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THE POTENTIAL OF A LASER-INDUCED FUSION DEVICE AS A THERMAL NEUTRON SOURCE

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ABSTRACT

Anticipating that a laser-induced fusion reaction will eventually be achieved, the potential of such a system as a source of thermal neutrons is considered. This source should provide bursts of thermal neutrons which would be at least three orders of magnitude more intense for time-of-flight experiments than the best existing neutron source. The major limiting factor appears to be the shock produced when each pellet reacts; this shock must be contained within the target room and should not destroy the moderators. Estimates indicate that this shock can be controlled. Consideration is also given to moderator design, shielding, beam tube windows and backgrounds.

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THE POTENTIAL OF A LASER-INDUCED FUSION DEVICE
AS A THERMAL NEUTRON SOURCE

R. M. Brugger

I. INTRODUCTION

In the last several years interest has expanded in the direct excitation of a fusion reaction by a laser^[1]. This heightened interest has occurred because of advances in laser^[2] and fusion technology and the perceiving of the advantages of this process to power generation^[1], space flight propulsion^[3], and peaceful uses of nuclear explosions. In addition to these uses, such a device may make an excellent neutron source for that research which requires thermal neutrons. It is not our purpose here to show that laser-induced fusion will eventually be realized, but our purpose is to investigate the potential of laser-induced fusion as a thermal neutron source when it does materialize. In the following sections, a conceptual design is presented, the neutron fluxes and experimental arrangements are described, and possible problem areas are mentioned.

The interest by scientists in sources of thermal neutron has been expressed in numerous conferences and publications^[4]. While the interest in thermal neutrons by nuclear physicists is diminishing, the interest by solid state physicists, crystallographers, biologists, agricultural experimentalists, medical researchers and others, is expanding. These scientists are recognizing the unique capabilities of this form of radiation to solve such diverse problems as determining the magnetic structures of crystals^[5], unravelling the phase problem when determining

the structure of large biological molecules^[6] and performing quickly biopsies for bone cancer^[7]. However, with the increased interest, there is an increased desire to have more intense neutron sources by which these investigations can be more accurately and quickly performed. A limit, that of the integrity of the fuel, has been reached by the conventional steady-state nuclear reactors, and there is little hope that major improvements will be forthcoming which will greatly improve the neutron output of these conventional sources. Therefore new ways, such as the laser-induced fusion, are being sought.

One way to increase the usable intensity of a neutron source is to pulse the source so that the neutrons are being produced only when they are needed for experiments. For many important experiments this produces more usable neutrons for a given average power. The manifestations of this approach are the IBR-I and IBR-II^[8] reactors which are in operation at Dubna, a pulsed reactor being built at Madras, India^[9], the SORA^[10] which is in the design stage at Ispra and the pulsed sources like VINS^[11] that have been proposed. However, these sources are still limited, as are the conventional reactors, by the integrity of the fuel.

The laser-induced fusion source (hereafter referred to as LIFS) can operate, in fact naturally will operate, in this pulsed mode thus realizing the gain due to pulsing. Additional gains are realized through the increased neutron production capability of the device because the fuel is taken to destruction during each pulse and through the more favorable ratio of neutrons/power of fusion as compared to fission. A LIFS holds the promise of increasing the number of neutrons usable for experiments by greater than 10^3 times as compared to the existing high flux research reactors.

II. LASER-INDUCED FUSION

To trigger a thermonuclear process which will be a power and a neutron amplifier will require the dissipation in a few nanoseconds of an amount of energy in excess of 10^{14} ergs into a volume of a few mm^3 of dense deuterium and tritium^[12]. Such a triggering can ignite, in principle, a little or an unlimited amount of thermonuclear material thus emitting a few or an unlimited number of neutrons. The lower limit, that of producing some neutrons (10^5 neutrons/pulse) with a laser trigger has already been achieved^[11]. The upper limit, that of producing a copious supply of neutrons with a laser trigger has not yet been reached, but fusion processes have been triggered by fissioning systems. However because the critical mass of a fissioning system has a minimum size, the energy released by this trigger is too large to be controlled in a convenient neutron source^[13]. Laser technology indicates that advanced lasers may possess the ability to impart the 10^{14} ergs to a pellet of deuterium-tritium. Under proper conditions this laser energy will be sufficient to raise the temperature of the deuterium-tritium to $\sim 5 \times 10^7$ °K and a thermonuclear reaction will ensue. The thermonuclear process can then multiply the power and the neutron intensity.

