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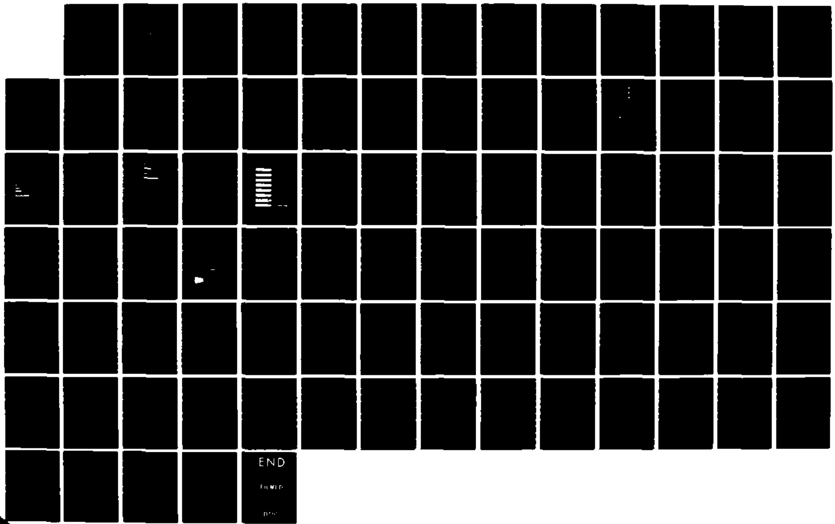

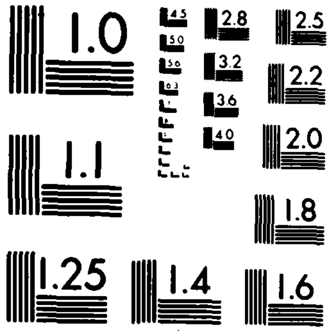

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Monterey, California

THESIS

HIGH ENERGY LASERS:
A PRIMER ON DIRECTED ENERGY
WEAPONS FOR SPACE USE

by

Richard F. Ziska

September 1984

Thesis Advisor: Allen E. Fuhs

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High Energy Lasers:
A Primer on Directed Energy Weapons for Space Use

by

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Submitted in partial fulfillment of the
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ABSTRACT

The rapid and inevitable commercialization and exploitation of space, which is now gaining increased momentum as the Space Shuttle program settles into a regular monthly schedule, is inescapably increasing our dependence on space-based systems of all kinds. These systems have become vital national interests, the defense of which must be considered whenever realistic wartime scenarios are developed. Consequently, the introduction of weapons into the space environment is an important option, the potential of which must be thoroughly investigated so as not to unwittingly jeopardize critical national assets and ultimately national defense.

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I. INTRODUCTION

A. HISTORICAL PERSPECTIVE

In 1954, Charles H. Townes and several of his students at Columbia University fabricated and successfully demonstrated a device called a "MASER" (Microwave Amplification by Stimulated Emission of Radiation (A. E. Siegman [Ref. 1]). This device produced electromagnetic amplification and operated at microwave frequencies. Soon afterwards, in 1960, T. H. Maiman of the Hughes Research Laboratories was the first to demonstrate the "optical maser," (D. C. O'Shea, R. W. Callen, and W. T. Rhodes [Ref. 2]) or electronic amplification at optical frequencies, which has come to be known as the "LASER" (Light Amplification by Stimulated Emission of Radiation). These devices validated the basic physical principles of laser energy generation which had been previously postulated in the early days of quantum theory.

Simultaneously, as a spinoff of 1950's research focused on applying "particle beam" concepts as a means of breeding fissionable material for military applications, the possibilities of eventually developing particle beams into effective weapon systems generated considerable interest.

The possible military applications of both of these infant technologies were immediately recognized. If matured technology could succeed in increasing the power output of these devices to sufficient levels, the revolutionary prospect of generating an extremely intense and controllable "energy beam" weapon could become reality. These weapons (collectively designated "DIRECTED ENERGY WEAPONS," or "DEW") offer the following attractive features:

1) The ability to deliver lethal energy at the speed of light over long distances.

2) The achievement of surgical targeting accuracy.

3) The realization of vastly improved retargeting slew rates. The "massless" and therefore "inertia-less" quality of the energy beam would reduce the retargeting problem to the simple movement of a mirror. This could markedly increase engagement frequencies in a high-target-density environment.

4) The virtual liberation from the conventional projectile limitations of gravity effects, aerodynamic forces, and requirements for extensive lead-angle information in fire control solutions.

