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Harlow G. Ahlstrom

MASTER

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Harlow G. Ahlstrom

FORWARD

Inertial confinement fusion is the present and future source of energy in our universe. Derivatives, such as solar, geothermal, wind, and biomass are proposed as future substitutes for possible fuel sources. All of these possible sources of energy while they may be considered to be renewable do not fulfill the single most important criteria of being unlimited. Fuel reserves of more than 100 billion years are accepted as "unlimited". The understanding of fusion has many "fathers", Bethe, Teller and many others, it has also had proponents (too many to list) as the world's energy supply. This author hopes that this Program's efforts will contribute positively to the advance to the time when fusion energy will positively contribute to the energy supply for mankind.

Controlled fusion is judged by us to be the world's most challenging technological problem. The potential benefit to mankind of an unlimited source of energy and thus a higher standard of living make the acceptance of this challenge worth our while. There are many dedicated scientists working on controlled fusion to make this dream a reality. Magnetic and inertial fusion are in a horse race that must not be allowed to falter or to be cancelled. Fusion is the future of the world and one of these approaches to fusion is vital to our future generations.

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I. INTRODUCTION

The basic concept of laser fusion has been described many times in the past.⁽¹⁾ Here we can summarize it in a simple statement of two requirements: fuel density times radius, $\rho r \geq 1 \text{ gm/cm}^2$ and temperatures $\geq 5 \text{ keV}$. The intense focusing capability of the laser, 10^{17} to 10^{18} w/cm^2 is used to create a plasma at the surface of a spherical pellet, the intense heating of the plasma by the laser provides the energy required to ablate the surface of the pellet and compress the fuel to densities of a 1,000 to 10,000 x liquid density of DT. The implosion process is tailored so that at peak compression the fuel also achieves a temperature of approximately 5 keV. At these temperatures and densities and where we have provided a sufficient large $\rho r \geq 1 \text{ g/cm}^2$ we will achieve efficient burn. As pointed out in the past, the reason for compressing the fuel is to achieve $\rho r \geq 1$ for pellet sizes which are sensible for fusion reactors. Since $\rho r \propto C^{2/3}$, where C is the compression, by compressing the fuel to 1,000 x liquid density, we reduce the requirement on the radius of the pellet by a factor of 100. Thus the goal of the Laser Fusion Program is to use lasers to demonstrate that these conditions can be achieved and thus prove the scientific feasibility of laser fusion.

Over the past several years, since 1974 at the Lawrence Livermore Laboratory, we have been pursuing these goals using a series of neodymium glass lasers as the driving sources. In Figure 1, we summarize our results and projections for the future in a chart where we plot the results as a function of the quality of inertial confinement n which

corresponds to r and the DT ion temperature. As seen in the figure, our experiments began with JANUS using a single beam in 1974 at a power of 0.2 TW. At that time we were able to achieve an n of several times 10^{11} and approximately a 0.5 keV ion temperature. In 1975 with two beams from JANUS and 0.4 TW, we were able to increase the fuel temperature to approximately 2 keV with approximately the same value of n . The major importance of the result in 1975 was that we were able to use the fusion reactions to demonstrate that the reactions produced were truly thermonuclear.⁽²⁾ By 1976 we had developed ARGUS at 4 TW and had achieved ion temperatures of approximately 10 keV.

This whole series of experiments was done with a type of target which is called an exploding pusher.⁽³⁾ The main idea in these experiments was to demonstrate that the laser could be used to achieve the fusion temperature conditions albeit at low fuel densities. This lower path shows that SHIVA and NOVA, the next laser coming on-line, could continue with this type of target and achieve higher values of n . However, this type of target with the energies available will not achieve break-even and is not a viable candidate for a fusion reactor target. In 1976 we also began our first series of experiments moving away from the exploding pusher concept in order to achieve high densities although at relatively low fuel temperatures with current laser systems.⁽⁴⁾ By 1978 with ARGUS at 2 kJ, we had achieved $10 \times$ liquid density and early in 1979 with SHIVA at 8 kJ we had achieved a $100 \times$ liquid density. The fuel temperature in these fuel compressions are kept low at approximately a half a kilovolt to maximize the fuel compression and provide only suffi-

cient number of thermonuclear reactions for diagnostic purposes. The achievement of 100 x liquid density from significantly less than liquid density as a starting point is indeed a significant achievement. To achieve this goal, we had to provide sufficiently uniform implosion of the target and, we had to achieve a condition which alleviated the problem of the Rayleigh-Taylor instability.⁽⁶⁾

The next step in the program to achieve greater than 1,000 x liquid density will also require significant developments. One is already in-hand, that is operation of SHIVA at its full energy potential of 15 kJ.⁽⁷⁾ Target designs exist which project these fuel densities; however, they require additional developments in the area of target fabrication. After once achieving 1,000 x liquid density, the program can then use this high density design and result to examine questions of stability through variations of the target parameters. We also plan to trade some of the final fuel density for temperature in order to produce a significant thermonuclear burn by achieving temperatures of 2 keV at these high densities. However, 2 keV and 50 x liquid density will not be sufficient to allow us to achieve self-trapping of the particles in the fuel and therefore cause the particles to raise the temperature of the burning fuel. This boundary is called the ignition boundary and is not expected to be achieved until we have at least the first phase of the NOVA system. This system is presently scheduled for completion in 1983 and the full NOVA system^{(8),(9)} which is expected to produce break-even or greater will be ready in 1985.

II. FUSION LASER SYSTEMS AT LLL

The Laser Fusion Program at Livermore has utilized four neodymium glass laser systems for the demonstration of important milestones in laser fusion and, we are constructing the NOVA system which will also be a neodymium glass laser system. The reader is referred to papers from the Livermore Solid State Program which describe our laser systems: JANUS a two beam, 8.5 cm output aperture system,⁽¹⁰⁾ CYCLOPS a single beam, 20 cm output aperture system,⁽¹¹⁾ ARGUS a two beam, 28 cm output aperture laser system,⁽¹²⁾ SHIVA the twenty beam, 20 cm output aperture system,⁽⁷⁾ and NOVA⁽⁸⁾ which has not yet been frozen in a final design.

All of these systems utilize rod amplifiers and disk amplifiers, Pockel's cells, Faraday rotators, and spatial filters. The technology for these laser systems has largely been developed at the Livermore Laboratory by the Solid State Laser Program. However, the manufacturing of the parts, fabrication of the glass, the finishing of the glass, and the coatings are all done in industry primarily in the United States but also in other countries.

