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OPTIMUM DESIGN OF HIGH-PRESSURE, LARGE-DIAMETER, DIRECT-NUCLEAR-PUMPED, GAS LASERS

by

James A. DeShong, Jr.

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DIRECT-NUCLEAR-PUMPED, GAS LASERS

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Reactor Physics Division

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OPTIMUM DESIGN OF HIGH-PRESSURE, LARGE-DIAMETER, DIRECT-NUCLEAR-PUMPED, GAS LASERS

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ABSTRACT

The principles of laser operation are discussed with emphasis on gas lasers. Previous work on small-diameter, direct-nuclear-pumped, gas lasers is surveyed. Techniques are developed for optimizing laser tube dimensions and gas pressure to obtain most efficient use of the nuclear fragment energy. These techniques are applied to calculate high-pressure, large-diameter, laser tubes for U^{235} and for B^{10} which both exhibit theoretical efficiencies two orders of magnitude larger than previous small-diameter tubes. The B^{10} laser appears feasible, because electrically pumped lasers of similar dimensions and pressure have operated in the pulse mode with up to 80-W output. The U^{235} laser is much larger in diameter and may require multiple-path operation.

I. INTRODUCTION

Laser pumping is the process whereby an inverted population is produced in the energy levels of the excited lasing atom. The pump raises the atom to the upper energy level by supplying photons, electrons, or heavy particles to excite it. Electrical power is required to operate the pump in most cases.

Interest in nuclear pumping of lasers stems largely from possible applications in space vehicles or remote-navigation beacons where compact, long-lived power is necessary. For example, a single, direct-fission-fragment-pumped tube could be incorporated in the nuclear stage of a space vehicle to provide for optical communication, optical radar, etc., without loading the small electrical supplies on such a vehicle with electrical pump requirements. Larger multiple units incorporated in the nuclear stage could be used for welding and fabrication of metal parts, space ship repair while in space, etc. In fact, applications are sufficiently numerous to have inspired a number of nuclear pumping experiments. These experiments have been directed toward solid-state pumping, because at present

the maximum power output of such devices is large as compared to gas lasers. The lack of success with such solid-state devices had stemmed mainly from the well-known, nuclear radiation-damage effects, which are simply being reaffirmed in most of the tests.

The gas laser, on the other hand, does not suffer from radiation damage, except that care must be used with mirrors and other components to insure that they are resistant to radiation damage and are placed in as low fields as possible. A survey of the gas laser literature conducted from October 1964 to the time of this writing resulted in the bibliography presented in Appendix D. It was concluded from this survey that the helium-neon laser is suitable for nuclear pumping.⁽¹⁾ Consequently, it was used for analytic purposes in the work reported herein.

The present report describes the results of a study on the effects of diameter and pressure on the nuclear pumping efficiency of gas lasers. The first part of the report is devoted to the principles of laser physics to provide background for the latter part in which techniques for optimizing the tube dimensions and pressure are developed. The techniques are then applied to calculate the optimum dimensions of large-diameter, high-pressure lasers for U^{235} and for B^{10} . Theoretical improvements in efficiency of two orders of magnitude are obtained by optimizing tube dimensions and pressure to use more of the nuclear-reaction fragment energy.

II. THE MASER AND LASER--HISTORY AND BACKGROUND

The name "maser" is the acronym of the phrase "Microwave Amplification by Stimulated Emission of Radiation." The name "laser" is obtained by substituting the word "Light" for "Microwave." The name "optical maser" is sometimes used because of the similarity of principle in the two devices. This usage may be objected to on the basis that the ratio of spontaneous to stimulated emission in the microwave region is negligible as compared to the near-infrared and visible region where resonant optical cavities must be employed to overcome the effects of the high ratio. The ratio continues to increase in the X-ray and gamma-ray parts of the electromagnetic spectrum. Since resonant cavities for multiple reflection are not available for these frequencies, the prospects of amplification by stimulated emission of radiation in this part of the spectrum are bleak. The electromagnetic spectrum is shown, in part, in Fig. 1. The microwave spectrum lies just above the radio spectrum, which is not shown. There is a small gap in coherent-energy generators between the upper edge of the maser spectrum and the lower edge of the laser spectrum located in the near infrared. The upper edge of the laser spectrum lies in the ultraviolet and represents the highest frequency at which coherent energy has been generated.

Fig. 1
Electromagnetic
Spectrum

The chronological history of the maser and the laser is brief. The maser was operated for the first time in 1954, having been conceived about two years earlier.⁽²⁾ In 1958, the laser was proposed.⁽³⁾ Two years later, in July 1960, the first operating laser was created using a pulsed flashlamp to excite a ruby crystal.⁽⁴⁾ This type of device is shown in Fig. 2. The ruby is maintained at low temperature to improve the ratio of spontaneous to stimulated emission. The helical flash source surrounds the ruby and is pulsed by means of a charged capacitor bank. Only pulsed operation of crystalline solids was possible until quite recently when continuous operation was obtained. The first continuous laser operation was obtained with the first gas laser, which was successfully operated in February 1961.⁽⁵⁾ This laser used helium-neon gas in a tube about 1 cm in diameter and 1 m long, which was terminated at each end by a flat, adjustable mirror to form a tunable optical cavity. Pumping was accomplished by using a radio-frequency discharge. The radio-frequency energy was capacitively coupled to the gas by metal bands around the tube. About 1 mW of power output was obtained at a wavelength of 1150 nm (1 nm = 1×10^{-9} meter).

Fig. 2
Solid-state Laser

III. GAS LASER PRINCIPLES

A. Nature of Coherent Light

Laser light is distinguished from ordinary light by virtue of its strong spacial and temporal coherence. Such coherence can best be demonstrated by simple experiments. Spacial coherence is demonstrated in Young's double-slit experiment shown in Fig. 3. The plane-wave chromatic source is shown impinging on the left side of the two slits. The interfering waves formed by the slits interact to produce the resultant diffraction pattern appearing on the screen at the far right. Such a pattern is not obtainable by ordinary light except by use of a pin hole between the source and the slits to obtain spacial coherence. The illumination is so low when the pin hole is used that only the first orders can be observed; many higher orders are obtained with laser light since no pin hole is needed. The spacial coherence of the laser beam is strikingly demonstrated by moving the laser so that different portions of the beam fall on the slits. The diffraction pattern will maintain a lobe spacing of $x = \ell\lambda/s$, where ℓ is the distance to the screen from the slits, s is the slit separation, and λ is the wavelength of the laser light.

Fig. 3. Spacial Coherence

Temporal coherence is illustrated by the Michelson interferometer experiment shown in Fig. 4. A plane wave impinges on the beam splitter in the center to develop two beams, one of which is reflected from the stationary mirror at the top and the other from the variable-position mirror at the right. The difference between the distances separating the mirrors from the beam splitter is represented by $\Delta\ell$. When $\Delta\ell$ is zero, interference patterns are present even for light with low temporal coherence. As $\Delta\ell$ is increased up to a few centimeters, however, the interference patterns

disappear when N , the number of cycles in the wave packet, is small. When $\Delta\ell > N\lambda/2$, the patterns disappear, because the returning light no longer meets light from the same wave packet. Figure 5 shows the relation between temporal coherence and line spectral characteristics. Time-domain wave packets of increasing length have been mathematically transformed to the frequency domain, giving the spectral results in the figure. Thus, as the packet length (L) increases with resultant increase in temporal coherence, the line width ($\Delta\lambda$) decreases, and monochromaticity increases. This indicates that the intrinsic width of a spectral line is inversely proportional to the packet length. The ratio $\lambda/\Delta\lambda$ is approximately equal to N , the number of cycles in the wave packet. For the gas laser, this ratio may be as high as 10^{14} under optimum conditions. The coherent path length for this case is roughly $N\lambda = 10^{14} \times 6328 \times 10^{-10}$ m, or 6×10^4 km. The coherence time $T = N\lambda/c = 6 \times 10^9/(3 \times 10^{10}) = 0.2$ sec. For a conventional monochromatic source, $N\lambda$ is about 6 to 8 cm, and $T = 8/(3 \times 10^{10}) \approx 0.3 \times 10^{-9}$ sec. It should be remembered that the wave packet lengths vary in a statistical fashion, and the above numbers represent average lengths.