These qualities, which would dramatically revolutionize the art of warfare, sparked instantaneous flurries of expectations and enthusiasm. The projected near-term employment possibilities were primarily tactical in nature. Communications, antiair warfare (both antiaircraft and antiship missile), antisubmarine warfare, minesweeping, laser-guided projectiles, laser radar, missile guidance systems, fire control pointing and tracking systems, meteorology, and environmental modification (such as burning through or away fog), were all possible tactical applications of direct interest to the naval forces (W. J. Beane [Ref. 3]). Space-based or strategic employment concepts, such as Ballistic Missile Defense (BMD) or Antisatellite (ASAT) weapons remained, at that time, only remote possibilities due to the embryonic state of the "Space" program and the prevailing political environment.

Initial investigations of DEW technologies, however, at least as far as major weapons applications were concerned, exposed serious technological and engineering questions regarding the fundamental soundness of the concepts themselves. Furthermore, even assuming the eventual solution of all major technological and engineering problems, it became increasingly apparent that the production and deployment of high-power, viable DEW systems would be very expensive.

Consequently, given the infant state of the art and the associated economic realities, the initial fascination for DEW's did not acquire the status of a high-national-priority program required to attract the Research and Development (R&D) funding levels essential for large scale development. Furthermore, the political impetus during these years was toward maintaining global stability through the policy of "MAD" (Mutually Assured Destruction), which culminated in the ABM (Anti-Ballistic Missile) Treaty of 1972 (A. B. Carter and D. N. Schwartz [Ref. 4]). Therefore, the remote (but theoretically possible) development and employment of DEW as widespread implements of a Ballistic Missile Defense (BMD) system were specifically banned by mutual national agreement. Although nominal DEW research and development efforts were maintained in the hopes of uncovering significant technological breakthroughs, no serious policy or monetary commitments materialized in the face of these prevailing political, strategic, and technological environments.

B. MOTIVATION FOR ACCELERATED DEW RESEARCH

The political, strategic and technological postures of both the United States and the Soviet Union have dramatically changed. Four highly significant occurrences have prompted the reevaluation of the low priority placed upon DEW research. These occurrences are:

1) The unqualified successes of the U. S. (and also U. S. S. R.) "Space" programs have forevermore exposed the space environment to utilization and exploitation on all levels; technological, commercial, and strategic. The unique advantages offered by this new "high ground" have already facilitated the development of a global communications network which provides virtually instantaneous transfer of information <u>from</u> anywhere <u>to</u> anywhere. A natural consequence of these unprecedented communication and surveillance capabilities, however, is a rapidly

growing dependence on the continued and reliable operation of all of these space-based systems especially in time of war.

2) The United States has unmistakably lost its nuclear superiority over the decade of the 1970's and may not be able to rectify the situation by a traditional expansion of the strategic nuclear arsenal because of an emerging national consensus against the deployment of "new" nuclear weapons. President Reagan's military modernization program, including the controversial "Peacekeeper" missile, is an attempt to close this "window of vulnerability." Its political future, however, is genuinely suspect.

3) Several unique technological advances have evolved which have revitalized the projected viability of adopting a "layered" BMD strategic concept. These are:

a) The significant advancement of DEW technology. Studies indicate that, given sufficient R&D support, all major DEW technological and engineering problems can be solved. When perfected, these weapons could initially be utilized in a satellite self-defense and ASAT role and then be expanded for use as the first, or "boost-phase" component of a layered BMD system.

b) The perfection of long-wave infrared optical sensors (LWIR). Combined with advanced on-board data processing capabilities and effective non-nuclear "kill" vehicles, LWIR will permit the development of an effective second, or "mid-course," BMD system layer.

c) The development of phased-array radars. This technology provides the unprecedented capability of acquiring and tracking very large numbers of high-speed reentry vehicles (RV's) required of an effective third, or "terminal-phase," BMD system.

4) The Soviet Union, which many believe agreed to the 1972 ABM treaty only to buy time to close the (then) rather large "technological gap," have been consistently investing "three to five times the American level of effort" (G. M. Van Keuren, Jr. [Ref. 5]) on DEW research in an attempt to achieve a quantum technological advantage.

Occurrence number one creates the day to day operational necessity of reliably maintaining and (if need be) defending critical space-based systems. Occurrence number two establishes the political need to identify and evaluate alternative strategic concepts in an attempt to re-establish strategic parity and improve global stability. Occurrence number three provides the technological confidence in the pursuit of these alternative weapon systems. And, finally, occurrence number four supplies the strategic imperative to at least maintain step with Soviet Union DEW research to preclude the likely event of a technological "Pearl Harbor" in space. Should the U. S. S. R. be the first to perfect and deploy creditable (or even "apparently" creditable) DEW systems in space, the U. S. must be in a position to at least match this deployment, or face the potentially disastrous dilemma of uncertainty as to the effectiveness of our retaliatory ICBM baseline. Such a situation would be an open invitation for political and strategic blackmail and is absolutely unacceptable!