SHIVA the system which we are now operating is a twenty beam system which has 2.5 cm and 5 cm diameter rod amplifiers; and 9 cm, 15 cm, and 20 cm diameter disk amplifiers. The system is assembled using the image relaying concept which was first put forward by John Hunt.⁽¹³⁾ All twenty beams are fully diagnosed at the laser output to determine the energy, spatial distribution of energy, temporal profile of the output pulse, and any prepulses. The system utilizes twenty incident beam

diagnostic packages, IBD, and twenty pointing focusing centering/reflected beam diagnostic packages, PFC/RBD.⁽¹⁴⁾ The beams on SHIVA are arrayed in two clusters of ten which approximate the focusing cone of $f/1$ lenses. The beams are arranged so that each beam has an opposite member through a diagonal in the target chamber. Thus each beam has its opposite member and the PFC/RBD system may be used for accurate alignment of the target and the focus of each one of the beams as has been done on our two beam systems, JANUS and ARGUS. The upper and lower clusters consist of two pentagonal arrays of beams, an inner pentagon and an outer pentagon. The inner cluster is rotated 36° with respect to the outer cluster. This arrangement of the beams on SHIVA allows significant room in the equatorial region for target diagnostics. In Figure 2, we show an artist's view of the SHIVA target chamber showing the beams arriving at the top and the bottom of the target chamber and a number of the target diagnostic instruments that are used in the experiments.

Three instruments that will be discussed more later in this paper are the Dante sub-kilovolt time resolved spectrometer, the FFLEX, filter fluorescer experiment, which is a time integrated, high energy x-ray spectrometer and the radiochemistry diagnostic which is used to measure the activation of various target materials. The SHIVA system has 146 amplifiers, 122 relay spatial filters, and 84 optical diode gates in the laser designs. There are more than 1,000 control points and more than 1,000 data records are taken on every shot. Through the use of microprocessors, fiber optic communication links, minicomputers, and a

higher level supervisory computer,⁽¹⁵⁾ we have been able to bring this system into operation. Microprocessors are located near the control function or data taking element and are used as front-end processors. There are more than 60 LSI-11 microprocessors in the SHIVA system. The LSI-11 microprocessors are connected back to a minicomputer to provide for central control and analysis of each one of the four functional blocks of the SHIVA control and data system. The four functional blocks are the power conditioning which includes the charging and firing of the capacitor banks and the timing for the remainder of the system, the laser diagnostics, the alignment system, and the target diagnostics system.

The SHIVA control system has been extremely successful and has represented a very significant savings in time and money in terms of the implementation and operation of the SHIVA laser target irradiation system. SHIVA has attained and exceeded its design goals. The original goal was 10 kJ in 1 nsec and 20 TW for pulses $\approx$ 100 ps. We have conducted a target campaign where we have fired a significant number of shots at 90 psec and powers of 10 to 27 TW. The 27 TW actually exceeded the damage threshold before the installation of the output spatial filters. However, now with the output spatial filters in the SHIVA system, the damage threshold has been increased to 30 TW.⁽⁷⁾ For long pulse operation, i.e. of the order of a nanosecond, we have done experiments in excess of 10 kJ and now with the output spatial filter, we can operate safely up to 15 kJ. The NOVA laser system which is intended to provide more than a factor of 10 increase in both power and energy capability as compared to SHIVA started out as a design study to determine what upgrade possibilities there were for the SHIVA system.

Developments in the Solid State Program in terms of laser design and materials led us to the conclusion that it was possible to make a significant extension of the technology of the solid state lasers to provide a facility in the range of 0.25 - 0.50 MJ. The full NOVA system has been proposed to Congress and the Department of Energy and at present the Congress has authorized the construction of Phase I of NOVA. Phase I would consist of half of the laser building and $\sim 0.4 - 0.5$ of the total laser capability.

Phase I of NOVA will occupy a new building immediately adjacent to the present SHIVA building and with the completion of Phase I it is planned to remove the SHIVA target chamber from the target room and restage and rebuild the lasers in the SHIVA building to conform to the NOVA design in the east wing. The full system will produce of the order of 300 kJ in 3 nsec and is expected to achieve target gains of break-even or greater. At scientific break-even the number of neutrons produced in a single reaction will be $\sim 10^{17}$. This is a number of neutrons not to be ignored. In Figure 3, we show one of the conceptual designs of the NOVA reaction chamber.⁽⁹⁾ In this design, we show a double-walled vessel which uses aluminum for the inner wall, contains water between the two walls, and utilizes fiber glass as the outer wall. The materials are chosen to minimize the long term activation of materials in the target chamber and to minimize the activation of materials in the target room and the target room itself. With yields expected from the NOVA system, we must begin paying serious attention to the location of diagnostic instrumentation. Although the diagnostic instrumentation is shown

schematically in the target room, in actuality we expect to have the electronic instrumentation outside the target room so that the diagnostics will extend through lines of sight through the seven foot concrete wall of the NOVA target room.

III. TARGET DIAGNOSTICS

In this section we will present characteristics of some of the target diagnostics which have been implemented for the ARGUS and SHIVA experiments. As is well known by now, the x-ray spectrum from a laser irradiated target is quite complex. It consists of a thermal portion of the spectrum which contains most of the energy and generally is in the region of a 100 eV to 1.5 keV. Since targets generally contain materials with $Z > 14$, we expect line radiation in the region of 1 to several keV and above this region we expect to see the signature of the suprathermal electrons which are produced in the laser absorption process.

The two portions of the spectrum which we will be concerned with in this paper are the thermal sub-keV portion of the spectrum and the suprathermal portion of the spectrum produced by the high energy electrons. We have improved our Dante spectrometer which utilizes windowless x-ray diodes and filtering materials to produce spectral discrimination in this portion of the spectrum. The most recent implementation of this system is a ten channel spectrometer⁽¹⁶⁾ designated Dante T. The aluminum photo-cathode in combination with materials such as CH, V, Cr, Fe, Co, Ni, Cu, Zn, Ge, and Al provides spectral discrimination in this region of the spectrum. We have utilized diodes with 200 psec and 50 psec response time. Typically the Dante spectrometer is coupled with Tektronix R 7912

transient digitizers for an overall response time of the order of a 0.5 nsec or to the Thompson CSF TSN 660 oscilloscope which has a bandwidth of 4 gigahertz.