Fig. 4
Temporal Coherence

Fig. 5
Wave-packet Line
Width

Some spectacular effects are achievable with coherent light of such extreme monochromaticity. The output of a laser has very low divergence, typical values ranging from 30 sec to 10 min of arc. This permits transmitting the beam over very large distances in media of low loss with little decrease in power. It is possible to use a lens to focus laser beams into a very small area. When this is done with lasers that can produce light pulses of 10 Joules (J) in 20 nsec, nonlinear optical effects are observed in various materials. The enormous electric field generated causes breakdown in gases. Frequency multiplication can be performed by passing the light through certain crystalline solids. The intense concentrated power can be used for burning very small holes through solids or for welding small parts together.

B. Stimulated Emission of Radiation

The basic radiation processes involved in a laser are illustrated in a simple way in Fig. 6. The first process is absorption, where the electron energy level is increased from E_1 to E_2 by some pumping means such as the incoming photon at the left. The second process is radiative decay from E_2 to E_1 , by spontaneous emission of a photon with a wavelength corresponding to the difference in energy levels ($E_2 - E_1$). A characteristic lifetime is associated with spontaneous emission, as will be seen in later calculations. The last process illustrated is stimulated emission. In this case, the incoming photon passing the atom has a wavelength corresponding to the difference in energy levels ($E_2 - E_1$) and stimulates the atom to emit a photon, which then leaves in company with the stimulating photon. The field of the emitted photon adds to the field of the stimulating photon, to result in a combined field whose energy is twice that of the original field. The two photons travel on in the same direction as the original to

Fig. 6
Absorption and Emission

stimulate additional atoms, in effect doubling the field energy at regular distance intervals. By this means, light amplification is produced in a single-pass light amplifier. If oscillation or lasing is desired, the photons are fed back and forth for hundreds of passes through the medium by means of mirrors to multiply until the field energy exceeds the losses and oscillation occurs.

C. Optical Cavity Resonator

The preceding description indicates that the spontaneous emission competes with the stimulated emission. Earlier it was pointed out that the ratio of spontaneous to stimulated emission was high in the optical region, requiring that some method be found to increase the stimulated emission without affecting the spontaneous emission. This can be done by placing two mirrors facing each other on a common axis to form a resonating optical cavity. The action of such a cavity is illustrated in Fig. 7. At the top of the figure, at A, the atoms in the cavity are in the ground state. At B, pumping photons are introduced to raise the atoms to the excited state. Spontaneous emission is starting at C, and a photon at the left on the axis is emitted traveling toward the mirror that forms the right end of the optical cavity. By stimulated emission, this photon multiplies to several photons, which are reflected to travel back down the cavity, stimulating additional emission as in D. All the photons so far created are reflected by the mirror forming the left-hand end of the cavity. This process continues to increase the population of photons, each photon undergoing about 100 reflections back and forth before leaving the cavity through the right-hand mirror. Finally, as the supply of excited atoms is exhausted, the photon population drops back to zero. The left-hand mirror is made opaque to give complete reflection; the right-hand mirror has a transparency of a few percent to serve as the output end of the device. As the internal photon population builds to a maximum and then back to zero, a corresponding pulse of a few percent of the photons being reflected is transmitted through the right-hand mirror as output. The foregoing discussion is oversimplified, but interest here is applied rather than rigorous. Sophisticated treatments of this subject are available.(6-10)

Fig. 7
Cascade Stimulated
Emission

The operation just described typifies pulsed laser operation. It is also possible to pump the gas laser continuously to provide excited atoms at a rate equal to that at which they are being used up in stimulated emission. The laser can then operate as a continuous-wave device.

The resonant optical cavity formed by the two mirrors can be thought of as having an optical gain that is proportional to the length of active cavity between the mirrors and inversely proportional to the losses due to diffraction, mirror imperfections, etc. The cavity is tuned by adjusting the mirrors to parallelism and correct spacing by means of micrometer adjustments. This is necessary to minimize the diffraction loss and to tune a mode to the peak of the emission spectrum. Various types of mirror systems include hemispherical, confocal, flat, etc., and the mirrors are coated with either metal or multiple-layer dielectrics. An example of a gas system using external mirrors is shown in Fig. 8. The mirrors of this system form a confocal configuration where the spacing between mirrors is equal to the mirror radius. Such a system has lower loss and less constraint on mirror alignment than a flat mirror system. For example, flat mirrors must be parallel to each other within approximately 6 sec of arc to secure oscillation; confocal mirrors need be parallel only within many minutes of arc, depending on the diameter of the mirrors.

Fig. 8. Confocal Gas Laser with Brewster Angle Windows

The ends of the lasing tube itself are closed with optical flats set at the Brewster angle. This minimizes reflection losses for radiation polarized in the plane of incidence, and results in a polarized output. Typical dimensions for a system of the type shown in Fig. 8 are 1 to 3 cm for the tube diameter, 1 to 8 m for the tube length, and mirror spacing about 10 to 20% greater than tube length. Outputs range from several milliwatts to several watts.

D. Helium-Neon Laser Pumping

Consider now the method by which atoms are pumped to the excited state and an inverted population is created to permit stimulated emission.

In general, energy is fed to a host atom of the lasing material, which in turn excites the lasing atom either optically or by a collision of the second kind. The host atom itself receives its energy optically, electrically, chemically, or by heavy-particle collisions as discussed later in Section IV.

Laser pumping covers a broad field, and many different principles are used to pump the various types of lasers. The helium-neon laser will be used as an example, since it is being considered for nuclear pumping. A simplified energy-level scheme of this device is shown in Fig. 9. The 2^3S level of helium has no optically allowed downward transitions because the singlet ground state is the only lower-lying state in the spectrum. Therefore, atoms in the 2^3S state will remain there until de-excited by some nonradiative process such as collision with the walls. In fact, this is the main loss of such metastables at low pressures with no other gas present. It can be seen in Fig. 9 that the $2s$ states of neon are very close to the 2^3S state of helium. Also, the $3s$ states are very close to the 2^1S state. In fact, energy is transferred from the helium to the neon states by collisions of the second kind with a cross section of about 10^{-16} cm^2 . From the $2s$ states, the neon atoms can radiate by allowed transitions to the ten $2p$ states or to the ground state. The probability of decay to the ground state is very much greater than that of decay to the $2p$ state at pressures in the micron range. However, at a pressure of about 1 Torr, the $2s$ state is kept highly populated by successive reabsorptions to the $2s$ state of emitted quanta of the $2s \rightarrow$ ground state resonance radiation. The result is an increase in the number of atoms making the $2s \rightarrow 2p$ transition. The transition probability for $2p \rightarrow 1s$ is much larger than that for the $2s \rightarrow 2p$, so that conditions required for an inversion of population are met. The $2s \rightarrow 2p$ transitions have wavelengths of 1000 to 1500 nm, with the strongest at 1,152.3 nm. The $3s_2 \rightarrow 2p_4$ transition has a wavelength of 632.8 nm, which is in the visible spectrum. The $3s_2 \rightarrow 3p_4$ transition has a wavelength of 3,390 nm.