C. PURPOSE OF THESIS

For the aforementioned reasons, DEW research has become a critical national priority. President Reagan, in his "Strategic Defense Initiative," has committed over $26 billion to BMD research over the next five fiscal years, $5.8 billion of which is dedicated to Directed Energy Weapons [Ref. 6]. Surprisingly enough, the Navy has been one of the major contributors to the development of DEW technology having developed, constructed and demonstrated the "NACL" (Navy Advanced Chemical Laser) and its successor, the "MIRACLE" (Mid Infrared Advanced Chemical Laser).

The purpose of this thesis is to act as a semi-technical "primer" on the basic concepts, components and operations of generic High Energy Laser beam generators, derivatives of which are presently under development by DARPA (Defense Advanced Research Projects Agency) for space-based applications [Ref. 7].

II. SPACE-BASED HIGH ENERGY LASER SYSTEM CONCEPTS

A. FUNDAMENTAL LASER PRINCIPLES

The damage mechanisms of a "LASER" weapon are unlike those of more conventional weapons, such as bullets or Phoenix missiles which ultimately rely on kinetic energy to inflict damage. The laser creates a beam of extremely intense coherent electromagnetic radiation. This radiation propagates at the speed of light and potentially can deposit extremely high energy densities on a distant target with pinpoint accuracy. The ability of a substance to "lase" is governed by certain laws of atomic physics. Quantum theory predicts that, under certain conditions, internal energy transitions of atoms or molecules will generate coherent electromagnetic radiation. This energy can be characterized by a unique frequency, or range of frequencies, dependent upon the "active laser medium" utilized and the energy levels involved in the transitions.

The key adjective in comprehending the essence of "LASER" energy is "coherent". Coherent electromagnetic radiation exhibits a high degree of spatial and temporal regularity. Figure 1 illustrates spatial regularity.

When a light wave exhibits exact spatial regularity, there is a completely predictable connection or correlation between the amplitude and phase at any one point on the

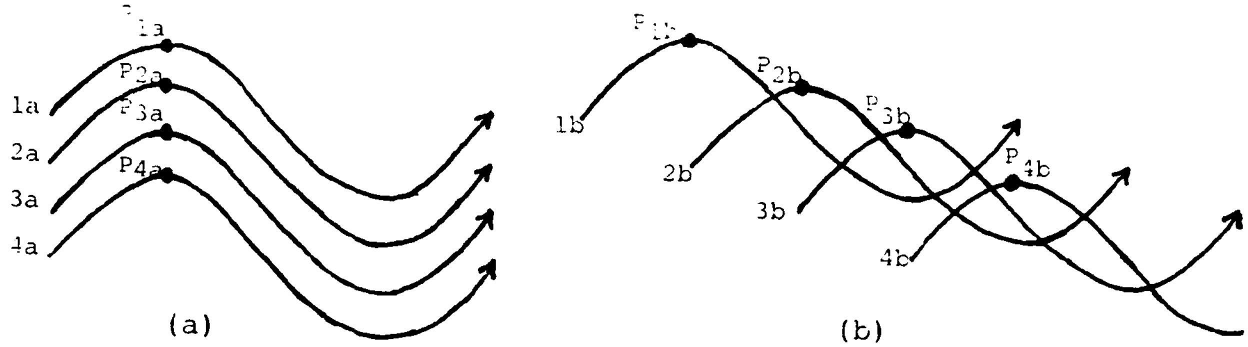


Figure 1. Spatial Regularity of "Coherent" Electromagnetic Energy.

wave and at any other point. For instance, assume that both light waves (a) and (b) in Figure 1 exhibit 100% spatial regularity, all waveforms have exactly the same frequency, and the points indicated on each waveform are the maximum amplitude. Standing at point P_{3a} on light wave (a), in which all waveforms are in phase with each other, one would always be assured of finding point P_{2a} directly above, and P_{4a} directly below the reference point. Likewise, standing at point P_{2b} on light wave (b), in which all waveforms are 90° out of phase in the manner shown, one would know exactly where to find points P_{1b}, P_{3b} or any other designated point on the light wave. This is complete "spatial" regularity.

Now consider "temporal" regularity. If the electromagnetic waves in Figure 1 maintain spatial regularity indefinitely, the waves are considered to exhibit complete "temporal" regularity. That is, having measured once the electric field variations at any two points on the respective waves, one could describe with complete certainty at a later time the status of the electric field at the second point simply by measuring the field at the first point.

The combination of both spatial and temporal regularity determines the degree of coherence exhibited by an electromagnetic wave. The highest degree of coherence among light sources is found in lasers.

This quality of coherence is primarily responsible for the laser beam characteristics of: a) intense brightness ("brightness" is the luminous power per unit area of the source per unit solid angle into which the source is radiating); b) directionality (highly collimated character); c) monochromaticity (single wavelength characteristics); d) and in some lasers, a high degree of polarization. Collectively, these attributes enable a sufficiently powerful laser beam to develop extremely high energy densities capable of damaging a target in a variety of ways.