Winterberg^[12] suggests for a power source a multiplication of X100 giving pulses of 10^{16} ergs and one pulse every 10 seconds. He states that the energy of each pulse would be equivalent to 100 Kgms* of TNT and the average power developed in the power source would be 100 MW. The fuel would be a deuterium-tritium pellet of 0.25 cm radius. A laser-induced fusion system similar to the system described by Winterberg, but having multiplication of one or greater, should make an excellent neutron source. For the conceptual design that follows, a multiplication of X10 will be assumed for demonstration.

*While Winterberg gives 100 Kgms of TNT, our calculations indicate 230 Kgms of TNT.

III. A LASER-INDUCED FUSION PULSED NEUTRON SOURCE

The laser-induced pulsed neutron facility might be as shown in Figures 1 and 2. The laser would be capable of delivering 10^{14} ergs in a 10^{-9} sec. pulse, one pulse every 10 sec. The pellet of deuterium-tritium would be about 0.25 cm in radius, and would be dropped from the ceiling of the target room. The laser would ignite each pellet as it reached the center of the room. To be an effective neutron source, the fusion source must multiply the energy introduced by the laser, thus producing neutrons from the $t(d,n)^4\text{He}+Q$ reaction while producing energy because in this reaction $Q = +17.6$ MeV. For the purpose of the following discussion, it is assumed that the fusion source will boost the laser energy by a factor of 10, thus producing 10^{15} ergs per pulse. Other parameters of the source are listed in Table I.

TABLE I
Characteristics of LIFS

Laser induced energy	10^{14} ergs/pulse
Laser induction time	few $\times 10^{-9}$ sec.
Multiplication of energy by fusion	$\times 10$
Energy output of LIFS	10^{15} ergs/pulse
Time of fusion pulse	$\sim 10^{-8}$ sec.
Repetition rate	one every 10 sec.
Average output power	10 MW
Radius of deuterium-tritium pellet	0.25 cm
Temperature of plasma	$\sim 5 \times 10^7$ °K

In the LIFS, neutron moderators might be placed on two sides of the target area as shown in Figure 1. These would moderate the fast neutrons down to thermal and redirect them toward the beam tubes and experiments. The moderators, which might be liquid methane, would be held in thin walled vacuum bottles. The room might be 2 meters in radius by 4 meters high with the target area at the center as depicted in Figure 2. The walls would need to be at least 4 meters thick constructed of fast neutron shielding material. The room would have an inner layer of B_4C to absorb those thermalized neutrons which might try to return from the shielding to the room. The outer 2 meters of the shielding would be moveable so that experimental equipment could be located closer to the target. This shielding would need to be replaced before operating the LIFS.

Cooling coils will be needed in the inner part of the walls because the 10 MW of power will be dissipated mainly in the walls. The walls must be a conductor to remove the one ampere of current produced by the alphas. The room will need to be evacuated to a soft vacuum to limit shock waves and scattering of neutrons. The vacuum system will need to remove the 1.1×10^{-2} gms of deuterium-tritium that is vaporized every 10 seconds. This vacuum system will provide cleanup and recycle of the deuterium-tritium. The system would need to be tight to prevent leakage of the several grams of tritium (several kilocuries) which might be in the system. However, this amount of radioactivity is not an unreasonable hazard even if it were all released at one time.

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Figure 1 Target area of LIFS showing moderators, beam directions, and irradiation facilities.

Figure 2 LIFS showing target room, laser and a few experimental instruments. See Table II for some of the possible experiments.