For the high energy, suprathreshold portion of the x-ray spectrum we have implemented what we call our filter fluorescer experiment or FFLEX.⁽¹⁷⁾ In the past we have used simple K-edge filter, in combination with detectors to provide spectral discrimination. However, as the spectra have become hotter, that is more energy in the suprathreshold tail, and a less rapidly falling spectrum, the contribution to a spectral channel from its response above the K-edge became significantly large and thus eliminated the spectral discrimination at the K-edge. To overcome this limitation we have gone to the addition of a fluorescer foil. The K-edge defines a region of the spectrum which is allowed to pass the first filter. This spectrum then impinges on a fluorescer foil which has its K-edge slightly below that of the prefilter. In this situation, most of the x-rays which are produced are due to x-rays between the two K-edges of the two filters. The rapidly falling cross section for the production of fluorescence radiation in the fluorescer foil by x-rays having passed through the prefilter above the K-edge produces very little response for the detector. Thus the combination of the K-edge prefilter and the fluorescer foil produces a narrow band response which can then be used to accurately define the suprathreshold x-ray spectrum. In our typical filter fluorescer experiment, we utilize ten channels which provide spectral discrimination from 2 keV up to 110 keV.

As discussed earlier in the introduction, an extremely important aspect of our program is to be able to measure the density in targets with relatively high density but low temperature. One technique is by the activation of radio nuclides in the target material to determine fuel and shell densities.^{(9) (18)} The DT fusion reaction produces the 14 MeV neutrons which then activate various materials in the target. If a seed material is placed in the fuel, then this can be activated for direct determination of the fuel ρ . An average fuel density can then be calculated. The activation of other materials provides information about the density radius product of those materials at the time of the burn of the fusion fuel.

More specifically we show schematically in Figure 4 we show schematically how the neutron from the fusion reaction could be used to determine the areal density of a SiO_2 pusher. Neutrons from the fusion reaction interacting with the ^{28}Si in the pusher produce ^{28}Al which is a radioactive nuclide. It has a beta gamma decay with a half-life of 2.24 minutes. β 's are emitted with an energy of 2.86 MeV and the γ 's with an energy 1.78 MeV. As shown in the equation, if the neutron yield is measured independently, which is true for our experiments, then if we are able to determine the number of ^{28}Al atoms produced, we can determine the $\rho\Delta r$ of the pusher material. Knowing the $\rho\Delta r$ of the pusher material is of course very useful but we would like to also be able to relate that information to the fuel density. We can either relate the measured $\rho\Delta r$ of the pusher to the fuel density using our complex target

relationship assumes that the mass of the fuel and the glass pusher is conserved. We also make the assumption initially that the density of the two materials are uniform although not equal. Finally, we make the observation that the pressure and temperature at the pusher-fuel interface must be continuous and equal and therefore, we will assume that the pressure and temperatures are uniform and equal throughout the pusher fuel regions.

Conservation of the masses of the fuel and pusher gives,

$$\frac{M_f(f)}{M_f(p)} = \frac{M_o(f)}{M_o(p)} \quad \text{Eq. 1}$$

where the subscripts o and f represent the initial and final states respectively and the f and p in brackets designate the fuel and pusher. Further using the assumption of uniform densities in the fuel and the pusher, we can write,

$$\frac{\frac{4}{3}\pi r_f^3(f) \rho_f(f)}{\frac{4}{3}\pi [r_f^3(p) - r_f^3(f)] \rho_f(p)} = \frac{\frac{4}{3}\pi r_o^3(f) \rho_o(f)}{\frac{4}{3}\pi r_o^2(p) \rho_o(p) \Delta r_o} \quad \text{Eq. 2}$$

where we have also assumed that the initial pusher thickness $\Delta r_o = r_o(f)$.

Simple algebraic manipulation leads to,

$$\rho_f(f) = \rho_o(f) \left\{ \frac{\rho_f(p) \Delta r_f}{\rho_o(p) \Delta r_o} \left[1 + \frac{2}{3} \frac{\Delta r_f}{r_f(f)} + \frac{1}{3} \left(\frac{\Delta r_f}{r_f(f)} \right)^2 \right] \right\}^{3/2} \quad \text{Eq. 3}$$

For cases where $\Delta r_f/r_f(f) \ll 1$, we need no further assumptions.

However, this is not generally true and we make the isobaric, isothermal assumption to obtain a relationship between $\rho_f(f)$ and $\rho_f(p)$. This leads to

$$\rho_f(p) = \alpha \rho_f(f) \quad \text{Eq. 4}$$

where α is determined by the degree of ionization of the pusher material. We can then write,

$$\rho_f(f) = [\rho_f(p) \Delta r_f]^{3/2} G[M(p), M(f), \alpha] \quad \text{Eq. 5}$$

In Figure 5, we plot the solution for the above assumptions which is shown as the solid line relating effective SiO_2 pusher $\rho \Delta r$ to the maximum fuel density. It is interesting to note that a range of 1D simulations essentially bounds this simple approximate solution. Another spatial distribution for the simple model is also shown. It is interesting to note that this rather extreme deviation from our simple assumption of uniform densities produces less than a factor of two difference in the inferred fuel density for a given pusher $\rho \Delta r$. Finally, we show the situation for a complete mixing of the pusher into the fuel such that there are equal amounts of pusher and fuel material in the fuel region. Again, the variation from the nominal case is less than a factor of two.

$$G = \left\{ \alpha \left(\frac{3}{4\pi} \right)^{1/3} \left[\left(\frac{M(p)}{\alpha} + M(f) \right)^{1/3} - M(f)^{1/3} \right] \right\}^{-3/2}$$

The very important result from this simple study of the use of activation of radio nuclides in pusher material is that it is a very effective determinate of the final fuel density and relatively insensitive to the distribution of fuel and pusher and even to mixing of the pusher into the fuel.⁽¹⁹⁾

Now let us examine for a moment how an experiment might be performed. In the analysis of the data one must know the fraction of the target collected in any collection system. It is well known in laser interaction experiments that a simple collector does not collect the geometrical fraction of target material that it intercepts. As a result, we must have a measure of the target fraction which is collected. One approach to solving this problem is to irradiate the target in a nuclear reactor with thermal neutrons and for targets containing glass pushers the ^{23}Na in the glass can be activated to produce ^{24}Na . ^{24}Na has a half-life of 15 hours and the target is counted before the experiment is performed. After the implosion experiment, the ^{28}Al activity can be counted for 5 minutes and then the remaining ^{24}Na activity can be counted for 24 hours. A second counting of the ^{24}Na produces the target fraction which is collected allowing the determination of the ^{28}Al activity produced in the SiO_2 pusher.