The fundamental building block of a HEL weapon system is the laser itself. Although a variety of techniques and substances have been employed in achieving the "lasing" action, there are only four basic physical principles of quantum mechanics upon which all atomic, ionic, or molecular laser action is founded. These four principles are:

1) Atoms (and ions and molecules) exhibit internal resonances at certain discrete characteristic frequencies dependent upon the particular substance and the energy transitions involved. These internal resonances occur at frequencies ranging from below the infrared extending to and beyond the optical regions.

2) A photon of energy interacting with an atom at or near one of its internal resonances will cause a response in the atom. Depending on circumstances, the atom may absorb the photon, or it may emit a photon of identical phase and amplitude of the incident photon.

3) The strength and algebraic sign (absorption = "-", emission = "+") of the total response that will be obtained from a collection of many atoms of the same kind, depend directly on the energy-level population difference, i.e., the difference in population between the lower and upper quantum energy levels responsible for that particular transition. If the medium is in thermal equilibrium, the net response is always absorptive.

4) If the population difference is such that there are more atoms in the upper energy level (N_u) than in the lower (N_ℓ) (called a "population inversion"), the total response of the collection of atoms will also be inverted--that is, the total response will change from

a net absorptive to a net emissive condition. The response is therefore amplification of the incident energy (A. E. Siegman [Ref. 8]). The degree of amplification or "gain" of the laser (α) is mathematically defined as:

$$\alpha = \sigma(N_u - N_\ell)$$

Sigma (σ) is the optical cross-sectional-area of the lasing media which is available for interaction with incident photons.

Principle 1, simply stated, means that each atom, ion or molecule has a distinctive set of discrete energy levels. The particular energy level in which an atom might be at any specific time is entirely dependent upon the "internally" stored energy. The greater the amount of "internally" stored energy, the higher the energy state of the atom. Multiatomic molecules and ions can store energy by internal atomic motions, such as vibrations and rotations, as well as by the rearrangement of electrons. Single atoms can store internal energy by the rearrangement of electrons only. Figure 2 gives examples of vibrationally, rotationally and electrically "stored" internal energy.

Generally speaking, electrically stored energy, or electronic excitation, stores the most energy, followed by vibrational excitation and finally rotational excitation. Any one, or any combination of energy storage modes can be

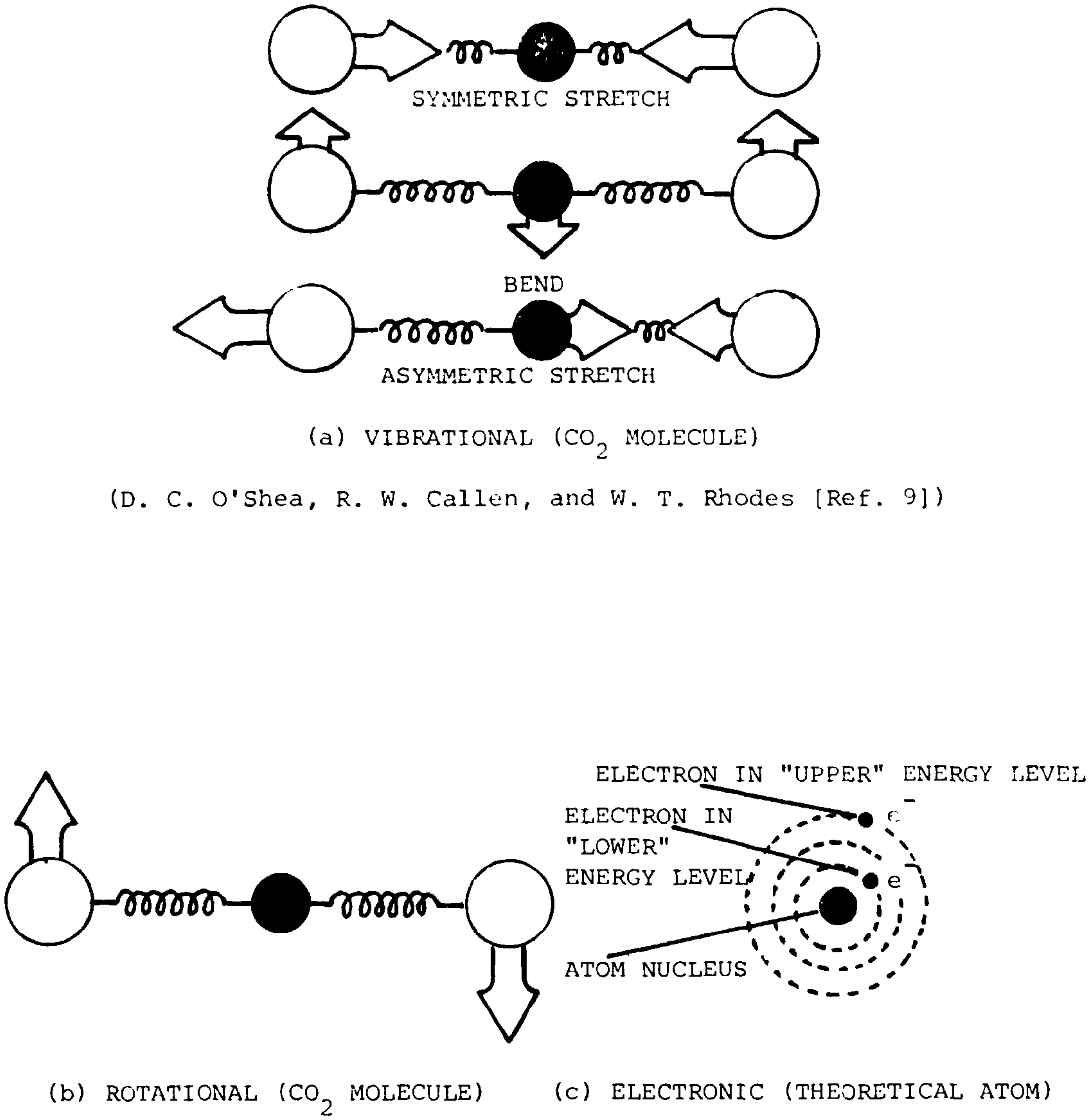
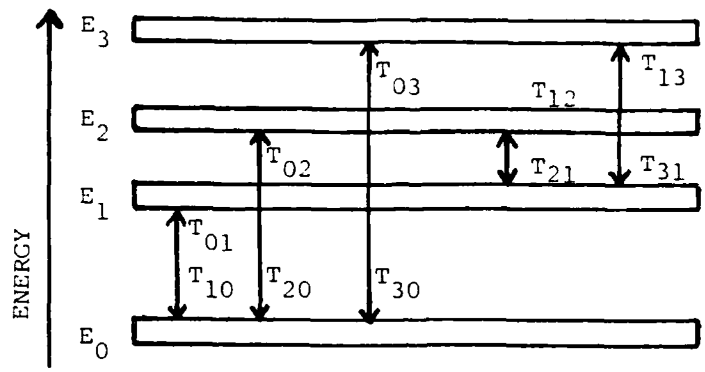