TABLE II

Possible Experiments Using LIFS

- Larger area beam for measuring partial nuclear cross sections.
- Small area beam for measuring total nuclear cross sections of very radioactive samples.
- Instrument for measuring dispersion relations of lattice vibrations in crystals.
- "Neutron Guide Tube" for extracting a thermal beam free of gammas and fast neutrons for (n,γ) measurements of nuclear structure and prompt activation analysis.
- λ shifter for measuring liquids and molecular properties with very cold neutrons.
- Beam for neutron radiography.
- Fission fragment beam for nuclear structure and fission physics studies.
- Beam for powder crystallography.
- Beam for powder crystallography of magnetically ordered crystals.
- Beam for single crystal crystallography.
- Beam for single crystal crystallography of magnetically ordered crystals.
- Beam for neutron molecular spectroscopy using "small κ " method.
- Fast neutron beam for nuclear structure and fast neutron damage studies.
- Rabbit for irradiation with fast neutrons for activation analysis.
- Rabbit for irradiation with thermal neutrons for activation analysis.
- Irradiation facility employing cryogenic containers for radiation damage studies.

As was stated in the Introduction, it is assumed that a laser-induced fusion system will be developed, therefore we will not speculate here as to the system. However, the system must be capable of inducing fusion, the pellet system must be able to accurately position the pellet at the center of the room and the laser optics will need to be protected against neutron and alpha damage.

Beam tubes will penetrate the target room walls aimed only at the target area or only at one of the two moderators. The few beam tubes which would be aimed at the target area will be for experiments in which 14 MeV neutrons are needed. A dozen or more beam tubes would be aimed at the moderators and these would be for experiments in which thermal or epithermal neutrons are needed. The collimation of the beam tubes should be such that only the moderators or the target area is observed, thus excluding neutrons of an undesirable energy from the other source. Several of the tubes would contain neutron guides which would pass only the near-thermal neutrons. Rabbit facilities for irradiating samples would be included, one close to the target area for 14 MeV irradiations, and one near or in a moderator for thermal neutron irradiation. Sources would also be placed near the moderators, one for producing particles for an on-line beta-ray spectrometer, and one for producing fission products for an on-line mass separator.

Most of the experimental instruments which would use the pulses of thermal neutrons for scientific investigations would be placed outside the room. These instruments might include crystallographic diffractometers, inelastic scattering diffractometers, choppers, spectrometers, neutron radiographic cameras, a beta-ray spectrometer and a mass separator.

IV. NEUTRON SOURCE INTENSITY

To estimate the neutron source intensity from the laser-induced fusion device with the characteristics of Table I, consider the following: a device having a fusion multiplication of $X10$ would produce:

$$10^{15} \text{ ergs/pulse} = 6.3 \times 10^{26} \text{ eV.}$$

In the $t(d,n)^4\text{He}$ reaction, one neutron is emitted for every 17.6 MeV produced. Thus, the number of neutrons produced per burst is:

$$6.3 \times 10^{26} \frac{\text{eV}}{\text{pulse}} \times \frac{1 \text{ neutron}}{17.6 \text{ MeV}} = 3.6 \times 10^{19} \text{ neutrons/pulse.}$$

Since these neutrons are produced in a burst of 10 nanoseconds, the peak rate is then 3.6×10^{27} neutrons/sec. Since there is one pulse every 10 seconds, the average neutron source or leakage rate is 3.6×10^{18} neutrons/sec. In comparison, the new electron linear accelerator used for neutron physics at Lawrence Radiation Laboratory, Livermore, California, which is the "state-of-the-art" for electron linear accelerators, produces 10^{14} neutrons/sec. and the proposed pulsed reactor VINS was estimated to produce 8.8×10^{16} neutrons/sec. In Table II, which provides further comparison, the last column in the table is probably the best comparison of the relative merits for thermal neutron research of the different sources and indicates that LIFS would be a truly intense source of thermal neutrons producing pulses many times more intense than the best existing sources.

TABLE III

Source Intensity of Several Neutron Facilities

Facility	Peak Neutron Leakage Rate (neutrons/sec)	Average Neutron Leakage Rate (neutrons/sec)	Peak Thermal Source Flux (Thermal neutrons/cm ² sec)
HFIR ^a (100 MW)	$(1.5 \times 10^{15} \text{ n/cm}^2\text{sec})^b$		9×10^{14} (steady state) ^c
LRL Accelerator ^d	10^{18} (4 μ sec) ^e	10^{14}	2×10^{13} (1 μ sec) ^{f,g}
LAMF WNR ^h	3×10^{19} (2 nsec) ^e	8×10^{14}	10^{14} (1 μ sec) ^f
Nuclear Explosion ⁱ (one 1 Kton shot every 6 months)	10^{30} (100 nsec) ^e	6.3×10^{15}	none
ING ^j		2×10^{19}	10^{16} (steady state) ^c
VINS ^k (1.5 MW)	10^{20} (4 μ sec) ^e	8.8×10^{16}	3.5×10^{16} (50 μ sec) ^f
LIFS (10 MW)	10^{27} (10 nsec) ^e	3.6×10^{18}	1.4×10^{18} (50 μ sec) ^f