In Figure 6 we show schematically how this system is implemented on SHIVA and we also show schematically a multiple shell target which has been irradiated. The multiple shells of course could each contain a material which could be activated by the neutrons from the fusion reaction thus providing information about the areal density of each one

of the shells at the time of the fusion reaction. In this system, the collector is an Al cylinder which is lined with reactor grade Ti or Ta foils. It is important that the collector foils not contain any trace materials which could be activated by the fusion neutrons from the reaction. After the experiment has been performed, the aluminum cylinder is retracted automatically through a gate valve and then released through another valve to fall down through a plastic tube to the basement of the SHIVA system where the counting system is located.

The counting system is shown schematically in Figure 7.⁽²⁰⁾ It consists of a 25.4 cm NaI crystal for measuring the gamma reactivity. It is a well detector in which we place a NE 102 fluor system which contains the Ti or Ta foils which have deposited on them the activated material from the target. The NE 102 fluor consist of a cylinder around which the foils are wrapped and then this cylinder and the foils are placed inside another cylinder of NE 102 fluor. This combination is then placed inside the NaI fluor thus producing a system which has a 100% efficiency for counting the β ray decay and 40% efficiency for counting the γ ray decay for a combined efficiency of 40%. Because of the extreme sensitivity of the large detector system to outside radiations, we place the counting station in the basement of SHIVA to provide significant concrete shielding against cosmic rays and other naturally, or artificially, occurring radiations. We also place the system inside a 10 cm thick lead chamber.

However, even with all of these precautions, we receive significant background due to cosmic rays which enter the NaI crystal, Compton scatter and produce coincidence counts in the NaI and NE 102 fluor

systems. To reduce the background due to cosmic rays, we have surrounded the counting crystals with Geiger tubes which also sense the arrival of cosmic rays and thus produce a triple coincidence in the counting system and are thus rejected. The background of this system in a five minute counting interval is two counts. Thus the utilization of this system with glass pushers has produced an extremely low threshold for determining the ρAr of glass pushers.

Another technique that we have developed to determine the size of the compressed fuel region is the utilization of a spatial discriminating crystal spectrometer which is designed to look at the line emission from argon contained in the fuel.⁽²¹⁾ A crystal spectrometer is used to provide spectral discrimination and a slit perpendicular to the direction of the spectral dispersion provides spatial discrimination in one direction. The difficulty in utilizing this type of system is that as the pusher becomes more dense, the opacity for the propagation of the seed material line radiation through the pusher increases thus eliminating the possibility of propagating this radiation out to the detector. Thus, as we go to pusher materials of higher density or higher opacity, we must go to seed materials with higher energy characteristic radiation thus requiring increased fuel temperature to generate the characteristic radiation.

In Figure 8 we summarize the density measuring capability of a number of different techniques. We plot the density confinement radius product as a function of the DT neutron yield. The various boundaries in the figure represent the boundary of applicability of various density

measuring techniques. In the past with low density targets, we have utilized imaging of the alpha particles to determine the size, shape, and distribution of the burning region of exploding pusher targets.⁽²²⁾ In this figure, we clearly see that this technique is limited to exploding pusher targets since the upper boundary of the density confinement radius product is 10^{-3} g/cm^2 . Thus this technique basically has no applicability for high density, intermediate yield targets. Of course, the technique can be utilized again when we can image the neutrons rather than the alpha particles.⁽⁹⁾

The four shaded regions showing Ar, Br, Si, and Cu represent the utilization of radiochemistry either of materials in the fuel, such as Ar or Br, or materials in the pusher, such as Si or Cu. Cu appears to offer a very significant advantage in that density radius products as high as 10^{-2} g/cm^2 can be measured with neutron yields of as low as several times 10^4 . The region of usefulness for the Si in the pusher is in the range of 10^6 to 10^8 neutrons. There is only a small shift over to the right for Br in the fuel and thus Br as a seed material in the fuel would be extremely useful in diagnosing the density of 100 x liquid density targets. Ar requires much higher yields in the order of 10^{10} to be useful for determining fuel density. The other boundary placed in this parameter space is the use of Ar imaging and here we show that as the neutron yield increases, basically the temperature of the fuel and pusher material are increasing thus reducing their opacity and making it possible to propagate the x-ray lines through the material surrounding the fuel. In summary, it appears that Cu is an extremely useful material

in the pusher in terms of activation for density determination. The material in the fuel that would be most useful is Br; however, Si is a useful material and can provide information about fuel density for targets with glass pushers with $\rho_{Ar} = 10^{-2} \text{ g/cm}^3$.

The final diagnostic technique which we wish to discuss in this paper is the use of an auxiliary x-ray backlighting source to provide radiographic information as to the density distribution in the target either as a function of position or as a function of time.^{(23),(24),(25)} In considering this type of diagnostic, we must remember that the laser target itself is a very intense emitting source of x-rays. Therefore, we must provide an x-ray source which has a significantly higher spectral intensity in a spectral regime of interest in order to make radiographic measurements. As shown in Figure 9, the concept is simply to use a separate laser source to irradiate an auxiliary target which emits intense line radiation which then passes through the implosion target, is spectrally discriminated by a monochromator of some type, imaged and either recorded as a function of time with a x-ray streak camera or recorded as a flash radiograph with a duration much less than the implosion time of the target. This type of diagnostic is not particularly sensitive as a density diagnostic but rather its importance is as a diagnostic which either provides information on the dynamics or in the flash radiograph mode provides significant information about symmetry of the implosion process.

With the ARGUS laser system, we have utilized one beam to produce the x-ray source and a static cold multi-shell target to demonstrate this

technique. In the particular experiment shown in Figure 10, we utilized a Sn disk as the auxiliary x-ray source which produced characteristic L line emission in the range of 3.8 to 4 keV. Actually in our study of auxiliary targets for x-ray backlighting, we found that Ti, helium like lines were a much more effective source. We showed that in this case we could convert one hundredth of a per cent of the incident laser energy into the helium like lines of Ti, which occur at 4.8 keV thus providing a very intense 400 megawatt source of line radiation for the probing of our implosion. However, in the demonstration experiment we did utilize the Sn x-ray emission to examine the transmission through a cold static glass microshell 143 μ m in diameter, 5 μ m wall thickness, with 50 μ m of CH plastic. In Figure 10, the target is shown schematically on the left. The data from the experiment is shown on the right and the relative intensity of the x-rays transmitted through the static target are shown at the bottom of the figure. This data clearly shows that we can identify the interface between the plastic and the glass and also the interface between the glass pusher and fuel. It is important to note that this will not always be true as the pusher material becomes higher and higher Z material, even with intense sources at 5 keV, we will not be able to penetrate the pusher and accurately determine the boundary between the fuel and the pusher. However, we will still be able to determine the boundary between the pusher and the ablator and to follow its dynamics.