Figure 2. Modes of Stored Internal Energy.

"excited" simultaneously in a particular lasing medium, depending upon the characteristics of the incident "excitation" energy.

Figure 3 is a quantum energy level diagram for a hypothetical molecule with four distinct energy level possibilities.



E_i = ENERGY LEVELS (i)

T_{ij} = "TRANSITIONS" FROM ONE ENERGY LEVEL (i) TO ANOTHER (j)

Figure 3. Quantum Energy Level Diagram.

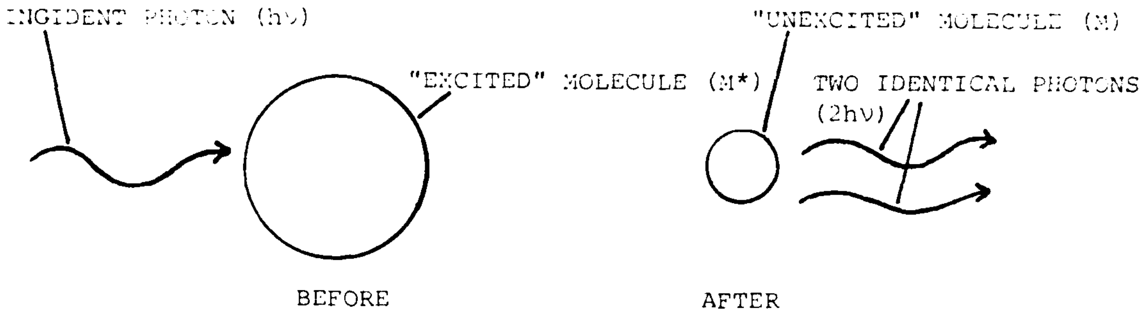
A molecule in the "ground state" (E_0), or level of least energy, may be "pumped" into a higher ("excited") energy level (E_1, E_2 or E_3) by the absorption and storage of energy provided by some external source. Once the molecule has achieved an elevated energy state, it has the tendency to shed its "extra" energy and return to a lower energy level and eventually to the ground state. When the molecule actually makes this transition from a higher (excited) to a lower (relatively unexcited) energy state (i.e., $\dot{T}_{31}$) it emits energy at a characteristic frequency unique to that particular transition. No two transitions for dissimilar atoms, ions or molecules are exactly the same, therefore each individual substance has its own characteristic emissive frequency. Additionally, multiple transitions are not only possible, but probable in most substances; consequently, these materials may simultaneously lase in a "range" of characteristic frequencies.