Fig. 9
Helium-Neon Laser
Energy Levels

The light gain per pass through the laser tube has been found to be approximately inversely proportional to the tube diameter, indicating that wall collisions may play an important role in emptying the 1s level. This is necessary since atoms in the 1s level are metastable and have a considerable cross section for electron-collision excitation to the 2p levels. Filling of the 2p level from the 1s level will stop oscillation in the $2s \rightarrow 2p$ transition.

The lifetimes of the four 2s levels have been found by experiment to range from 100 to 160 nsec, under conditions of complete trapping of the radiation corresponding to transitions from the 2s levels to the ground state. The transitions from the 2p levels have lifetimes at least an order of magnitude smaller than the 2s levels. This difference in lifetimes makes it possible to secure an inversion of population between the 2s and 2p levels, which is the necessary and sufficient condition for lasing.

E. Calculation of Threshold Density

The minimum population density of excited neon atoms (Ne_{TH}^*) that must be produced to just offset losses and reach the oscillation threshold may be calculated by the equation:⁽¹¹⁾

$$\text{Ne}_{\text{TH}}^* = \frac{4\pi^2 \nu^2 \Delta \nu_D t_{\text{spont}}}{c^3 (\pi \ln 2)^{1/2} t_{\text{photon}}}, \quad (1)$$

where c/ν = emission wavelength (λ).

The spontaneous emission lifetime (t_{spont}) is the reciprocal of the probability per second that an excited lasing atom in the upper state will spontaneously emit a photon and change to the lower state. The lasing atom is initially selected because it has levels closely matching those of the host atom to allow energy transfer, but its spontaneous-emission lifetime must also be considered since it determines the threshold density.

The photon lifetime (t_{photon}) may be defined as the time for the cavity energy to decay to $1/e$ of its original value in the absence of an amplifying medium.

The energy-reflection coefficient is $r = 1 - \alpha$, where α contains all the more important loss terms such as

1. Transmission and absorption in the mirrors;
2. Absorption in the amplifying medium due to mechanisms other than $E_1 \rightarrow E_2$ transitions;
3. Scattering by optical inhomogeneities;

4. Diffraction by the mirror apertures;
5. Mode conversion, e.g., losses due to imperfect mirrors.

After N reflections, $r^N = 1/e$ or $N \ln r = -1$. If r is nearly unity, $N \approx 1/(1 - r)$, and the time for decay to $1/e$ of the original value is given by

$$t_{\text{photon}} = NL/c = L/c(1 - r) = L/\alpha c, \quad (2)$$

where

L = distance between mirrors,

α = the total losses expressed as a fraction per pass between mirrors,

and

c = speed of light.

For cavity resonators, Q has the same significance as for an ordinary resonant circuit. It is equal to the cavity resonant frequency divided by two times the difference between the cavity resonant frequency and the frequency at which the cavity response is 70.7% of its response at resonance. The Q also expresses the ratio of energy stored in the fields of the resonator to the energy lost per cycle, or

$$Q = 2\pi \frac{E_{\text{stored}}}{E_{\text{lost per cycle}}}. \quad (3)$$

But

$$\frac{E_{\text{stored}}}{E_{\text{lost per cycle}}} = \frac{1}{\alpha/(L/\lambda)} = \frac{L\nu}{\alpha c}, \text{ since } \lambda = \frac{c}{\nu}. \quad (4)$$

Therefore,

$$Q = 2\pi\nu(L/\alpha c) = 2\pi\nu t_{\text{photon}}. \quad (5)$$

The term $(\pi \ln 2)^{1/2}$ in the denominator of Eq. (1) converts the Doppler-broadened line of the pure gas to the Lorentzian-shaped line that results with a gas mixture. The Doppler-broadened line width ($\Delta\nu_D$) is obtained from the expression

$$\Delta\nu_D = \frac{2\sqrt{2R \ln 2}}{c} \cdot \nu \cdot \sqrt{T/M} = (3.08 \times 10^{-6}) \nu, \quad (6)$$

where

R = gas constant,

T = absolute temperature ($^{\circ}\text{K}$),

and

M = weight of neon atom.

Thus, for $\nu = 2.6 \times 10^{14}$ cps, $\Delta\nu_{\text{Doppler}} = 8.1 \times 10^8$ cps.

A typical calculation for the threshold density required for the 1150-nm line is shown in Appendix A. Note that the threshold density is proportional to ν^3 , since $\Delta\nu_D \approx \nu$. This emphasizes the difficulty of securing lasing at higher frequencies.

Three other line widths that are interesting to compute and compare are the natural line width, the resonant optical cavity width, and the laser line width. The natural line width is

$$\Delta\nu_N = \frac{1}{2\pi t_{\text{spont}}} = 1.6 \times 10^6 \text{ cps.} \quad (7)$$

The resonant optical cavity width can be obtained from Q as follows:

$$\begin{aligned} Q &= 1.7\nu/\Delta\nu_{\text{cavity}} \text{ for } Q \gg 1 \\ &= 2\pi\nu t_{\text{photon}} \\ &= 2\pi \times 2.6 \times 10^{14} \times 3.3 \times 10^{-7} \\ &= 5.4 \times 10^8. \end{aligned} \quad (8)$$

Then

$$\Delta\nu_{\text{cavity}} = 1.7 \nu/Q = \frac{1.7 \times 2.6 \times 10^{14}}{5.4 \times 10^8} = 8 \times 10^5 \text{ cps.} \quad (9)$$

The resonant frequency of a cavity mode is

$$\omega_N = N\pi c/L \text{ for the } N\text{th mode.} \quad (10)$$

Therefore, the separation between adjacent modes for a 1-m cavity with plane mirrors is

$$\begin{aligned}\Delta\nu_{\text{mode}} &= \pi c/L \text{ radians, or } c/2L \text{ cps,} \\ &= \frac{3 \times 10^{10}}{2 \times 10^2} = 1.5 \times 10^8 \text{ cps}\end{aligned}\quad (11)$$

From the discussion on coherence in Section III-A, the ratio $\lambda/\Delta\lambda$ approached 10^{14} for the gas laser. Then the laser line width is

$$\Delta\nu_{\text{laser}} = 2.6 \times 10^{14}/10^{14} = 2.6 \text{ cps.} \quad (12)$$

The spectral characteristics calculated above are shown qualitatively in Fig. 10.

NOTE: FWHM = FULL WIDTH AT HALF MAXIMUM

Fig. 10. Laser Spectral Characteristics

IV. PUMP TYPES

The previous discussion of pumping started from the excited states. In this section, the pumping methods used to produce these excited states are described.

The optical pump usually provides a broad spectrum of essentially white light and pumps by brute force, with only a small portion of the spectrum pumping effectively. The most common optical pump is the flash tube, which usually is filled with argon. The tube is fired by a condenser bank, which supplies very large pulses of energy. Other optical pumps used include: sun-powered optical systems, electrically exploded wires, fluorescing materials excited by electrons, gammas, etc., and detonation of high explosives to form ultraviolet light from the shock wave.

The electrical pump generally takes one of two forms. In one form, radio-frequency energy in the 30- to 50-megacycle range is capacitively coupled to the gas of a gas laser. This type is shown in Fig. 8. In the second form, a direct-current, cold-cathode discharge is used through arms attached to the main tube. The semiconductor laser also uses direct current. Efforts have been made to pump by the electrical pinch effect as well.