Thus, in summary we have developed a number of, or improved a number of, diagnostic techniques which provide us with significant new information about the plasma interaction, the density of the implosion, or the dynamics and symmetry of the implosion process.

IV. LASER PLASMA INTERACTION EXPERIMENTS

In our experimental program we are concerned not only with implosion experiments but also with understanding the coupling of the laser energy to the fusion targets. As a result, we have spent a considerable fraction of our resources in developing diagnostic techniques and methods to examine the interaction physics. In 1975 we first observed the effects of Brillouin scattering on small targets with short pulse lengths.⁽²⁶⁾ The observation was made by measuring the polarization dependence of the scattered 1.06 μm light. Although the effect was small at that time, it was suspected and predicted theoretically that this would become more evident and become a stronger effect for larger targets and longer pulse lengths. In May 1976 with experiments on CYCLOPS where larger spot sizes and longer pulses were used, the ratio of the light scattered perpendicular to the plane of polarization compared to the that in the plane of polarization grew to as large as 4.⁽²⁷⁾ We felt at this time that this was clear evidence of the existence of Brillouin scattering. Since then we have done a considerable number of additional experiments to examine these effects. One of the clearest signatures of Brillouin scattering is a red shift in the backscattered light. Since the incident photon is resolved into a sound wave and a backscattered photon, the photon coming back toward the laser must be red shifted. Doppler shifts tend to produce a blue shift of light due to the outward motion of the critical density surface or the surface from which the photons are scattering. Thus one way of observing the effects of Brillouin scattering is to use a spectrograph to spectrally resolve the backscattered light.

In Figure 11 we show an example of the use of the spectrograph coupled to a Livermore high speed streak camera to also provide temporal resolution of the spectrally resolved backscattered light. In the experiment shown, the laser oscillator produced a 100 psec pulse which was inserted into a pulse stacker designed to produce a square pulse. Due to the instability in the pulse stacker for this particular application, a significant modulation in the output of the laser was observed. As shown on the right in the figure the output laser pulse contains four well resolved 100 psec pulses. The target was irradiated with this pulse shape and the time resolved spectrum of the backscatter is shown on the left side of the figure. It is interesting to note that the structure observed in the incident pulse is replicated in the time resolved spectral shift of the backscattered light. Also, essentially all of the backscattered light is red shifted which of course does not allow for the effect of the blue shift due to the Doppler effect of the outward moving critical density surface. The amount of light back reflected through the focusing lens is typically about 8-10%. To obtain an accurate picture of the amount of Brillouin scattering, one must also resolve the side scattered light, that is that light which is not back reflected through the focusing lens. For high Z targets irradiated at intensities of the order of mid 10^{14} w/cm² which pulsed in the range of 0.5 - 1.0 nsec the typical Brillouin scattering component is 25-30% of the incident light.

Rosen and Phillion⁽²⁸⁾ have used the information from the red shift of the Brillouin scattering light to obtain information about the time history of the temperature in the corona of the target. They have shown

that the mean spectral shift of the Brillouin scattered light;
 $\Delta\lambda \sim I_L^{0.3}$. They have also shown that they can obtain temperature
 information about the corona and that for disks irradiated at about
 3×10^{14} w/cm² the corona temperatures are ~ 5 keV whereas for disks
 irradiated at 3×10^{15} w/cm² the corona temperatures are ~ 20 keV.

We have continued to measure the suprathreshold x-ray spectrum from
 laser irradiated targets in an attempt to determine the suprathreshold
 electron spectrum which is created by the interaction of the laser with
 the target. Over the years we have accumulated a significant amount of
 data in this area⁽²⁹⁾ and as mentioned earlier in the section on
 diagnostics we have recently implemented the filter fluorescer experiment
 in an attempt to provide accurate determination of the suprathreshold x-ray
 spectrum. This has been a very useful instrument but unfortunately, it
 has not led to more repeatable data on the suprathreshold x-ray spectrum.
 In fact with the better definition we have observed even more scatter in
 the data. One might imagine that there is some unstable process
 occurring or that there may be a possibility that the distribution of
 high energy x-rays is not isotropic in space. In fact, Yablonovich has
 shown in an experiment with a CO₂ laser that the electrons produced by
 resonance absorption are significantly directional. Thus one might
 expect that if these electrons are not scattered sufficiently in high Z
 target that they will produce a nonisotropic distribution of high energy
 x-rays. To examine this question, we fielded a number of NaI photodiode
 detectors filtered with Be and Cu.⁽³¹⁾ The response function of these
 detectors to x-rays is effectively that of a calorimeter above 35 keV.

These detectors were utilized on SHIVA. They were arrayed primarily to view the polar variation since this was the suspected direction of largest variation. However, we also arrayed several detectors at a constant polar angle in various azimuthal positions. The data from three target shots on SHIVA are shown in Figure 12. The first two experiments were gold disks irradiated with the lower ten beams of SHIVA. Ninety degrees in the figure represents the plane of the target. Zero degrees is the axis of the upper ten beams and 180 degrees is the axis of the lower ten beams. The third experiment was a glass microshell target irradiated with all twenty beams and it produced nearly the same distribution of high energy x-rays in space. As shown in the lower part of the figure the azimuthal distribution of the x-rays at the upper peak of the polar distribution shows no variation for the three points obtained. One should also note that the SHIVA beams on the gold disk or glass shell target approximate a radial distribution of polarization. Thus one would expect that whatever distribution was obtained would be axially symmetric as is the case shown by the data. The highly directional nature of the high energy x-rays on these experiments is very suggestive of a directional distribution of high energy electrons. Resonance absorption would tend to produce an oscillation of the high energy electrons into the surface of the disk. However, the angle of the lobes appears to suggest that the electrons are oscillating along the surface of the disk. This conclusion seems to be more reasonable because the energy associated with the angle of the lobes with respect to the horizontal, if the electrons are oscillating parallel to the surface of

the disk, would correspond to approximately 200 keV electrons whereas if the electrons were oscillating perpendicular to the surface of the disk, the angle of the lobes would correspond to 5 keV electrons. This data certainly suggests additional experiments to determine more completely the nature of the electron spatial distribution.

