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PROGRESS IN INERTIAL CONFINEMENT FUSION AT LAWRENCE LIVERMORE NATIONAL LABORATORY

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Lawrence Livermore National Laboratory

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PROGRESS IN INERTIAL CONFINEMENT FUSION AT LAWRENCE LIVERMORE NATIONAL LABORATORY*

Abstract

The goals of the Inertial Fusion Program at the Lawrence Livermore National Laboratory are to study matter under extreme conditions of temperature and pressure and to produce fusion energy from inertially confined fusion fuel. With the conclusion of recent multi-kilojoule 0.53 μm and 0.26 μm experiments on Novette, we have demonstrated vastly improved plasma conditions compared to those previously obtained at LLNL with similar energies at 1.06 μm and elsewhere with 10 μm radiation. The lower preheat environment obtainable with short wavelength light has lead to 3X improvements in the compression of targets on Novette compared to similar targets on Shiva with 1.06 μm. Subsequent experiments on Nova with short wavelength light will begin in 1985. They are expected to demonstrate the necessary compression conditions required for high gain fusion to occur when irradiated with a multi-megajoule driver. These recent results, together with improved calculations, and innovations in driver and reactor technology, indicate that high gain inertial fusion will occur and is a viable candidate for fusion power production in the future.

The goals of the Inertial Confinement Fusion Program at the Lawrence Livermore National Laboratory are twofold. The first is to study matter under extreme conditions of very high temperature, pressure and nonequilibrium local conditions. The second is to produce fusion energy from inertially confined fusion fuel to study the fusion process and to provide efficient energy production for electrical power. With recent experiments, the program has made great progress toward these goals, and reached a new level of understanding. To place the program's results in perspective, I review its history. In the 1960's the laser and the inertial fusion concept were invented and development began. In the 1970's the first moderate size laser systems were designed and a variety of experiments were conducted to determine the important physics principles governing the target compression process. In this time period problems with long wavelength irradiation were discovered. In the 1980's the goal is to demonstrate satisfactory control over the relevant physics of target irradiation and compression. We have already begun these demonstrations using the Novette laser and we plan to complete them using the soon to be

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finished 100 kJ level multi-wavelength Nova laser system. In the early 1990's we anticipate demonstrating efficient fusion burn and high gain in the laboratory with a future multi-megajoule laser fusion facility.

The Novette Nd:glass laser system[1], Fig. 1, was assembled on an accelerated schedule in 1982, in an existing laboratory building. The system contained Nova style laser hardware and controls, the refurbished and modified Shiva target chamber, and a complete suite of target diagnostics, most of which came from Shiva. Novette delivered 18 kilojoules in 1.05 μm, 1 nanosecond pulses which were then frequency converted to the second or to the fourth harmonic. The 9 kJ at 0.53 μm focused on target made it by far the most powerful green light target irradiation facility operating in the world, and the 1.5 kJ of focused UV radiation

Figure 1. View of the Novette laser facility. Target chamber is in the foreground and the two laser chains can be seen in the background.

made it the most powerful UV laser in the world. Each of its two relatively compact arms has exceeded the total output of all of Shiva's 20 arms at 1 μ. Novette was assembled in well under a third of the time required to build Shiva, needs less than half of Shiva's manpower to operate, and has achieved a better shot rate on target.

Each of Novette's two beam lines was optically very similar to those in the Nova laser so the emerging beams were 74 cm in diameter. Harmonic conversion takes place in two unique mosaic arrays of potassium dihydrogen phosphate (KDP) crystals. The two ~4.5 TW green laser pulses so produced were focused onto targets by two, 74 cm aperture f/4 doublet lenses. A second array was used to double the 0.53 μ light to produce 1.5 kJ of 0.26 μ light from one beam. About half of Novette's experimental time has been devoted to plasma physics studies whose aim is to better understand short wavelength driven inertial confinement fusion. The balance was divided between high density implosion research and non-local thermodynamic-equilibrium plasma experiments. Novette provided a high energy density, flexible experimental facility which bridged the gap between Shiva and Nova while simultaneously probing each detail in the Nova design. As a test bed for the Nova laser, Novette provided the first operational test of split disk amplifiers and of harmonic generation with large-aperture, multi-element KDP crystal arrays. The performance of Novette certified that the Nova laser will perform above the baseline specifications for the system.