Several processes exist by which an excited molecule can relinquish its internally stored energy (called "relaxation"), including intermolecular collisions, collisions with physical boundaries (walls) and "spontaneous emission" (the process of emitting a characteristic wavelength photon without any external stimulus). However, the process that enables "LASER" action to occur is termed "stimulated emission," and is illustrated in Figure 4.

Upon interacting with a characteristic wavelength photon, an already excited molecule (M*) radiates an identical photon in phase, amplitude, direction and polarity with the incident photon.

$$M^* + h\nu = M + 2h\nu$$

Having relinquished its excess energy, the formerly "excited" molecule now returns to the "unexcited" state.



h = PLANKS CONSTANT

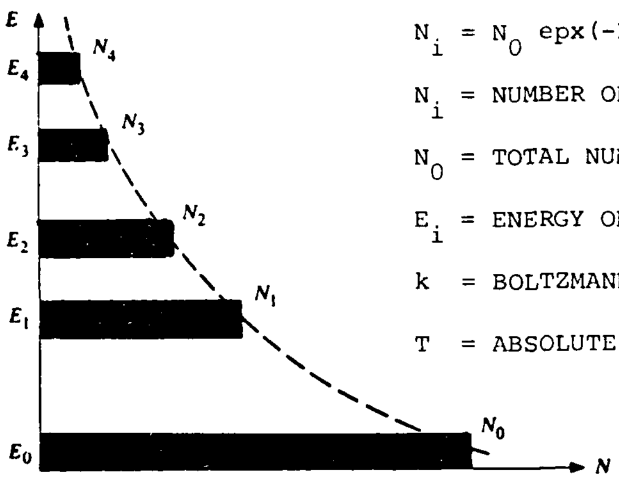
ν = FREQUENCY OF RADIATION

hν = ENERGY OF CHARACTERISTIC PHOTON

Figure 4. Stimulated Emission. (A. E. Fuhs [Ref. 10]).

Conversely, if the molecule happened to be in the ground state when interacting with the incident photon, it would have "radiatively absorbed" the energy, and been "pumped" into the corresponding "excited" energy state.

In Figure 4, the net electromatnetic radiation of the system (atomic, ionic or molecular) has doubled. This coherent "light amplification by stimulated emission of radiation," if greatly magnified, is the desired end-product of a laser generator. However, many loss mechanisms exist (such as spontaneous emission, radiative absorption, intermolecular and boundary (wall) collisions mentioned previously) which absorb, prevent or otherwise neutralize this "stimulated" radiation. In fact, as principle 3 states, all normal positive-temperature thermal equilibrium conditions will always exhibit a predominantly absorptive response. This phenomena is described by the "Boltzmann" distribution which specifies the fraction of atoms found, on the average, in any particular energy state for any given equilibrium temperature. Figure 5 mathematically states this relationship, and illustrates a hypothetical Boltzmann distribution for a molecule with five energy levels.



$N_i = N_0$ epx$(-E_i/kT)$

N_i = NUMBER OF ATOMS IN UPPER ENERGY LEVEL

N_0 = TOTAL NUMBER OF ATOMS IN SYSTEM

E_i = ENERGY OF ATOM IN i^{TH} ENERGY LEVEL

k = BOLTZMANN'S CONSTANT (1.38×10^{-23} joules/°K)

T = ABSOLUTE TEMPERATURE IN DEGREES KELVIN

Figure 5. Boltzmann Distribution. (D. C. O'Shea, R. W. Callen, and W. T. Rhodes [Ref. 11]).

Although the set of discrete energy levels of Figure 5 is unique only to this particular molecule, Boltzmann statistics require that the distribution of molecules in thermal equilibrium be an exponential function (dashed line). Consequently, no matter how high the temperature of a system happens to be, if it is in thermal equilibrium, there will always be more atoms in lower energy levels than in higher. This situation precludes the net release or amplification of incident photons because the relative number of "absorbers" (atoms in lower energy levels), combined with the energy loss mechanisms of wall and intermolecular collisions and spontaneous emissions, far exceed the number of possible "stimulated emitters," thus ensuring a predominantly absorptive medium.

To achieve "LASER" action, therefore, a state of non-equilibrium must be attained, which is characterized by a numerical predominance of atoms or molecules residing in "excited" rather than "unexcited" energy states. This condition is called a "population inversion" since the thermal equilibrium model defined by the Boltzmann distribution is reversed or "inverted" for the energy levels involved in the transition. Figure 6 depicts a population inversion condition in a four-level system, in which energy level three (E_2) contains more molecules than energy level two (E_1).