We have also done a series of experiments to examine the x-ray emission from various Z disk materials. The primary purpose of this particular series was to examine the viability of various materials as x-ray backlighting sources for the diagnostic technique discussed earlier in Section III. However, in addition, using the Dante spectrometers, we obtained information about the overall emission of x-rays from these various Z disk materials.⁽³²⁾ As expected the fraction of x-rays emitted compared to the laser energy increased uniformly with increasing Z although appearing to saturate in the region of Au and U. Since the experiments were all done at one intensity, this is quite reasonable as one would expect that the effective Z of the plasma would not continue to increase unless the intensity were also increased. However, we also observed in one experiment where we increased the laser intensity on the target to $3 \times 10^{15} \text{ w/cm}^2$ from $5 \times 10^{14} \text{ w/cm}^2$, that there was a drastic reduction in the number of x-rays emitted by the target. This is a very interesting result and we examined the effect further by looking at the Dante signal from the 520 eV channel of the Dante spectrometer. This particular channel had the Thompson CSF TSN 660 oscilloscope connected to the detector which gave it an overall response time of

190 psec. Since the laser pulse was one nanosecond FWHM, we obtained significant information about the variation of the x-ray emission as a function of time.

Shown in Figure 13 are the signals from this detector for Be, Ti, Sn, Au, and U. The interesting thing to note is the apparent broadening of the FWHM as we decrease the Z of the material. However, as we examine the various signals, we see that it is really more a distortion of the shape of the signal rather than an increase in the FWHM of a Gaussian pulse. The U signal appears to be quite Gaussian. However, the Au signal appears to have a small distortion near the peak of the pulse. The distortion is much more apparent with Sn and completely obvious with the Ti where it appears that the x-ray emission was rising normally and then was somehow clamped and not allowed to increase. Then the Be signal takes on more meaning, indicating that the clamping of the x-ray emission occurred very early in the pulse. Now with Be one would expect that the plasma is completely stripped and therefore the x-ray emission is solely from bremsstrahlung and therefore we would not expect to see the effect of stripping of the electrons during the pulse. One can interpret this data as some kind of mechanism which is inhibiting the emission of x-rays by the target as the intensity increases.

The one experiment that was done with gold at the higher intensity is shown in Figure 14 along with the data for the lower intensity. The appearance of an apparent inhibition mechanism is quite striking in this case. As the pulse comes up for the higher intensity, the x-ray emission is quickly clamped and we clearly see the effect of fewer x-rays being

emitted at the higher intensity for this target. It should be remembered that in this case the intensity was changed simply by changing the size of the focal spot. One interpretation of these results could be to determine an intensity threshold for thermal conduction inhibition which has been observed in other experiments.^{(26),(28)} At this point again many more experiments are suggested and this effect will be further investigated in the future.

In our program of examining the laser plasma interaction processes we continue to uncover new phenomena or if not new phenomena at least new signatures of these phenomena. We have only brought up a few of the important salient points in the laser plasma interaction section. Clearly there are many more that are being investigated and will be investigated in the future.

SECTION V. IMPLOSION EXPERIMENTS

The experiments that were performed on SHIVA as it was being brought into activation were all of the exploding pusher, low density nature. These experiments were designed to prove the quality of the laser operation. Thus these experiments were performed with single beam illumination, four beam illumination, ten beam illumination from one side, and finally with all twenty beams from both sides. After the system activation was complete, we began a series of experiments with all twenty beams to further demonstrate the performance of the system using the exploding pusher, low density targets. One of the alignment aids that has been implemented on the SHIVA system is a system called LITAR. This is a code which allows one to take the designated lens coordinates for a

particular irradiation pattern and display the calculated absorption pattern on a color television screen. This code has proved extremely useful for the experimentalist and the target designer to arrive at an irradiation geometry. The polar microscope which is centered in the upper cluster of ten beams of the SHIVA system provides x-ray spatial distributions which can be compared with the LITAR predictions. This code and this diagnostic instrument have given useful information about the symmetry and the azimuthal distribution of the absorbed energy from this polar view. A four channel x-ray microscope also views the target at 90° to the center line of the beam clusters.

The typical color enhanced x-ray micrograph and the 2-D computer calculation of the x-ray distribution using the two dimensional glow code are shown in Figure 15. The experiment and the calculation show that most of the absorption occurred on the pole caps of the spherical micro-shell target and that there was significant distortion from spherical symmetry in the implosion and burn of the fuel. This was further demonstrated by data taken with the alpha zone plate camera which images the distribution of the alpha particles from the burn. This data along with the indicated pAr measurement from the neutron activation of the SiO₂ pusher are shown in Figure 16. From the alpha zone plate data one would infer an average density of 0.1 g/cm³ or approximately 0.5 x liquid density. The radiochemistry measurement of the silicon pusher, Ar gave a value of approximately 7×10^{-4} gm/cm². Using the simple theory of exploding pusher targets,⁽³³⁾ one can calculate the target performance

which gives the fuel density and the ρr of the pusher. This calculation has been made and is in reasonable agreement with the alpha zone plate image data.

We have also utilized the argon line imaging technique with these exploding pusher targets since $\rho r \sim 10^{-3} \text{ gm/cm}^2$. A slitted spectrograph has been used to provide one dimensional spatial imaging of the emission from the fuel and corona regions. Potassium lines from the potassium trace element in the glass pusher produce images which extend out into the corona and also provide an image of the outer region of the stagnated pusher. The argon inside the glass microshell provides a spatial distribution of the helium like and the hydrogen like alpha lines. These lines are very well resolved spectrally and produce distributions which have base widths of approximately 50 μm and 45 μm respectively. The difference in the spatial extent of the helium like and hydrogen like lines implies either a temperature gradient across the fuel pusher interface or more likely the time integration effect due to the temperature rising as the stagnation of the pusher and the fuel occurs. As the pusher and fuel stagnate, the temperature rises rapidly and one would expect that the helium like lines would be excited before the hydrogen like lines and therefore the spatial extent of the helium like lines would be expected to be greater than that of the hydrogen like lines. The point to be made here is that any time integrated emission from the fuel region requires significant code interpretation to determine the density and is not a simple straightforward diagnostic of the final fuel density.

We have also implemented our zone plate camera in the coded imaging mode to image the high energy x-rays from the fuel region. Figure 17 shows one of our gold zone plates which has been implemented with a stack of films and filters to produce a large dynamic range for an individual energy and to produce images at successively higher energies through the film stack.