- a. A. Snell, 4th Geneva Conference, Sept. 1971 (to be published).
- b. For HFIR, which is a steady state reactor, we quote the peak thermal flux in the core, which is not the leakage rate.
- c. For HFIR and ING, which are steady state sources, we quote the perturbed thermal flux at the end of a beam tube.
- d. S. C. Fultz, C. L. Whitten and W. J. Gallagher, IEEE Transactions on Nuclear Science, Vol NS15 #3 pp. 533-537 (1971).
- e. In parentheses is time width of pulse of fast neutrons.
- f. In parentheses is time width of pulse of thermal neutrons.
- g. Estimated from experience with similar accelerator at ORNL; O. D. Simpson, private communication.
- h. R. R. Fullwood, CONF-710402, Vol. II, I-50 (1971).
- i. Ref. 13.
- j. Ref. 15.
- k. Ref. 11.

V. EFFICIENCY OF PRODUCING NEUTRONS

A fusion system is quite efficient for producing neutrons per unit of power produced. From fusion one gets about one neutron per 17.6 MeV while from fission one gets one neutron per 100 MeV, or about 6 times fewer neutrons per unit of power. The one neutron per 17.6 MeV of LIFS is similar to the yield of a high energy proton accelerator like NEVIS^[14] or ING.^[15]

VI. PRESSURE ON WALLS

Since the LIFS produces a considerable amount of energy in the bursts, the control and confinement of this energy is a major problem and limiting parameter of LIFS. Consider the pressure on the walls of the target room produced by each burst. The deuterium-tritium pellet is a sphere of $r = 0.25$ cm. The volume of the sphere is 0.065 cm^3 and a mixture of deuterium and tritium would have the density of about 0.17 gm/cm^3 . Thus the deuterium-tritium pellet weighs 1.1×10^{-2} gms. The volume of the room is $5.0 \times 10^7 \text{ cm}^3$ while the walls + top + bottom of the room have an area of $6.3 \times 10^5 \text{ cm}^2$. When the pellet explodes, the number of grams of pellet hitting each square cm^2 of wall is:

$$\frac{1.1 \times 10^{-2}}{6.3 \times 10^5} = 1.7 \times 10^{-8} \text{ gm/cm}^2.$$

The temperature of the plasma will be about $5 \times 10^7 \text{ }^\circ\text{K}$ which corresponds to 4 keV of energy. The velocity of deuterons of this temperature is $6.3 \times 10^7 \text{ cm/sec}$. The pulse of particles hitting the wall will be led by 14 MeV neutrons followed by 3.5 MeV α particles; these will contain most

of the fusion energy but less than 3% of the mass of the pellet. (See next section for the determination of this 3%.] The neutrons and α 's, since they are monoenergetic, will reach the wall with a time spread of the same magnitude as the pulsing of the pellet or about $\sim 10^{-8}$ sec. About 10% of the energy will be imparted to the remaining deuterium-tritium at particle energies near 4 keV. The energy carried by the neutrons will be ignored at this point since the interaction of the neutrons will be over a large volume because they are penetrating particles. For thin sections like beam tube windows most neutrons will pass on through causing little effect.