This population inversion condition is achieved by initially "pumping" large numbers of ground-state (E_0) molecules directly to the fourth energy level (E_3). "Pumping" refers to the application of some arbitrary external energy source, which is in some way transfered to or directly absorbed by the ground state molecules

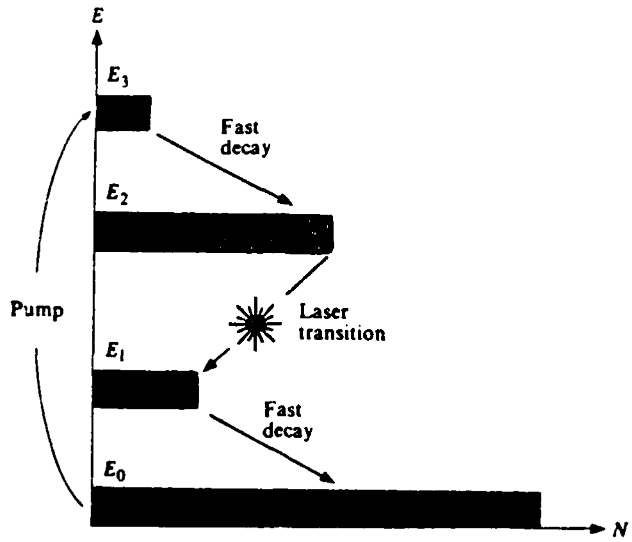


Figure 6. Population Inversion Distribution. (D. C. O'Shea, R. W. Callen and W. T. Rhodes [Ref. 12]).

causing excitation (by the internal storage mechanisms discussed previously) of the molecules to elevated energy levels. Various pumping sources are: optical pumping (flashlamps); electrical discharge; gasdynamic flow; electron-beam; chemical reactions; and nuclear pumping. Promising pumping schemes for space-based HEL weapons applications are discussed in Section II, C; D; and E.

The tendency of a molecule upon attaining energy level four (E_3) is to "relax" or return to a more stable (lower) energy level. Each individual substance (apart from the universal relaxation mechanisms of collisional deactivation) has its own decay or relaxation characteristics, which determine statistically the lifetime of a molecule in any particular upper energy level. In this example, decay transitions from E_3 to E_2 and E_1 to E_0 are very fast, compared to the transition from E_2 to E_1 which is relatively slow or "metastable". Consequently, the population of E_2 increases and eventually leads to a distinct population inversion between E_2 and E_1. If energy level E_2 is now "stimulated" by spontaneously emitted photons of the characteristic frequency, or by some appropriate external photon source, the molecules will revert to E_1 through lasing, and produce a net coherent energy release.

These four fundamental laser principles are illustrated in Figure 7.

Initially, the unexcited medium resides in an optical cavity ("LASER CAVITY") in a state of thermal equilibrium. A pumping mechanism (in this case electrical pumping) provides an external source of energy (energetic electrons, "e^-"). These "energetic" electrons transfer a certain amount of energy to the lasing medium through collisional processes, thus creating a population inversion. A characteristic frequency photon is then introduced into this excited medium by a spontaneously emitting atom which emits a photon that just happens to travel along the centerline axis of the cavity. Each successive excited molecule is then "stimulated" by an incident photon to