In Figure 18 we summarize the density and neutron yield achieved for three classes of targets. The data in the lower right hand corner at neutron yields of the order of 10^{10} are from exploding pusher targets irradiated with SHIVA. The density in this case is determined utilizing alpha imaging and typically we achieve approximately 0.5 - 1.0 x liquid density where these targets typically started from densities of about .01 x liquid density. The second class of targets typically achieved from 4 - 10 x liquid density. As can be seen, we produced lower neutron yield for these experiments while we achieved essentially a factor of ten higher final fuel density. The last series of experiments achieved densities in the range of 40 to 150 x liquid density and again we were required to lower the temperature of the final fuel in order to achieve these densities.

In the coming years as we continue to push to higher and higher densities, the things that must be done are to operate SHIVA at its full energy capability for long pulses and to be able to fabricate the targets which have been designed to achieve these higher densities. The success of the program in achieving these ablative driven implosions over the

last year gives us a high degree of confidence in achieving the fabrication requirements, the laser irradiation requirements and the diagnostics to measure the achieved densities. The program is now well on its way towards achieving densities of interest for inertial confinement fusion reactors. In fact, the n products are now in the range of several times 10^{14} . We have already demonstrated with low density implosion targets that we can achieve the temperatures required for ignition. So now the problem remains to achieve densities in the range of 1,000 to 10,000 x liquid density and at the same time drive the target to temperatures appropriate to ignition, break even and finally net energy gain.

SECTION VI. LASER FUSION REACTOR REQUIREMENTS AND CHARACTERISTICS

Our System's Studies Program has been conducting studies for a significant period of time to determine the requirements for an inertial confinement fusion reactor driver. This of course also includes studies of reactor target design by our target design group. Presently, it appears that the range of energies which may be required to produce a significant gain target to drive a fusion reactor is 0.5 - 3.0 MJ. The power requirements range from 100 to 400 TW. The efficiency of the required driver is determined primarily by the target gain. Optimistic estimates of target gain are as high as 1,000; more pessimistic values range down to as low as 200. With these gains, powers and energies, the repetition rate for an appropriate fusion reactor appears to lie in the

range of one to ten Hertz. The requirement on pointing accuracy is tens of microradians from the final laser mirror or focusing element to the target.

The two final most important requirements are the ability to focus over large distances so as to prevent damage to the final optical element and the preheat characteristics of the driver. In a fusion reactor where a typical energy release may be in the order of the equivalent of hundreds of pounds of TNT, it is clear that the final element which focuses the beam must be a significant distance from this repetitive reaction. The two most likely candidates which satisfy this requirement are lasers and heavy ion beams which both can be focused from large distances to the appropriate target diameter of approximately 5 mm. Finally, the selection of the driver must take into account the requirements on minimizing the preheat caused in the fuel and inner pushers by high energy particles. It is for this reason that CO_2 lasers look less favorable than lasers operating in the 3,000 Å to 1.0 μ m wavelength regime.

A laser system which looks particularly attractive from the point of view of efficiency, architecture and wavelength from the plasma physics point of view is the KrF laser.⁽³⁴⁾ It has a wavelength of 2,490 Å with a radiative life time of 6 ns. The 6 ns of course identifies it as a nonstorage medium and therefore we must find a way of efficiently pumping the medium and extracting the laser energy over times of the order of a microsecond but with pulse lengths of the order of 10 ns. The

intrinsic efficiency of such a laser is 24% and projected efficiencies for a real system are as high as 10%. 2% has already been demonstrated. There are two approaches to extracting the laser energy in a short time from a long pulse excitation. One is simply the reinvention of the pulse compression method which involves running short pulses through in sequence and then recombining them with mirrors to provide a single short pulse. The second is to use Raman scattering as a method of compressing the pulse in time.

In Figure 19 we show schematically the test bed system which is being fabricated at the Livermore Laboratory to investigate the questions of the physics of the KrF laser, the optical properties and the problems of stacking and pulse compression by Raman means to provide the necessary short pulse. This system utilizes the double discharge configuration for the oscillator and amplifiers up to an energy of several joules and then utilizes the electron beam excitation of the gain medium for amplifiers to produce energies of 20 and 200 joules at the final output. The 200 joules is provided in a long pulse and then studies will be made to determine our ability to compress this pulse by means of stacking and by Raman compression.

From the point of view of the target physics and laser physics, the KrF laser now appears to be one of the most promising concepts. However, the shortness of the wavelength is worrisome in that present experiments on damage thresholds indicate that materials will not stand more than 1 J/cm^2 as compared to damage thresholds of $4 - 10 \text{ J/cm}^2$ for wave-

lengths in the range of 0.5 - 1.0 μm . In any case, the program is building a test bed to study these questions and to determine the viability of KrF or other rare gas halide lasers as fusion reactor drivers.

Our System Study Program has also been working diligently on reactor configurations. The most promising which we have come up with is the so-called Hylife chamber.⁽³⁵⁾ The basic concept here is to move the Li blanket from outside of the reactor vessel and place it inside in the form of jets surrounding the implosion explosion region. In Figure 20 we show schematically how these jets would be arranged to allow the beams to enter the interaction regime and still provide the effective Li thickness to absorb the neutrons, reduce the power flux of neutrons on the first wall of the reactor, and radically alter their spectral distribution to that of more nearly a thermal distribution of neutrons. In Table 1 we list the characteristics of the Hylife chamber. The major point to note is that we have reduced the first wall neutron fluence from approximately 6 MW/m^2 to 0.3 MW/m^2 for a reduction in flux of a factor of twenty. Further, the spectrum of the neutrons is significantly softer thus reducing the concern for first wall damage due to the neutron fluence. Utilizing this concept, we show in Figure 21 a reactor concept. The salient features of this system are that the laser building, the building where the laser pulses are generated, is separate from the containment building where there are significant requirements on the containment of radioactive material produced in the reaction chamber and its

surroundings. Thus the high technology optical system is removed a significant distance and does not have the same containment requirements. The laser beams enter through containment release sections into the laser reactor chamber producing the reaction. Also, the electrical generating equipment, as in a fission reactor, is also separated from the stringent containment requirement building which contains the radioactive material. This HyLife concept may not be the one that is finally implemented as an inertial confinement fusion reactor but it provides a number of very useful features and characteristics against which we can judge any other reactor configuration proposal.