The α 's represent $4/5$ of the 3% of the mass and the mass of those α 's hitting each cm^2 of wall will be:

$$M_{\alpha} = 4/5 \times 0.03 \times 1.7 \times 10^{-8} = 4.1 \times 10^{-10} \text{ gm/cm}^2.$$

Alpha particles of 3.5 MeV energy have a velocity of 1.3×10^9 cm/sec. While each α is stopped in 10^{-12} sec, it is the integral pressure of all α 's in a pulse that produces the pressure and these impinge on the wall for the 10^{-8} sec. Thus:

$$F = m \frac{\Delta V}{\Delta t} = 4.1 \times 10^{-10} \times \frac{1.3 \times 10^9}{10^{-8}} = 5.3 \times 10^7 \text{ dynes.}$$

Thus the pressure pulse on the walls produced by the α 's from the α flash is:

$$P = \frac{F}{A} = \frac{5.3 \times 10^7}{1 \text{ cm}^2} = 5.3 \times 10^7 \text{ dynes/cm}^2 = 770 \text{ lb/sq in.}$$

An additional lesser pressure will be exerted on the thick sections of the walls by the neutron. However, on the thinner beam tube windows, which are the major concern, the neutrons will add only a small additional pressure because most of the windows are designed to pass most of the neutrons.

The remainder of the deuterium-tritium as it expands will carry 97% of the mass but only about 10% of the energy, mainly that energy introduced by the laser. Deuterium atoms with energies of 4 keV will be traveling with a velocity in the range of 6.3×10^7 cm/sec., assuming that little of the energy of the α 's is transferred to the plasma. But, because the deuterium and tritium are spread over a thermal distribution centered at 4 keV, their interaction time with the wall will be roughly 10^{-6} sec.

The pressure is then:

$$P = \frac{F}{A} = 0.97 \times 1.7 \times 10^{-8} \frac{6.3 \times 10^7}{10^{-6}} = 1.0 \times 10^6 \text{ dynes/cm}^2 = 15 \text{ lb/sq. in.}$$

Approaching this estimate of pressure in another way, if the 10^{14} ergs of energy is all imparted to the 1.1×10^{-2} gms of pellet, the velocity of the pellet will be $v = \sqrt{2E/m} = 1.4 \times 10^8$ cm/sec. Since this velocity is about twice the velocity for 4 keV deuterons, it indicates that if the pellet absorbed all of the 10^{14} ergs from the laser and exploded and interacted with the wall in about 10^{-6} sec., the pressure would be 30 lb/sq. in. In like manner if the pellet absorbed the full 10^{15} ergs and exploded the pressure on the wall would be about 100 lb/sq. in. These estimates indicate the pressure produced by the expanding pellet is small as compared to the α flash. The sum of the pressures of the neutrons, α 's and pellet on the thin beam tube windows is then about 800 lb/sq. in.

As a check of this estimate the pressure can be calculated another way. The LIFS produces 10^{15} ergs each burst in a room volume of $5 \times 10^7 \text{ cm}^3$. The pressure can be estimated by:

$$P = \frac{E}{\text{vol.}} = \frac{10^{15}}{5 \times 10^7} = 2 \times 10^7 \text{ dynes/cm}^2 = 290 \text{ lb/sq. in.}$$

which is in reasonable agreement with the first estimate of 800 lb/sq. in.

One might also consider the effect of the α 's on the wall from another point of view. On each square cm of wall there is about 1 μ amp of current of 3.5 MeV α 's in pulses of 10 nanosecond duration. This is a similar condition to that experienced in pulsed Van de Graaff's in which damage to the cooled target is modest.

These rough calculations indicate that the major shock on the walls of the room will be caused by the α particles or α flash and the maximum pressure produced will be less than 1000 lb/sq. in. Such pressures can be easily confined by the shielding walls of the room. At these pressures the beam tube windows will have to be no thicker than that needed to provide adequate safety against rupture of the evacuated room which is 1/2 to 1 cm thick.

VII. BURNUP OF PELLET

The percent burnup of the pellet for each burst is needed in the calculation of the previous section. To obtain this, consider that the total number of atoms in the pellet will be:

$$\frac{\text{Number of atoms}}{\text{pellet}} = \frac{1.1 \times 10^{-2}}{2.5} \times 6 \times 10^{23} = 2.6 \times 10^{21} \text{ atoms.}$$

If all these atoms were fused in pairs at 17.6 MeV per pair, the energy would be:

$$E = 17.6 \times \frac{2.6 \times 10^{21}}{2} = 2.3 \times 10^{22} \text{ MeV} = 3.7 \times 10^{16} \text{ ergs.}$$

Since this is 37 times the energy of the proposed LIFS, the efficiency of burnup per pulse is about 3%. It is this 3% that is used in the calculations of the previous section.