The recently completed, very successful series of inertial confinement fusion experiments conducted using the Novette laser provide an extension of the data base achieved on Shiva with 10 kJ at 1.06 μ wavelength in the late 1970's. Under short wavelength irradiation conditions, we have achieved a higher quality compression than ever before, we have achieved fusion temperatures and pressures with very low preheat levels, and we have measured the primary source of hot electron production in long scalelength plasmas.

The plasma experiments conducted with Novette were specifically intended to explore laser-plasma interaction physics in large, Nova-size plasmas. To do this, we used the Novette laser to irradiate solid (disk) targets and to explode thin gold or plastic foils. The disk targets produced axial plasma scalelengths that were hundreds of laser wavelengths long, and the foil targets produced plasma scalelengths of several thousand laser wavelengths. This is sufficient to approach or exceed the predicted thresholds for many laser-plasma instabilities. These successfully executed experiments showed that short wavelength light indeed couples in a very collisional fashion to the inertial confinement fusion plasma leading to very low electron preheat levels. Figure 2 shows data taken with the Novette laser and compares it to previous data taken with Shiva, Argus at LLNL and with data taken at other institutions. These experiments continue to exhibit the very high absorption at shorter wavelengths earlier at plasma scalelengths 10X larger than previously used.

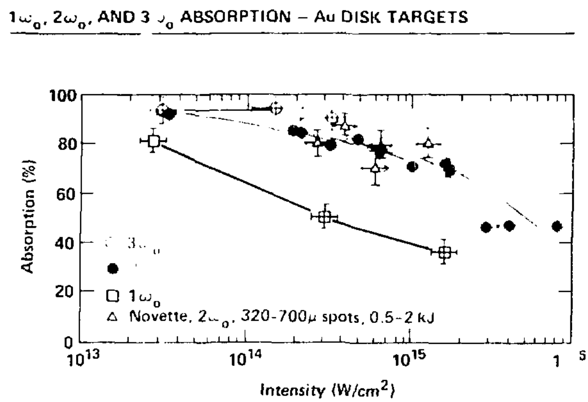

Figure 2. Short wavelength light 0.5 μ, 0.35 μ, and 0.26 μ, is absorbed more effectively on disk targets than 1 μ light. This trend has been verified using the Novette laser over plasma dimensions 10X larger than these used on previous experiments.

With the lower preheat levels obtainable for a given laser intensity and hence given drive condition, allowed us to compress targets to threefold higher densities[2] compared to similar experiments using the Shiva laser at 1.06 μ, see Fig. 3. Finally we have conducted a series of careful experiments to show that the source of hot electrons in the laser plasma interaction is primarily due to the Raman interaction at 0.1 critical density.[3] Figure 4 shows that the production of hot electrons is directly proportional to the production of Raman scattered radiation, which occurs near one-tenth of the critical density.

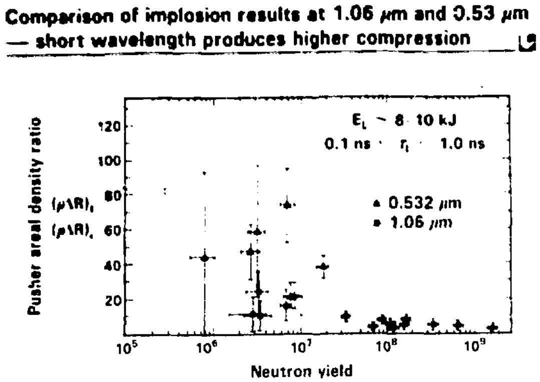

Figure 3. 3X improvements in compression have been measured using the Novette laser. These improvements arise because the compression environment is free from preheat and purely ablative compression can occur.