Chemical pumping is of interest with liquid lasers such as the chelates.

Four methods of nuclear pumping are being attempted elsewhere. The first, mentioned above under optical systems, uses gamma rays produced by large sources or by a reactor to produce fluorescence. The second uses the (η, γ) reaction in gadolinium or samarium coated on a calcium tungstate lasing rod. The gammas that are produced excite the laser material directly with no intermediate fluorescing material. The third method attempts to pump the semiconductor laser directly with gammas or other means. The fourth method, which seems to show most promise, uses nuclear reactions to produce energetic heavy particles such as alphas or fission fragments, which then excite the lasing atoms. This method is probably confined to the pumping of gas lasers because of the radiation damage that would be done to a solid-state device by such heavy particles.

V. DIRECT NUCLEAR PUMPING OF SMALL-DIAMETER GAS LASERS

A. Calculation of Threshold Neutron Flux

The use of energetic heavy particles to pump a helium-neon laser system has been described.⁽¹⁾ Detailed calculations have been made for fission-fragment pumping of a laser configuration like that in Fig. 8 with the inner wall of the tube coated with one fission-fragment range thickness of either U^{235} or B^{10} .⁽¹²⁾ The tube used in the calculations had an area of 1 cm^2 and was 100 cm long.

The same configurations have been independently calculated by the author along lines similar to those used in the above reference but using other sources for nuclear data wherever possible. These calculations are given in Appendixes B and C. The results for Ne^* obtained for a neutron flux of $10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1}$ were $Ne^* = 5.4 \times 10^7$ for U^{235} , and $Ne^* = 2.0 \times 10^7$ for B^{10} . These compare well with the values of $Ne^* = 2.7 \times 10^7$ for U^{235} , and $Ne^* = 2.1 \times 10^7$ for B^{10} .⁽¹²⁾ The difference in the U^{235} figures results almost entirely from the larger fission-fragment dE/dx value obtained in Appendix B. This value was derived using Refs. 15, 16, and 17.

B. Comparison of Direct and Indirect Nuclear Pumping Efficiencies

Direct and indirect nuclear pumping represent the two main methods by which long-unattended laser operation may be attained for use as space or sea beacons, etc. For direct nuclear pumping, the excited-state power at threshold, using data of Appendix A, is

$$N_p^* = \frac{N_e^* \text{ atoms cm}^{-3} \text{ sec}^{-1} \times V \text{ cm}^3 \times (\text{eV/excited atom}) \times 1.6 \times 10^{-12} \text{ erg/eV}}{10^7 \text{ erg/J}}$$

$$= \frac{1.1 \times 10^{15} \times 10^2 \times 20 \times 1.6 \times 10^{-12}}{10^7} = 0.35 \text{ W (at 632.8 nm).} \quad (13)$$

The fraction of excitation energy used per 632.8 nm photon emitted is about 10^{-1} . About 3×10^{-3} of the excitation energy appears as useful output, the remainder being lost to unwanted wavelengths and modes. The power output of the laser beam then is

$$P_{\text{output}} \approx 0.35 \times 3 \times 10^{-3} \approx 1 \text{ mW (at 632.8 nm).}$$

The power dissipation to produce threshold density can be calculated from the results of Appendixes A and B.

For B^{10} (10 Torr Helium-Neon)

$$\Phi = 5.5 \times 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1} \text{ to produce threshold density.}$$

For U^{235} (10 Torr Helium-Neon)

$$\Phi = 2.04 \times 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1} \text{ to produce threshold density.}$$

The α particle range in B^{10} [from the (η, α) reaction] is about 1 mg/cm^2 , compared to about 12 mg/cm^2 for the fission-fragment range in UO_2 for U^{235} fission. The thermal cross section for B^{10} is 4020b compared to 582b for U^{235} . Then the reaction rate for a thermal flux (Φ) is

$$\begin{aligned} B^{10} \text{ reaction rate} &= 567 \text{ cm}^{-1} \times 4 \times 10^{-4} \text{ cm} \times \Phi \\ &= 2268 \times 10^{-4} \Phi; \end{aligned}$$

$$\begin{aligned} U^{235} \text{ reaction rate} &= 27.5 \text{ cm}^{-1} \times 6.9 \times 10^{-4} \text{ cm} \times \Phi \\ &= 190 \times 10^{-4} \Phi. \end{aligned}$$

Therefore, if one range thickness of material is used on the tube wall in each case, the reaction ratio for the same thermal flux is

$$R_R = 2268/190 = 11.9.$$

Then for threshold lasing, the ratio of heat dissipation of B^{10} to U^{235} is

$$R_H = R_\Phi \times R_R \times 2.3 \text{ MeV}/193 \text{ MeV}.$$

Since

$$R_\Phi = 5.5/2.04 = 2.7,$$

$$\begin{aligned} R_H &= 2.7 \times 11.9 \times 1.19 \times 10^{-2}, \\ &= 0.382. \end{aligned}$$

The reaction power density for continuous operation at the lasing threshold for B^{10} is

$$\begin{aligned} P &= 2.27 \times 10^{12} \times 5.5 \times 2.3 \times 1.6 \times 10^{-13} \text{ W cm}^{-2} \\ &= 4.6 \text{ W cm}^{-2}. \end{aligned}$$

The total power dissipation is

$$\begin{aligned} P_T &= 4.6 \text{ W cm}^{-2} \times 353 \text{ cm}^2 \\ &= 1.62 \text{ kW (thermal)}. \end{aligned}$$

For U^{235} continuous threshold operation,

$$\begin{aligned} P &= 1.9 \times 10^{11} \times 2.04 \times 193 \times 1.6 \times 10^{-13} \\ &= 12.0 \text{ W cm}^{-2}; \\ P_T &= 12.0 \times 353 \\ &= 4.2 \text{ kW (thermal)}. \end{aligned}$$

The direct pumping efficiency is

$$\begin{aligned} \frac{P_{\text{output}}}{P_T} &= \frac{10^{-3}}{1.62 \times 10^3} \approx 6.2 \times 10^{-7} \text{ for } B^{10}, \\ &= \frac{10^{-3}}{4.2 \times 10^3} \approx 2.4 \times 10^{-7} \text{ for } U^{235}. \end{aligned}$$

The above efficiency compares with indirect pumping as follows. The efficiency to reach the excited atomic state has been computed for a conventional system, which first converts nuclear energy to electrical

energy with 30% efficiency.⁽¹²⁾ If 0.7 of the electrical energy is converted to radio-frequency energy and 0.7 of the radio-frequency energy is coupled to the laser, the fractional efficiency is $0.007 \times 0.3 \times 0.7 \times 0.7 \approx 10^{-3}$ to go from nuclear fuel to excited states. The factor 0.007 represents the efficiency with which radio-frequency energy is converted to excited atom energy in the upper level. It is an empirical number derived from an operating radio-frequency pumped laser which requires about 3000 eV of radio-frequency energy to produce one excited atom (≈ 20 eV) in the upper level. The fraction of excited-state energy appearing in the output beam is again 3×10^{-3} .

The indirect pumping efficiency is

$$\frac{P_{\text{output}}}{P_{\text{input}}} = 10^{-3} \times 3 \times 10^{-3} = 3 \times 10^{-6}.$$

The above discussion indicates that the B^{10} direct method has about one-fifth the efficiency of the conventional method and that the U^{235} direct method has about 1/12 the efficiency of the conventional method. This situation will be substantially improved in Section VI.