VIII. MODERATORS

The fissioning pellets provide a copious supply of fast neutrons, but the principal experiments for which LIFS is proposed requires thermal neutrons. Thus moderators will need to be placed close to the target position to moderate and direct the neutrons toward the experiments.

The moderators on LIFS might be similar to those proposed for VINS. Two containers 20 cm x 20 cm x 4 cm would form wings on both sides of the target area. These would moderate the fast neutrons and direct them toward the beam tubes. Since hydrogenous materials are the best moderators of neutrons, the moderating material could be liquid or solid H_2 or CH_4 , water or ice or some other hydrogenous material. These could be self contained systems separated from the room and target area so that any decomposition of the hydrogenous moderator would not pollute the deuterium-tritium mixture. The moderator assemblies could be inserted into the room through the ceiling, thus allowing easy maintenance and replacement. The

containers could be made of a light material with a heavier wall toward the target area to absorb the α flash.

The moderators should be placed close to the target area to obtain a high conversion ratio of fast neutrons to thermal neutrons. Each moderator might be placed as close as 10 cm from the target where the pressure due to α 's in the burst would be 400 times the pressure at the wall or about 4×10^5 lb/sq.in. This pressure is above the compressive strength of aluminum and near the compressive strength of harder materials. Thus while aluminum can't be used, it seems reasonable that a material can be found to face the moderator container which can take the shock of the α flash or erode at a controllable rate. Or the moderator could be moved further from the target but with a reduction in beam current. These moderator containers, since they are relatively simple and thus inexpensive, can be replaced at regular intervals if the erosion of the surface is a problem.

The energy absorbed by the moderators will come mainly from the neutrons. Since the neutrons carry $4/5$ of the energy, the neutrons will deposit in the moderator material less than $4/5$ of 10^{15} ergs times the fractional area of a sphere covered by the moderator. Thus the maximum energy absorbed is:

$$E = 10^{15} \times 4/5 \times 0.016 = 1.3 \times 10^{13} \text{ ergs} = 310 \text{ Kcal/burst.}$$

Because not all the neutrons would interact with the moderator and the ones that interact would not lose all their energy, less than 310 Kcal/burst will be deposited in the moderator material of each moderator.

The volume of each moderator is 1600 cc. If filled with liquid methane, which has a heat of vaporization of 138 cal/gm, the heat required to vaporize the methane would be 90 Kcal. Thus each burst would flash off the methane moderators. This would not be much of a problem as far as refilling the moderator every 10 sec., but its undesirable effects on the moderation and time of burst of neutrons is speculative. The flashing of the cold moderator might cause undermoderation, which would reduce the current of low energy neutrons to the beam tubes. On the other hand, the flashing of the moderator might act as a chopper and cut off the long time tail from a burst thus improving the time resolution for experiments.

Liquid methane is the preferred moderator because of its superior moderating properties at low temperature for cold neutrons. If the flashing of the methane is too much of a disadvantage several other approaches can be followed. One would be to freeze the methane and use the latent heat of fusion and the heat capacity of the solid and liquid to limit the heat available for vaporization. Another approach might be to use ice instead of methane, ice having a larger heat capacity and heat of fusion.

Water with its high specific heat might also be acceptable. The 14 MeV neutrons, since they have a longer mean free path in hydrogen than do 1 MeV neutrons, may require larger moderators than selected above. This larger size might cause a lengthening of the pulse of thermal neutrons and introduce a greater time uncertainty in the experiments because of the poorer space definition of the source of neutrons. Both of these effects on the resolution should be small because relatively long flight paths are

suggested in the LIFS plan given in the preceding sections. Graphite, beryllium and "egg crating" could also be considered.

It appears that the behavior of the moderators is a limiting factor in the effectiveness of LIFS for thermal neutron research^[16]. Experimenting with moderators under these extreme conditions is needed to accurately predict their behavior and to indicate the best material and geometry.

The above paragraphs discuss the moderators as being two slabs, placed on two sides of the target area. Other geometries can be considered such as a toroid encircling the moderator and viewed from the side. Flat plates might be placed between the target area and beam port which view the target area. These plates would employ a decoupler to separate the effects of one moderator from its neighbor. As sketched in Figure 1, the moderators are inserted through ports in the ceiling so that they can be interchanged easily and quickly.