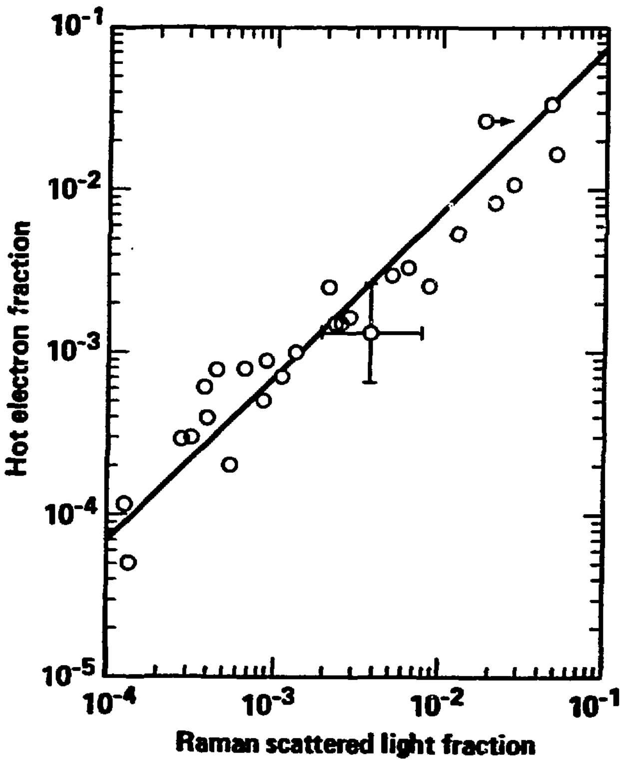

Figure 4. The correlation between hot electron production and Raman scattered light is convincing evidence that the Raman instability is the principal source of hot electron preheat in ICF plasmas.

These experiments further verify the reduction in the magnitude and impact of laser-plasma instabilities that can be realized with short wavelength irradiation. The performance available with Novette has also allowed us to extend our short wavelength laser-plasma interaction data base toward obtaining a better understanding and quantification of instability thresholds and given us added confidence that we will obtain conditions suitable for driving high-gain ICF targets with short wavelength lasers.

The Nova laser, Figs. 5 and 6, is designed to produce 80 to 120 kJ of 1 μ light, 70% of the 1 μ levels at either the second harmonic or the third harmonic, and to do this with a high degree of controllable pulse shaping.[4] This laser will be completed in the Fall of 1984. With this instrument we expect to show that the laser plasma interaction is understandable and acceptable over plasma scalelengths associated with reactor targets (~1 cm). We also anticipate showing that targets can be compressed to the necessary fusion conditions (except for sufficient fuel ρr) which are to 500X to 1000X liquid DT densities with the formation of a hot spot (the ignition source for the fusion capsule), and to show that the hot spot occurs with proper symmetry.