Continuous electrical excitation of a laser at gas pressures exceeding 10 Torr is difficult because of buildup of excess electron population. On the other hand, direct nuclear pumping of a laser at several hundred Torr may be possible since it is likely to create a lower electron population. Its efficiency then would be better than that of the conventional method by a large amount, as discussed in Section VI.

A further important advantage of direct-nuclear-pumped lasers is that electric and magnetic fields can be applied to the tube for control purposes unlike electrically pumped lasers; e.g., magnetic fields can be used for Zeeman splitting to tune the oscillation frequency, or for prevention of radiative loss at unwanted frequencies.

VI. EFFECTS OF TUBE RADIUS AND GAS PRESSURE IN DIRECT NUCLEAR PUMPING OF GAS LASERS

A. Multiple-path Laser Considerations

A multiple-path laser may be thought of simply as a very long laser whose light path has been folded up by means of mirrors to occupy a tube of increased diameter and much shorter length. Paths as long as 68.4 m have been obtained by this means.⁽²⁴⁾ Such a multiple-path laser will have a much lower threshold than a single-path laser with the same tube size. The maximum power density will be approximately the same for both types. Therefore, their maximum power outputs will also be approximately equal for the

same tube size. In the actual case, the maximum output of the multiple-path laser will be somewhat less because of inability to utilize the full volume without beam overlap.

All in all, a multiple-path laser seems desirable mainly from the gain standpoint and not from the power standpoint. However, it might have one advantage from the power standpoint. Tubes with multiple paths close to the outer walls should facilitate emptying of the lower level to the walls. This might permit operation with larger-diameter tubes than in the case of single units and thereby make more efficient use of the fission-fragment energy.

B. Influence of Tube Radius and Gas Pressure on Efficiency

Early experimental laser work indicated that electrically pumped, continuous-wave, gas lasers have maximum output when operating conditions satisfy the expression,⁽²⁵⁾

$$p \times d = 3.5 \text{ Torr-mm}, \quad (14)$$

where

p = helium pressure in Torr,

and

d = tube diameter in mm.

The ratio of helium to neon was 5/1, and the expression was found to hold for a tube-diameter range of 1 to 15 mm. The existence of such a relation between pressure and diameter is assumed to be due in part to the need for optimizing the coupling of the electrical energy to the gas, and in part to the need for emptying the lower levels by diffusion to the container walls.

The electrical coupling problem, which requires low pressures for efficient operation, is not present in the case of direct nuclear pumping. Therefore, operation at much higher pressures should be possible, particularly since higher pressure enhances the coupling of the heavy-fragment energy to the gas. Moreover, recent work has demonstrated pulsed-gas-laser peak outputs up to 80 W at pressures from 60 to 240 Torr of helium in tubes of 2- to 4.45-cm ID and 150-cm length.^(24,26,27)

In the following work, the conditions required to provide maximum nuclear-energy coupling to the gas are investigated. Expressions relating pressure and tube radius are derived subject only to the constraint of a

maximum pressure. Pressure broadening of the fluorescent line starts around 100 Torr, with consequent increase in the oscillation threshold. The pressure limit of other experiments indicates that pressure broadening becomes dominant at about 240 Torr; 300 Torr was therefore selected as the maximum usable pressure.

The radius of the single-tube unit is the main variable. If, for the moment, the necessity for emptying the Ne_{1s} level by diffusion to the walls is neglected, the effects of increased radius on coupling and output can be considered. The neutron flux required to produce threshold density is independent of the tube radius (r), because the energy (dE) deposited in the gas increases with r , and the heavy-fragment source-layer area increases with r , but the tube volume also increases as r^2 , just balancing off the former effects. The power output increases as the volume or r^2 ; the power input increases with r . Therefore, the efficiency should increase directly with the radius. However, the rate of energy deposition per unit path length (dE/dx) decreases as the fragment energy (E) decreases. This reduces the efficiency as the radius is increased, and there is the possibility of an optimum radius for maximum efficiency. The maximum useful tube diameter corresponds to the heavy fragment range, which is inversely proportional to gas pressure.

C. High-pressure, Large-diameter (HPLD), Laser Calculations

1. HPLD Laser Pumped with U^{235} Fission Fragments

The fission-fragment energy loss per centimeter of travel in general decreases as residual range decreases, because the fragment picks up electrons as it slows down.⁽¹⁸⁾ This effect can be approximated by a straight-line relation between residual range and rate of energy loss as in Fig. 11. The condition prevailing as the fragment enters the gas is designated I, and the condition as it leaves is designated O. The average path length of the fragment through the gas is $2r$ (from Appendix B). The average energy (ΔE) deposited in the gas by a fragment may be calculated as follows:

$$\begin{aligned}\Delta E &= \int_{R_I}^{R_0} (dE/dx) dR = \int_{R_I}^{R_0} -KR dR = \left[-\frac{KR^2}{2} \right]_{R_I}^{R_0} \\ &= (K/2)[R_I^2 - R_0^2];\end{aligned}$$

but

$$R_0 = R_I - 2r;$$

then

$$\Delta E = (K/2)[R_I^2 - (R_I - 2r)^2] = 2Kr(R_I - r); \quad (15)$$

Fig. 11. Fission-fragment Energy Loss per Centimeter, as a Function of Residual Range

since

$$(dE/dx)_I = Bp,$$

where p = pressure in Torr,

and

$$R_I = (dE/dx)_I / K = Bp / K; \quad (16)$$

therefore,

$$\Delta E = 2r[Bp - Kr]. \quad (17)$$

The constants B and K are calculated from data of Appendix B, as follows:

$$\left(\frac{dE}{dX}\right)_I = \frac{10.8p}{760} \text{ MeV cm}^{-1}, \text{ when } E_I = 45.05 \text{ MeV};$$

$$B = 10.8/760 = 1.421 \times 10^{-2};$$

$$E_I = KR_I^2/2 = (Bp)^2/2K = 1.421^2 \times 10^{-4} p^2/2K;$$

$$K = 2.241 \times 10^{-6} p^2.$$

By substitution,

$$\Delta E = rp[2.842 \times 10^{-2} - 4.482 \times 10^{-6} rp]; \quad (18)$$

but rp has a maximum limit, since $\Delta E \leq E_I = 45.05 \text{ MeV}$; therefore,

$$(rp)_{\text{limit}} = 3170.$$

Maximum efficiency is obtained when ΔE is maximum or $\frac{d(\Delta E)}{d(rp)} = 0$:

$$\frac{d(\Delta E)}{d(rp)} = 2.842 \times 10^{-2} - 2 \times 4.482 \times 10^{-6} rp = 0;$$

$$(rp)_{\text{max. efficiency}} = \frac{2.842 \times 10^{-2}}{2 \times 4.482 \times 10^{-6}} = 3170. \quad (19)$$

Therefore, the maximum-efficiency point corresponds with the limit condition above.