IX. BEAM TUBE WINDOWS

In Section VI it was shown that the beam tube windows can be relatively thin. One half to one centimeter of aluminum, because of its low neutron cross section, would make excellent windows. However, if for some reason the windows of the beam tubes have to be thicker than the 1 cm suggested above, filters may be used. These neutron filters take several forms. For cold neutrons, cooled blocks of polycrystalline material having relatively high energy Bragg cutoffs are placed in the beam. These blocks scatter all neutrons above the Bragg cutoff while passing most neutrons below the cutoff. A typical cold neutron filter^[17] is a piece of beryllium 25 to 50 cm long. When cooled to liquid nitrogen temperatures

it passes most neutrons with energies less than 0.005 eV while stopping all higher energy neutrons.

For passing only thermal neutrons, cooled single crystals of certain materials are placed in the beam as filters. These pass most neutrons near thermal energies, but scatter higher energy neutrons and a few thermal neutrons that have energies that satisfy the Bragg relation for the alignment of the crystal. A typical example of these thermal neutron filters^[17] is a single crystal of bismuth of 15-20 cm length.

A few filters are available for use in the resonance range^[18]. These are lengths of Sc, Fe and Si metal which pass neutrons of 2, 24 and 144 keV, respectively. These filters can be >50 cm long. Filters of these three types can pass neutrons of the stated energies while excluding γ rays and neutrons of most other energies thus giving monoenergetic beams. In addition, all of the filters mentioned above can be made thick enough to stop the shock of the LIFS.

An additional way to tailor or modify the beams of neutrons is by the use of neutron guide tubes^[19]. These curved tubes which provide total reflection for lower energy neutrons act as low pass filters for neutrons, thus excluding fast neutrons and gammas. These guide tubes could have advantages for several experiments.

X. COLLECTION OF DATA

The electron linear accelerators use data collection systems that operate on pulses while the instrumentation of experiments on the nuclear explosions are current devices. The peak neutron rates of the

linear accelerators is 10^{18} neutrons/sec. while for nuclear explosions it is 10^{30} neutrons/sec. Since LIFS is predicted to have a peak rate near 10^{27} neutrons/sec its rate falls closer to the nuclear explosions indicating that attention will have to be given to data acquisition. Either buffering and/or integration of signals may be required.

XI. BACKGROUNDS

The minimizing of false signals or backgrounds in the experiments is always an important consideration. The major source of backgrounds in those experiments outside the target room will be from 14 MeV neutrons leaking through the 4 meter shielding walls and through the beam tubes. Four meter thick walls should be thick enough to reduce the 14 MeV neutron leakage to a level where small signals from sensitive experiments can be detected above the background. Similar thicknesses of shielding are adequate for steady state research reactors of greater than 1 MW and linear accelerators. At this thickness the streaming through holes and beam tubes probably causes more background than leakage through the walls.

Leakage of fast neutrons down the beam tubes will be a problem as it is in all reactors. This can be limited by good design of the tubes, experimental shielding and filters. Filters, guide tubes and choppers will be a great help in certain experiments to limit the current of neutrons from the beam tubes. Another selection factor, which can limit backgrounds, is the difference in arrival time at an experiment of fast and thermal neutrons; this time difference will eliminate some of the neutrons that do leak through the shielding from arriving at the detectors at a time

when these neutrons would interfere with data. In the detailed design of LIFS, shielding calculations would be made to verify the adequacy of the 4-meter shielding and the arrangement of the beam tubes and filters.

The LIFS should be far superior to reactors and linear accelerators as far as gamma backgrounds are concerned, since there will be no gamma flash as in a linear accelerator and no fission product gammas as in a reactor. Some gammas will be produced by fast and thermal neutron capture but these will be many orders of magnitude smaller than that produced by a reactor.

The α flash of about 1 amp is unique to the LIFS but these α 's will not be able to penetrate the walls of the target room. Care should be exercised in selection of construction materials to minimize (α, n) and (α, γ) reactions which would produce backgrounds.