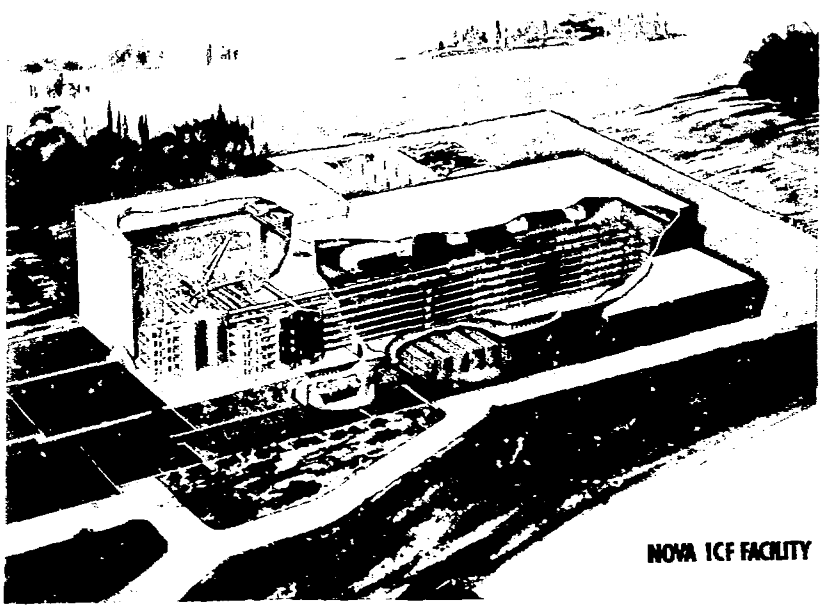

Figure 5. Cutaway schematic of the Nova facility.

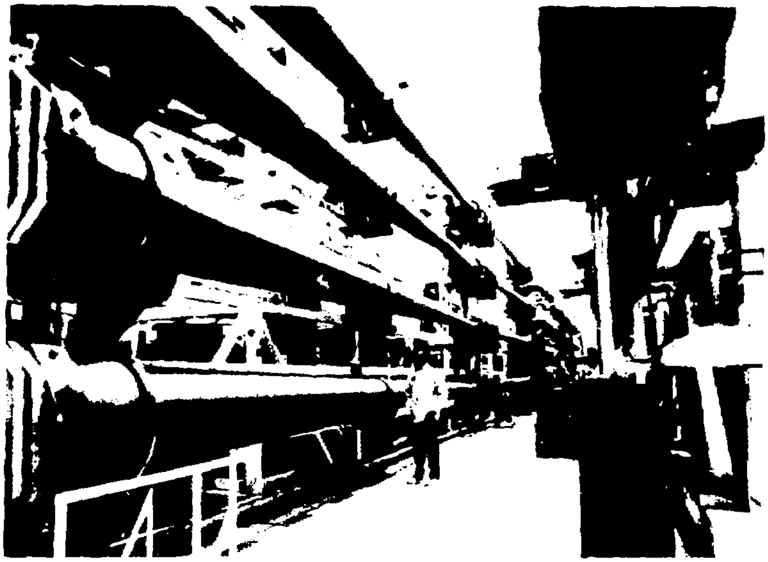

Figure 6. Output section of the four Nova beam lines.

The Nova experiments will provide the required data to set the size of a high gain test facility. We anticipate the high gain driver to be a 5 to 10 MJ laser producing a wavelength less than or equal to 1/2 micron, and providing complex pulse shapes with typically 10 nsec time variations. This laser will be used to drive a variety of target configurations for fusion as well as other experiments such as x-ray laser research, etc. On this system a variety of target designs can be optimized to reach as low an energy threshold as possible for fixed high gain. Also target research would be conducted to reach the highest gains possible with a fixed energy input, as well as to design the simplest, cheapest targets for subsequent application in a reactor environment. Together with these planned target performance demonstrations, we are developing technologies based on high repetition rate, high efficiency solid systems, gas systems, and on the free electron laser. In addition, we are developing economical reactor technologies for commercial fusion and gain.

Our ultimate objective is to apply inertial fusion technology to the generation of commercial energy.[5] It must be competitive with expected fission reactor technology and coal/steam-turbine technology expected in the early 2000's. To make fusion competitive (both MFE and ICF) with these competing technologies, costs need to be reduced over those associated with present systems. Inertial fusion physics permit competitive costs to be attained if we are able to take advantage of potential system performance improvements. Examples of these improvements may be:

1) achieve higher gain by improving the quality of the implosion.
2) reduce the energy threshold of the high gain reactor by using polarized fuel.
3) design drivers that are multiplexed to drive several reaction chambers at the same time, thus reducing their effective cost per reactor unit.
4) use the high quality heat of the fusion reaction to achieve a higher thermal conversion efficiencies than present steam cycle of ~35%.
5) take advantage of potentially simplified reactor concepts available with inertial fusion processes by making them more compact and by using nonflammable heat transfer medium.

With experiences of these last two years and with our projections for the future, we are confident that the inertial fusion process holds great potential for the future.