All that remains is to select the pressure, which will determine r for maximum efficiency and permit completion of the calculations. The

pressure should be set as high as possible since the threshold flux is inversely proportional to pressure. The fact that pressure broadening of the fluorescence line begins to set in at about 100 Torr must be considered, but experiments have been performed successfully with pressures up to 250 Torr. Therefore, a pressure of 300 Torr and a laser tube diameter of 20 cm will be used. From Appendix B:

$$\begin{aligned}
 p &= 10 \text{ Torr;} \\
 \text{tube diameter} &= 1.125 \text{ cm;} \\
 \Delta E &= 0.16 \text{ MeV/fragment;} \\
 \Phi_{\text{TH}} &= 2.04 \times 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1}; \\
 (P_{\text{IN}})_{\text{TH}} &= 4.2 \text{ kW thermal;} \\
 (P_{\text{OUT}})_{\text{TH}} &= 1 \text{ mW;} \\
 \text{Efficiency} &= P_{\text{OUT}}/P_{\text{IN}} = 2.4 \times 10^{-7}.
 \end{aligned}$$

Then, the HPLD U^{235} laser may be calculated as follows:

$$\begin{aligned}
 p &= 300 \text{ Torr;} \\
 \text{tube diameter} &= 20 \text{ cm;} \\
 \Delta E &= 45 \text{ MeV/fragment;} \\
 \Phi_{\text{TH}} &= \frac{0.16}{45} \times \frac{20}{1.125} \times 2.04 \times 10^{13} = 1.29 \times 10^{12}; \\
 (P_{\text{IN}})_{\text{TH}} &= \frac{1.29 \times 10^{12}}{2.04 \times 10^{13}} \times \frac{20}{1.125} \times 4.2 = 4.7 \text{ kW thermal;} \\
 (P_{\text{OUT}})_{\text{TH}} &= 1 \text{ mW} \times \left(\frac{20}{1.125} \right)^2 = 316 \text{ mW.}
 \end{aligned}$$

The efficiency has increased by a factor of $(316/4.7) \div (1/4.2) = 316 \times (4.2/4.7) = 282$ times. The HPLD U^{235} laser efficiency is $0.316/4700 = 6.7 \times 10^{-5}$ at threshold. This value is about 25 times that for the electrically pumped case, estimated earlier to be 2.4×10^{-6} . The large diameter of 20 cm would probably require multiple-pass operation if wall collisions are the only means of emptying the lower level. The HPLD B^{10} laser is much more favorable in this respect, as will be seen in Section 2 below.

2. HPLD Laser Pumped with B¹⁰ Fragments

The B¹⁰ heavy-fragment energy loss per centimeter of travel is essentially constant and independent of residual range except at energies that are low relative to 0.9 MeV, the energy of the fragment as it enters the gas. The average energy ΔE deposited in the gas by a fragment then is a straightforward calculation:

$$\begin{aligned}\Delta E &= \int_{R_I}^{R_0} (dE/dx)_I dr = \int_{R_I}^{R_0} -K dR = [-KR]_{R_I}^{R_0} \\ &= K[R_I - R_0];\end{aligned}$$

but

$$R_0 = R_I - 2r;$$

then,

$$\Delta E = 2Kr; \quad (20)$$

since

$$K = (dE/dx)_I = Bp; \quad (21)$$

substituting Eq. (21) into Eq. (20) results in

$$\Delta E = 2Brp. \quad (22)$$

The constant B is obtained from data of Appendix C, as follows:

$$\left(\frac{dE}{dx}\right)_I = \frac{4.4 \times 10^{-3} p}{10} \text{ MeV cm}^{-1}, \text{ when } E_I = 0.9 \text{ MeV};$$

$$B = 4.4 \times 10^{-4}.$$

By substitution,

$$\Delta E = 8.8 \times 10^{-4} rp; \quad (23)$$

but rp has a maximum limit, since $\Delta E \leq E_I = 0.9 \text{ MeV}$; therefore,

$$(rp)_{\text{limit}} = \frac{0.9}{8.8 \times 10^{-4}} = 1020.$$

In the case of B¹⁰, the efficiency continues to increase with increasing radius up to the above limit.

Again it is desirable to set the pressure as high as possible for the same reasons given in Section 1 above for the U^{235} laser. Therefore, a pressure of 300 Torr and a laser tube diameter of 5 cm will be used. From Appendix C:

$$\begin{aligned}
 p &= 10 \text{ Torr;} \\
 \text{tube diameter} &= 1.125 \text{ cm;} \\
 \Delta E &= 5.0 \times 10^{-3} \text{ MeV/fragment;} \\
 \Phi_{TH} &= 5.5 \times 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1}; \\
 (P_{IN})_{TH} &= 1.62 \text{ kW thermal;} \\
 (P_{OUT})_{TH} &= 1 \text{ mW;} \\
 \text{Efficiency} &= P_{OUT}/P_{IN} = 6.2 \times 10^{-7}.
 \end{aligned}$$

Then, the HPLD B^{10} laser may be calculated as follows:

$$\begin{aligned}
 p &= 300 \text{ Torr;} \\
 \text{tube diameter} &= 5 \text{ cm;} \\
 \Delta E &= 0.9 \text{ MeV/fragment;} \\
 \Phi_{TH} &= \frac{5.0 \times 10^{-3}}{0.9} \times \frac{5}{1.125} \times 5.5 \times 10^{13} = 1.35 \times 10^{12}; \\
 (P_{IN})_{TH} &= \frac{1.35 \times 10^{12}}{5.5 \times 10^{13}} \times \frac{5}{1.125} \times 1.62 = 179 \text{ W;} \\
 (P_{OUT})_{TH} &= 1 \text{ mW} \times \left(\frac{5}{1.125} \right)^2 = 19.8 \text{ mW.}
 \end{aligned}$$

The efficiency has increased by a factor of $(19.8/0.179) \div (1/1.62) = 19.8 \times 1.62/0.179 = 179$ times. The HPLD B^{10} laser efficiency is $19.8 \times 10^{-3}/179 = 1.1 \times 10^{-4}$ at threshold. This value is about 46 times that for the electrically pumped case, estimated earlier to be 2.4×10^{-6} . The 5-cm diameter is comparable to the 4.5-cm diameter used in pulse experiments at 240 Torr reported in the literature; therefore, successful operation of the HPLD B^{10} laser would seem optimistic if not assured. (27)

VII. CONCLUSIONS

Large-diameter, high-pressure, direct-nuclear-pumped gas lasers show theoretical efficiencies two orders of magnitude larger than those obtained previously for small-diameter tubes. Lasers filled with helium at a pressure of 300 Torr and made with large-diameter tubes optimized for that pressure require a flux of about 10^{12} neutrons $\text{cm}^{-2} \text{sec}^{-1}$ to reach the lasing threshold. The power output of such types is about two orders of magnitude higher at threshold than the output of the small-diameter types, at least under pulse conditions.

Boron-10 used as a pumping medium has the following characteristics: (1) The thermal efficiency is good. (2) The optimum diameter of 5 cm required for maximum efficiency at a pressure of 300 Torr corresponds to the diameter of high-pressure lasers whose feasibility has already been demonstrated with electrical pumping. (3) Residual radioactivity is low. (4) Neutron absorption is high.

Uranium-235 used as a pumping medium exhibits the following properties: (1) The thermal efficiency is fair. (2) The optimum diameter of 20 cm required for maximum efficiency at a pressure of 300 Torr may require folding the light path into an annular shape near the walls to increase the rate at which the lower neon level is emptied. The feasibility of the folded light path has been demonstrated with electrically pumped lasers. (3) Residual radioactivity is high. (4) Neutron multiplication properties are available.

Thus each of the two materials has advantages and disadvantages which must be considered for the particular use the designer has in mind. For example, the B^{10} laser would act as a poison element in a reactor and could be considered as a control rod or could be used to attain longer reactor core life by depletion of the B^{10} . The U^{235} laser, on the other hand, would permit consideration of a reactor using such lasers as fuel elements in a large multiple array to achieve high laser beam power.