Many of the new high intensity neutron sources such as the Livermore linear accelerator have been built underground to provide shielding. A superior approach seems to be to place LIFS with its target room on a pedestal with a minimum of shielding beyond or above the experiments. Thus neutrons that leak through the target room shielding or down the beam ports will be allowed to continue drifting away from the experiment and would not be reflected by other shielding back into the experiments. This proved to be quite effective at experiments on the Materials Testing Reactor in Idaho.

After LIFS has been operated for a while, some deuterium-tritium will be imbedded in the faces of the moderator holder and the inner surface of the target room wall. As more deuterium-tritium is ejected from the target

with energies approaching 4 keV some reactions between the ejected and imbedded materials will occur to produce neutrons. These will act as secondary neutron sources, coming from undesirable locations and at undesirable times. Some consideration will need to be given to shielding the beam tubes from these sources and to removing the imbedded heavy hydrogen at regular intervals.

XII. INDUCED RADIOACTIVITY

The average fluxes of both fast and thermal neutrons produced by LIFS are of the magnitude of a present fission reactor of greater than 1 MW. Thus the induced radioactivity inside the target room will be high enough to prevent re-entry into the room after the source has been used; this is the same condition experienced by the steady state reactors. Fortunately, the number of components in LIFS inside the room are few and these can be built and arranged so that they can be extracted into shielded casks and removed to a hot cell for modification or repair. The room can also be designed so that it can be flooded with water and opened at the top, thus allowing access through the water as is done with a swimming pool reactor. In the design of LIFS, consideration should be given to the kinds of construction material in the target room to limit the induced activity, particularly materials that generate activities with half lives greater than a few hours.

XIII. OVERLAP

In other operating and proposed pulsed neutron sources, the effective flux has been boosted by increasing the repetition rate. This increase

reaches a limit when one encounters overlap, which is when slower neutrons from one burst are being recorded at the same time as faster neutrons are recorded in a successive burst. LIFS will experience none of this since the 10 sec. between bursts is ample time for all neutrons to be captured or drift away. Because of no overlap, very long flight paths can be used, even for slow neutron experiments.

XIV. STEADY STATE LIFS

One might consider using the LIFS as a pseudo-steady state source even though it naturally operates in a pulsed mode. Conceptually, it might look like Figure 3 which is a modification of the power source proposed by Lubins and Fraas^[1]. The laser beam would enter from the top and ignite the deuterium-tritium pellet at the center of a vortex of liquid metal. The liquid metal would be used as a coolant, a shock suppressor and as an initial moderator of the neutrons. The liquid metal would be surrounded by a several meter diameter annulus of D_2O which would moderate the neutrons to thermal. Operating at 10 MW and with an average leakage flux at the target of 3.5×10^{18} neutrons/sec. the average flux of thermal neutrons in the D_2O and 1 meter from the target would be of the order of 10^{13} neutrons/cm²sec. Re-entrant beam tubes could have average thermal fluxes of 10^{14} neutrons/cm²sec. This flux would be modulated with a 10 sec. period, but it could be used for steady state experiments employing instruments similar to those used on the present steady state reactors.

The flux of the 10 MW steady state LIFS is less than the flux produced by several of the existing high flux research reactors. However, it would

Figure 3 "Steady State" LIFS showing target area, moderators and re-entrant holes.

have the advantages of providing more neutrons per unit of power than the conventional reactors. In addition, the steady state flux can be increased if the laser-induced fusion power sources are increased to their projected power of 100-1000 MW^[11].

XV. CONCLUSIONS

The preceding sections present a conceptual design for a laser-induced fusion source of thermal neutrons. This concept, even at 10 MW average power, is shown to provide at least three orders of magnitude increase of useable thermal neutrons as compared to the best existing steady state research reactors and electron linear accelerators. The pulses of thermal neutrons and the repetition rate are such that long flight paths can be used to provide excellent resolution with no overlap.

The principal anticipated limiting features have been considered. The largest uncertainty is the laser ignition of fusion but for the purposes of this paper it was assumed that a laser-induced fusion source will be developed. The containment of the pressure produced in the reaction, the sources of background and the arrangement of shielding and moderators have been shown to be tractable. The largest uncertainty, other than the feasibility of inducing fusion, seems to be the integrity and behavior of the moderator. However, enough compromises exist in the moderator design that do not seriously limit the capability of LIFS that this moderator design has several alternate acceptable solutions.

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