SECTION VII. SUMMARY

Over the last several years we have made significant progress in the understanding of the laser plasma interaction through the use of new diagnostic instrumentation and techniques. We have also implemented the SHIVA system and operated the world's most complex laser system and produced significant target data. In the implosion experiments with the SHIVA system, we have achieved densities greater than $100 \times$ liquid density of DT. The significance of this result is that we have had to overcome the questions of achieving a spherically symmetric implosion and obviating the problem of Rayleigh-Taylor instability. We see no major obstacle in the future to attaining the densities appropriate to efficient burn of microfusion pellets for application to fusion reactors. Further, we have identified a laser system which may provide the architecture required for a fusion reactor driver and we have an

agressive ongoing program to investigate this option for a fusion reactor driver. In addition, our Systems Studies Program has identified a reactor configuration which solves many of the important problems associated with laser fusion reactors. This is not to say that a question of the configuration of an inertial confinement fusion reactor has been settled but rather that there is a very attractive possibility and one which can be used to judge other possibilities and grade them with respect to their performance compared to the Hyliife reaction chamber.

Thus we hold great hope for the possibility of inertial confinement fusion as an eventual energy source to provide energy for the world.

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Density Measurements by Neutron Activation

Figure 6

LASER FUSION – PROGRESS PROJECTIONS

Figure 1

02-30-1278-4586

Figure 2

THE EFFECTIVE $\rho\Delta R$ OF THE GLASS MICROSPHERE IS DETERMINED
BY MEANS OF "RADIOCHEMISTRY"

$$t_{1/2} = 2.24 \text{ min}$$

$$E_{\text{max}}(\beta^-) = 2.86 \text{ MeV}$$

$$h\nu(\gamma) = 1.78 \text{ MeV}$$

$$[\rho\Delta R]_{\text{pusher}} = 476 \frac{[\text{No. } {}^{28}\text{Al atoms produced}]}{[\text{Neutron yield}]}$$

MAXIMUM $\langle \rho \rangle$ FUEL VS EFFECTIVE PUSHER ($\rho \Delta r$)

Figure 5

Density Measurements by Neutron Activation

10.2cm Thick Walled
Pb House - Lined With
Cd and Cu Sheets

25.4cm x 25.4cm
NaI T. Well Crystal
With 5cm x 15.34cm
NE 102 Scintillator

GM Guard Detectors

Amplification, Discrimination,
Coincidence, and Counting
Electronics

Unclassified

PRESENT DENSITY DIAGNOSTIC OPERATING REGIMES

X-RAY PROBING/BACKLIGHTING:

47

40-90-0679-1944

Figure 9

X-RAY PROBING RESULTS: (RECONSTRUCTED IMAGE)

Double shell
target

Washer
(420 μm I.D.)

5 μm
glass shell

X ray backlighting
image
(10 μm resolution)

Radial x ray transmission profile

40-90-0679-1887

TIME-RESOLVED SPECTRUM OF THE BACK-REFLECTED LIGHT SHOWS PEAK RED SHIFT AT TIMES OF MAXIMUM LASER POWER

Streaked spectrum
shot 38092911

Laser pulse shape

49

Figure 11

20-90-1278-4431

HIGH ENERGY X-RAY ANGULAR DISTRIBUTION

Shot =	Target	Beam ::	Beam energy	Pulse	Data
89060702	Disk	1 - 10	639 J	200 ps	•
89060817	Disk	1 - 10	626	100	X
89061107	Ball	1 - 20	1900	100	□

20-50-0679-1905

Figure 12

Z DEPENDENCE OF THE TIME-RESOLVED SUB-keV X-RAY EMISSION FROM LASER-PRODUCED PLASMAS

Laser
 $I = 5 \times 10^{14} \text{ W/cm}^2$
 1 ns FWHM

XRD
 520 eV channel
 190 ps resolution

20-50-0679-1864

Figure 13

TIME-RESOLVED SUB-keV X-RAY EMISSION FOR Au-DISKS AT DIFFERENT
LASER INTENSITIES (XRD: 940 eV CHANNEL, 170 ps RESOLUTION)

$$I = 5 \times 10^{14} \text{ W/cm}^2$$

$$I = 3.3 \times 10^{15} \text{ W/cm}^2$$

0 2 ns

Laser pulse fiducial

20-50-0679-1865

Figure 14

2.0 keV X-RAY PHOTOMICROGRAPH (SHIVA 88100604)

Experiment

Calculation

50-60-0478-1415

5/79

Figure 15

NEUTRON ACTIVATION

Exploded pusher

$$\rho \Delta R)_p \simeq 6.9 \times 10^{-4} \text{ g/cm}^2$$

(rad chem)

Compressed core

$$\rho_f \sim 0.1 \text{ g/cm}^3$$

(α zone plate)

MULTI-SPECTRAL X-RAY IMAGING OF COMPRESSED HIGH DENSITY TARGET (TECHNIQUE)

A Fresnel Zone Plate X-ray Camera employing a multilayer filter-film pack records multiple x-ray images, along a single line of sight, in separate energy bands of a compressed high density target.

High density target

Multi-layer filter film pack

Zone plate coded aperture

40-90-0679-1895

Figure 17

FUEL DENSITY AT BURN TIME VERSUS NEUTRON YIELD

20 15 0579 1727

Figure 1

RAPIER: A LASER PULSE COMPRESSOR TESTBED

57

Figure 1

HYLIFE CHAMBER CROSS SECTION

50

95-01-1078-3352

Figure 20

Figure 1

HYLIFE CHAMBER CHARACTERISTICS

Fusion energy yield per shot	2700 MJ
Repetition rate	1 Hz
Effective lithium thickness	1 m
Lithium jet diameter at midplane	20 cm
Lithium jet velocity at inlet	4.4 m/s
Lithium pumping power	17 MW_e
Lithium temperature (ave.)	500 °C
Temperature rise in lithium per shot	11 °C
Tritium breeding ratio	1.7
First wall radius	5 m
First wall neutron fluence	
with lithium	0.32 MW/m²
without lithium	5.76 MW/m²

60

Table 1

ACKNOWLEDGMENTS

In the preparation of this paper I have drawn from LLL's total Laser Fusion Program. The Program Office provides overall Program direction, the Solid State Program is responsible for our present and future target irradiation facilities, the Advanced Quantum Electronics Program is responsible for identifying future reactor drives and our Systems Studies Group provides the reactor systems information. The major thrust of this paper has been to present the diagnostics and experimental data provided by the Fusion Experiments Program which is closely coupled to the Targets Program. These two programs encompass Code Development, Plasma Theory, Target Design, Target Fabrication, Diagnostics Development, Diagnostics Operation, Experiments Operation and Data Management and Analysis. The outstanding accomplishments of these two programs and their groups are directly responsible for the results presented in this paper.

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