APPENDIX A

Calculation of Oscillation Threshold Density

The threshold density required to start oscillation can be calculated using the following expression:⁽¹¹⁾

$$Ne_{TH}^* = \frac{4\pi^2 \nu^2 \Delta \nu t_{spont}}{c^3 (\pi \ln 2)^{1/2} t_{photon}}, \quad (A-1)$$

where

$$c/\nu = \text{emission wavelength} = 1153 \text{ nm or } 632.8 \text{ nm},$$

$$\Delta \nu = \text{Doppler-broadened line width} = 9 \times 10^8 \text{ cps at } 1153 \text{ nm},$$

$$t_{spont} = \text{spontaneous emission lifetime} = 10^{-7} \text{ sec},$$

and

$$t_{photon} = \text{photon lifetime} = \frac{L}{\alpha c} = \frac{10^2}{0.01 \times 3 \times 10^{10}} = 3.3 \times 10^{-7} \text{ sec}. \quad (A-2)$$

The 1153-nm neon line requires a threshold density of

$$\begin{aligned} Ne_{TH}^* &= \frac{4\pi^2 \times 9 \times 10^8 \text{ cps} \times 10^{-7}}{(1.153 \times 10^{-4} \text{ cm})^2 \times 3 \times 10^{10} \text{ cm/sec} \times (\pi \ln 2)^{1/2} \times 3.3 \times 10^{-7}} \\ &= \underline{1.8 \times 10^7 \text{ atoms cm}^{-3}} \text{ (for tube } 1 \text{ cm}^2 \text{ in area and } 100 \text{ cm long).} \end{aligned}$$

Since the Doppler-broadened line width is proportional to ν , Ne_{TH}^* is inversely proportional to λ^3 . The 632.8-nm neon line then requires a threshold density of

$$Ne_{TH}^* = 1.8 \times 10^7 \times \left(\frac{1.153}{0.6328} \right)^3 = \underline{1.1 \times 10^8 \text{ atoms cm}^{-3}}.$$

Threshold fluorescence power output for a volume of 100 cm^3 is

$$\begin{aligned} P_{fc} &= \frac{Ne_{TH}^* h \nu V}{t_{spont}} \approx \frac{1.8 \times 10^7 \times 6.6 \times 10^{-27} \times 2.6 \times 10^{14} \times 10^2}{10^{-7} \times 10^7 \text{ erg/J}} \\ &= 3.1 \times 10^{-3} \text{ W (at } 1153 \text{ nm)} \\ &= 34.4 \times 10^{-3} \text{ W (at } 632.8 \text{ nm)}. \end{aligned} \quad (A-3)$$

The threshold power of the laser beam itself is only about 3% of the above fluorescence power because energy is lost both by spontaneous emission and by loss of stimulated emission into unwanted lines and modes. Many schemes for curing the latter difficulties are presently appearing in the literature.^(13,14)

APPENDIX B

Calculation of the Neutron Flux Required to Pump a Small-diameter Helium-Neon Laser with U^{235} Fission Fragments

The number of fission fragments entering the gas is calculated as follows.

$$\Sigma_f = 582 \times 10^{-24} \text{ cm}^2/\text{atom} \times 0.0473 \times 10^{24} \text{ atoms cm}^{-3} = 27.5 \text{ cm}^{-1}.$$

Then F , the number of fissions per square centimeter per second, is

$$F = 27.5 \text{ cm}^{-1} \times t \times \Phi \quad (t = U^{235} \text{ thickness}). \quad (\text{B-1})$$

$$\text{Let } t = 1 \text{ fission-fragment range}^{(15)}$$

$$= 6.9 \times 10^{-4} \text{ cm}.$$

$$\text{Let } \Phi = 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1}.$$

Therefore,

$$F = 27.5 \times 6.9 \times 10^{-4} \times 10^{13} = 1.90 \times 10^{11} \text{ fissions cm}^{-2} \text{ sec}^{-1}.$$

Then R , the number of fission-fragment recoils entering the gas per square centimeter per second, is

$$R = \frac{2F}{4} = \frac{2 \times 1.90 \times 10^{11}}{4}$$

$$= 9.5 \times 10^{10} \text{ F.F. cm}^{-2} \text{ sec}^{-1} \text{ entering the gas}. \quad (\text{B-2})$$

The average path length of the fission fragment through the tube is $\bar{p} = 2r = 1.125 \text{ cm}$, where r is the tube radius.⁽¹⁶⁾ The energy of the average fission fragment entering the gas is derived as follows.

A spectrum for a 3μ source (approximately half our source thickness) shows a measured spectrum with an average energy $<50 \text{ MeV}$.⁽¹⁷⁾ The average energy for zero thickness is 83; therefore, the reduction passing through $t/2$ is approximately $0.6E_0$. Then two-thirds of the particles will appear at the surface with an average energy of 50 MeV, and about one-third with $50 \times 0.6 = 30 \text{ MeV}$; therefore, the average energy for t thickness is $50 \times 2/3 + 30 \times 1/3$ or 43 MeV.

A 43-MeV fission fragment has a residual range of 1.7 cm and a $dE/dx = 53 \text{ MeV/cm}$ in argon at NTP.⁽¹⁸⁾ Then the dE/dx is proportional to the electron density of the medium, and

$$\begin{aligned} dE/dx (\text{He}) &= 0.204 dE/dx (\text{Ar}) = 53 \text{ MeV cm}^{-1} \times 0.204 \\ &= 10.8 \text{ MeV cm}^{-1} \text{ at NTP.} \end{aligned}$$

Then,

$$\begin{aligned} \frac{dE/dx (\text{He})}{(10 \text{ Torr})} &= \frac{\text{Total } 10.8 \times 10^6 \text{ eV cm}^{-1}}{76} \times 1.125 \text{ cm} \\ &\approx 160,000 \text{ eV/fragment passing through tube.} \end{aligned}$$

The curve for argon in Ref. 18 can be used for helium (taking proper account of the difference in the electron density of the medium), because the fission-fragment electron gain is nearly the same in both gases.⁽¹⁹⁾ Reference 19 also shows (p.203) a residual 43-MeV range of about 1.7 cm for both fragments in argon, which agrees with Ref. 18.

The fission-fragment power delivered to the gas per cubic centimeter of tube volume is determined as follows:

$$\begin{aligned} \text{Area of coating per cm length} &= 3.53 \text{ cm}^2; \\ \text{Volume of tube per cm length} &= 1 \text{ cm}^3; \\ P_{FG} &= R \times dE/dx (\text{He}) \times \text{area/volume} \\ &= 9.5 \times 10^{10} \times 160,000 \times 3.53/1 \\ &= 5.4 \times 10^{16} \text{ eV cm}^{-3} \text{ sec}^{-1}. \end{aligned} \tag{B-3}$$

Approximately one excited helium atom is produced per 100 eV, and the lifetime is $\approx 10^{-4}$ sec.⁽¹²⁾ The equilibrium-excited population then is

$$\begin{aligned} \text{He}^* &= \frac{P_{FG} \times \tau_{\text{He}^*}}{100} = \frac{5.4 \times 10^{16} \times 10^{-4}}{10^2} \\ &= 5.4 \times 10^{10} \text{ atoms cm}^{-3}. \end{aligned} \tag{B-4}$$

The collision cross section for He^+ ions on neon gas is of the order of $3 \times 10^{-15} \text{ cm}^2/\text{atom}$; therefore, the transfer cross section will be assumed to be at least $10^{-16} \text{ cm}^2/\text{atom}$.⁽²⁰⁾

