detector was required. On Nova this started with a Wolther X-ray microscope and then to gated pin hole imaging (below). It took time and shots! The technology was then transferred to OMEGA by the early part of this decade [5]. The less complicated target for a double area backlighting system is shown in Figure 2b.

The overall time for the development of backlighting on Nova and OMEGA has been from about 1987 to only the last few years on OMEGA. Why so long? One answer was the development time for the detectors, partially limited by shot rate. Another is simply the cycle time to advance technology limited by shot rate.

4 High speed gated X-ray imaging for ICF

The ability to take high-speed ($\sim$100 ps) gated X-ray images is now routine in ICF. It was developed mainly at LLNL in the 80's and 90's [6]. Gold coating of a microchannelplate in the form of a microstrip transmission line, allows a voltage $V(t)$ to be applied. As microchannelplate electron gain is proportional to $\sim V^n$ where $n \sim 10$ [7], time gating is achieved with shortening of voltage pulse $V(t)$ as in Figure 3.

Generating a 1 kV, 100 ps voltage pulse into the low impedances of the microchannelplate was solved by Kentech Instruments, Ltd. [8] based on low cost avalanche transistor technology, allowing low jitter pulsers to be mounted close to the micro-channel plate assembly, a necessity for the fast rise time of the pulses.

The first of many gated X-ray imagers was installed on Nova about 1988. The facility eventually had many reliable gated X-ray imagers: in 1992 [9] the facility had five facility run gated X-ray imaging systems. One of the key experiments they were used on was to demonstrate control of the symmetry of X-ray drive by studying the distortion of the X-ray emission from imploded cores [10]. The accurate measurements of the symmetry control allowed by this technique and a large enough number of shots to achieve accurate results showed that unexpected effects of beam steering were occurring in the propagation of high power unsmoothed laser beams through a flowing plasma.

Nowadays in optical imaging we are used to high quality images with millions of pixels and large dynamic range. Disappointingly the gated X-ray imaging remains low image quality. This is an inherent result of the low dynamic range because of the saturation of the micro-channel plates coupled with the relatively low number of pixels available and the backgrounds. A technology other than gated micro-channel plates is needed to bring image quality up to what we expect in relation to the low cost electronic cameras available in almost every home.

5 Fast electron transport in ICF

At this conference there has been a lot of work presented [11] on fast ignition physics and in particular the transport of electrons at $I\gamma^2 \gtrsim 10^{19}$ W μm^2/cm^2. As the current is much higher than the Alfvén current, a return current is generated and the electric field needed to drive this return current can resistively inhibit the transport of the electrons.

In the late 70's it was discovered that if $I\gamma^2 \gtrsim 10^{15}$ W μm^2/cm^2 the laser beam energy goes into fast electrons and is decoupled from accelerating targets. Experiments pioneering techniques of K_α fluor layers buried in targets [12] and also discovering the phenomenon of resistive inhibition in special low density gold targets [13] were carried out at the Rutherford Laboratory and elsewhere. Developments in targets, with layered fluor targets and with 2% normal density gold were the key to advances our understanding of fast electron transport in the 80's.

6 Hydrodynamic instability experiments in ICF

In perturbation theory a system equilibrium is perturbed and the linear growth of that perturbation can often be calculated. For hydrodynamic instabilities such as the Rayleigh-Taylor system a fluid interface is perturbed by a sine wave and as long as its amplitude $\ll 2\pi/k$, where k is the wave number, the linear growth rate is readily calculated to be $\gamma = (ka)^{0.5}$. For imploding systems this is fortunately reduced by ablative stabilization, so that $\gamma \sim (ka)^{0.5} - Akv_A$, (where $A \sim 3$), and by material strength. The theory for both of these effects is inaccurate and has been refined by experiments.

The experimental analogue of the mathematical harmonic analysis above is shown in Figure 4. A small perturbation is applied to an accelerating surface and the growth of that perturbation is observed by radiography and time resolved instruments. In ICF this was first done in the eighties on a small laser and with early time resolving instruments [14]. After the evolution of more reliable time resolving imaging instruments and a sufficient number of shots a large number of experimental studies were made [15] of the ablative stabilization in ICF and more

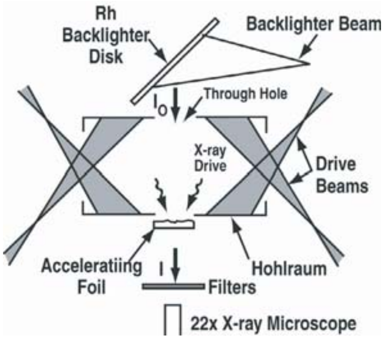

Fig. 4. The experimental arrangement to measure the growth of an initial perturbation on the upper surface of an accelerating foil.

recently measuring material strength in high strain rate conditions.

7 Summary

There has been a remarkable evolution in the sophistication of our understanding of phenomena in ICF since the seventies. However it has taken many decades. Why? In general it is because of the evolution of our understanding follow a naturally cycle time. Given the limited number of shots (say tens) available to any team of investigators on a large facility, it takes a timescale of a year to evolve the reliable operation of a new experimental set-up. It can be limited by diagnostics, targets or laser. The cycle time, like the evolution of a new product such as a car, is then naturally measured in years. Part of this is how long we take to learn facts and broadly accept them. Ensuring an adequate number of high quality experiments helps and a necessary but not sufficient condition is the availability of a high shot rate.

In the future we need to learn how to operate high shot rate facilities where the shot rate can be once every second or higher. A new era of our understanding the physical systems of ICF will then evolve.

In the work described here I have been lucky enough to work with many scientists mainly in the UK and then the US and in other countries. I owe many insights to these colleagues. Work supported by the US Department of Energy under Contract No. DE-AC03-01SF22260.

The proofs have not been corrected by the author.

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