Then the transfer rate is determined as follows:

$$\begin{aligned} N_{\text{Ne}} &= 2.69 \times 10^{19} \times 0.2/760 = 7.08 \times 10^{15} \text{ atoms cm}^{-3}; \\ \text{He}^* \text{ to Ne}^* &= \text{He}^* \times 7.08 \times 10^{15} \times 10^{-16} \times V_{\text{He}^*}; \end{aligned}$$

$$V_{\text{He}^*} = 1.1 \times 10^5 \text{ cm/sec at } 293^\circ\text{K};$$

$$\begin{aligned} \text{He}^* \text{ to Ne}^* &= 5.4 \times 10^{10} \times 7.08 \times 10^{15} \times 10^{-16} \times 1.1 \times 10^5 \\ &= 4.17 \times 10^{15} \text{ transfers cm}^{-3} \text{ sec}^{-1}. \end{aligned}$$

From the above, it can be assumed that all He^* transfer to Ne^* . The equilibrium-excited population for Ne^* , where Ne^* lifetime $\approx 10^{-7}$ sec, (11) then is

$$\text{Ne}^* = \frac{P_{\text{FG}} \times \tau_{\text{Ne}^*}}{100} = \frac{5.4 \times 10^{16} \times 10^{-7}}{10^2} = 5.4 \times 10^7 \text{ atoms cm}^{-3}. \quad (\text{B-5})$$

Finally, the neutron flux required for oscillation at each wavelength for U^{235} may be calculated using the threshold values of Ne^* calculated in Appendix A:

$$\Phi(632.8 \text{ nm}) = \frac{1.1 \times 10^8}{5.4 \times 10^7} \times 10^{13} = 2.04 \times 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1};$$

$$\Phi(1153 \text{ nm}) = \frac{1.8 \times 10^7}{5.4 \times 10^7} \times 10^{13} = 3.3 \times 10^{12} \text{ neutrons cm}^{-2} \text{ sec}^{-1}.$$

APPENDIX C

Calculation of the Neutron Flux Required to Pump a Small-diameter
Helium-Neon Laser with B¹⁰ Fragments

The number of alpha fragments entering the gas is calculated as follows:

$$\Sigma_A = 4020 \times 10^{-24} \text{ cm}^2/\text{atom} \times 0.141 \times 10^{24} \text{ atoms cm}^{-3} = 567 \text{ cm}^{-1}.$$

Then F, the number of reactions per square centimeter per second, is

$$F = 567 \text{ cm}^{-1} \times t \times \Phi \quad (t = B^{10} \text{ thickness}). \quad (\text{C-1})$$

Let $t = 1$ alpha-fragment range⁽²¹⁾

$$= 4 \times 10^{-4} \text{ cm}.$$

$$\text{Let } \Phi = 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1}.$$

Therefore,

$$F = 567 \times 4 \times 10^{-4} \times 10^{13} = 2.27 \times 10^{12} \text{ reactions cm}^{-2} \text{ sec}^{-1}.$$

Then R, the number of fragment recoils entering the gas per square centimeter per second, is

$$\begin{aligned} R &= \frac{2F}{4} = \frac{2 \times 2.27 \times 10^{12}}{4} \\ &= 1.14 \times 10^{12} \text{ frag cm}^{-2} \text{ sec}^{-1} \text{ entering the gas.} \end{aligned} \quad (\text{C-2})$$

The average path length of the fragment through the tube is $\bar{p} = 2r = 1.125 \text{ cm}$, where r is the tube radius.⁽¹⁶⁾ The average energy of the fragments emitted from the gas side of the B¹⁰ layer is 0.62 of the initial energy of 1.46 MeV, or 0.9 MeV.⁽²²⁾ The cross section (σ_i) for He⁺⁺ on helium gas is

$$\sigma_i = 2.7 \times 10^{-16} \text{ cm}^2/\text{He atom}.$$

The number of ionizing collisions per centimeter of path is

$$N_C = 2.7 \times 10^{-16} \text{ cm}^2/\text{atom} \times 35.5 \times 10^{16} \text{ atoms cm}^{-3} = 96 \text{ cm}^{-1}.$$

The energy deposited per centimeter is⁽²³⁾

$$\begin{aligned} dE/dx &= 96 \text{ collisions/cm} \times 46 \text{ eV/ion pair} \\ &= 4416 \text{ eV cm}^{-1}. \end{aligned}$$

The energy deposited per recoil fragment is

$$E_{\text{FRAG}} = \bar{p} \times dE/dx = 1.125 \times 4416 \\ = 4968 \text{ eV/fragment.}$$

The recoil fragment power delivered to the gas per cubic centimeter of tube volume is

$$P_{\text{RF}} = R \times E_{\text{FRAG}} \times \text{Area/Volume} \\ = 1.14 \times 10^{12} \times 4968 \times 3.53/1 \\ = 2.0 \times 10^{16} \text{ eV cm}^{-3} \text{ sec}^{-1}. \quad (\text{C-3})$$

Approximately one excited helium atom is produced per 100 eV, and the lifetime is $\approx 10^{-4}$ sec.⁽¹²⁾ The equilibrium-excited population then is

$$\text{He}^* = \frac{P_{\text{RF}} \times \tau_{\text{He}^*}}{100} = \frac{2.0 \times 10^{16} \times 10^{-4}}{10^2} \\ = 2.0 \times 10^{10} \text{ atoms cm}^{-3}. \quad (\text{C-4})$$

The collision cross section for He^+ ions on neon gas is of the order of $3 \times 10^{-15} \text{ cm}^2/\text{atom}$; therefore, the transfer cross section will be assumed to be at least $10^{-16} \text{ cm}^2/\text{atom}$.⁽²⁰⁾ Then the transfer rate is determined as follows:

$$N_{\text{Ne}} = 2.69 \times 10^{19} \times 0.2/760 = 7.08 \times 10^{15} \text{ atoms cm}^{-3}; \\ \text{He}^* \text{ to Ne}^* = \text{He}^* \times 7.08 \times 10^{15} \times 10^{-16} \times V_{\text{He}^*}; \\ V_{\text{He}^*} = 1.1 \times 10^5 \text{ cm/sec at } 293^\circ\text{K}; \\ \text{He}^* \text{ to Ne}^* = 2.0 \times 10^{10} \times 7.08 \times 10^{15} \times 10^{-16} \times 1.1 \times 10^5 \\ = 1.53 \times 10^{15} \text{ transfers cm}^{-3} \text{ sec}^{-1}.$$

From the above, it can be assumed that all He^* transfer to Ne^* . The equilibrium-excited population for Ne^* , where Ne^* lifetime $\approx 10^{-7}$ sec,⁽¹¹⁾ then is

$$\text{Ne}^* = \frac{P_{\text{FR}} \times \tau_{\text{Ne}^*}}{100} = \frac{2.0 \times 10^{16} \times 10^{-7}}{10^2} \\ = 2.0 \times 10^7 \text{ atoms cm}^{-3}. \quad (\text{C-5})$$

The neutron flux required for oscillation at each wavelength for B^{10} is

$$\Phi(632.8 \text{ nm}) = \frac{1.1 \times 10^8}{2.0 \times 10^7} \times 10^{13} = 5.5 \times 10^{13} \text{ neutrons cm}^{-2} \text{ sec}^{-1};$$

$$\Phi(1153 \text{ nm}) = \frac{1.8 \times 10^7}{2.0 \times 10^7} \times 10^{13} = 9.0 \times 10^{12} \text{ neutrons cm}^{-2} \text{ sec}^{-1}.$$

APPENDIX D

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