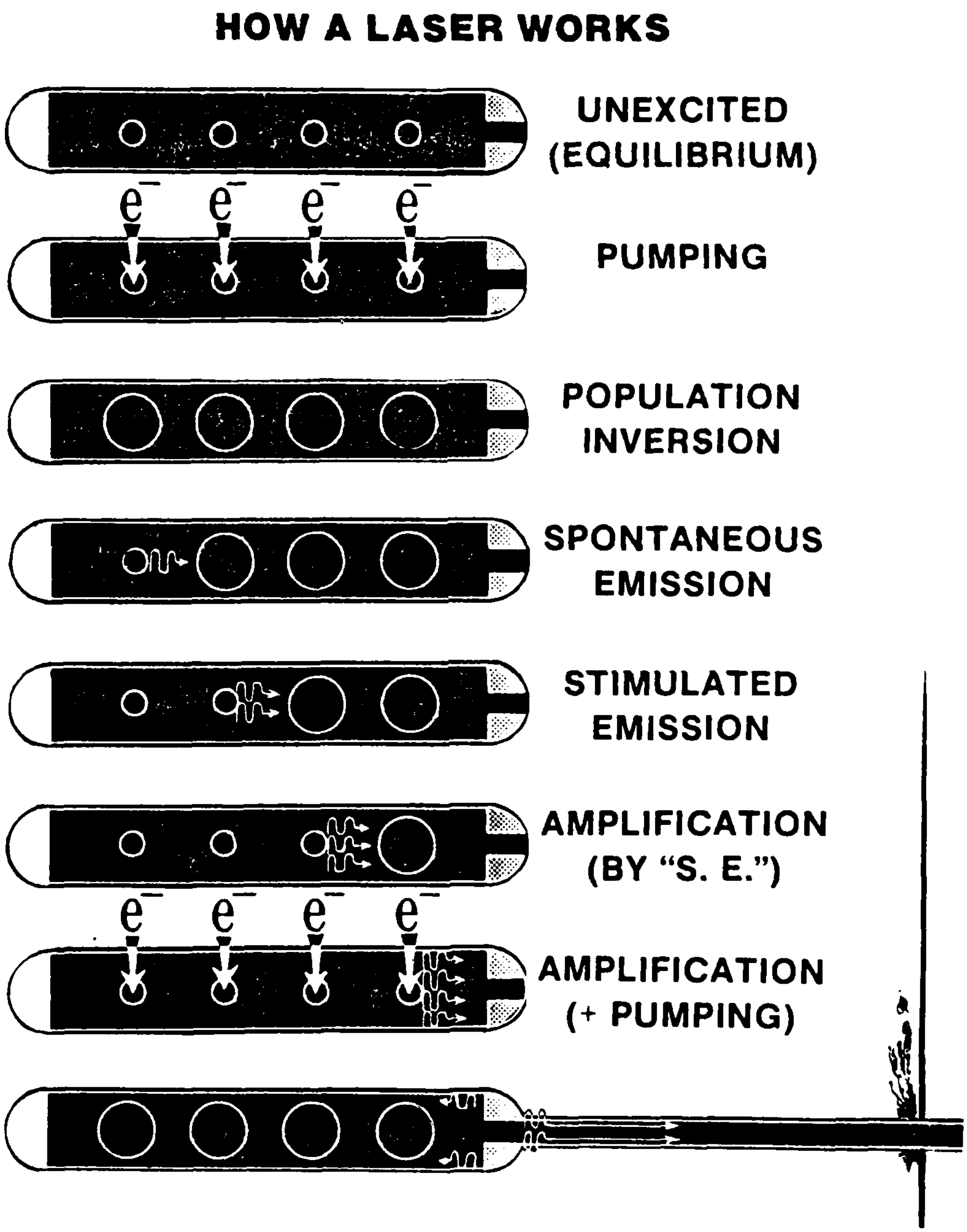


Figure 7. Electronically Pumped Laser Sequence.

coherently emit one identical photon to the traveling cavity wave, thus amplifying the original signal four times in a single pass.

However, the amount of single-pass amplification provided by most gaseous active media is measured in fractions of a percent per centimeter of optical pathlength. In many cases, this is a level much too low to be useful for even low power applications in a single pass device of reasonable length. Therefore, the development of high-power-output lasers usually requires the employment of a "resonant cavity," which utilizes mirrors at either end of the laser cavity to reflect the coherent energy back and forth through the active medium many times. If the mirrors are accurately separated at a distance of $n\lambda/2$ (A. E. Fuhs, [Ref. 13]) multiples of the characteristic wavelength, the laser energy is constructively reflected and the cavity amplitude intensifies. Finally, as exemplified in Figure 7, if one of the mirrors is 100% reflective (left mirror) and the other only partially reflective (say 95%), a certain percentage of the intense cavity energy can be extracted as the "laser beam". Consequently, even though the gain of the single pass amplifier may be quite small for most inverted media, the resultant amplification provided by multiple passes can be substantial.

The possible combinations of active lasing mediums, pumping mechanisms, and internal laser cavity optics (resonant cavity geometries) are virtually endless and are reflected in the almost exponential rise in laser applications. Optimum systems for space-based, HEL applications are presently being selected from an ever-expanding list of attractive high-power candidates. Whichever system (or systems) is eventually selected, however, will almost certainly contain the best trade-off of power, size, weight and cost. Three very promising systems are chemical infrared lasers, free electron lasers and nuclear pumped x-ray lasers. Prototypes of these lasers are presently under development by DARPA in support of the President's Strategic Defense Initiative.

B. APPROPRIATE LASER SELECTION CRITERIA

The decision as to which active lasing medium is best suited for a space-based HEL weapon application must be approached on the basis of the specific mission of the weapon. "Space to Earth," "Space to Space" and all of the intermediate possibilities are weapon employment options which must be carefully analyzed before an intelligent selection of an active medium is possible. For instance, the beam propagation environment (i.e., space only, or space and atmosphere) has a direct bearing on the most advantageous lasing medium. Also, some active media, and their individual characteristic lasing frequencies, have superior atmospheric propagation characteristics; some have a higher operating efficiency level; some systems are small in relation to their power output; some are more conducive to the fabrication of reliable and maintainable systems; and some have superior damage mechanisms. The trade-offs go on and on.

The output energy and/or power obtainable from a given laser medium are characterized by both the microscopic properties of the gain medium and by its associated power "scaling laws". "Scaling laws" refer to the unique proportionality relationships which apply to the physical expansion or contraction of different laser generation systems. These laws define the independent and dependent variables involved, and suggest the ultimate limits to which a given system may be expanded or contracted. Key microscopic laser variables of the gain medium are:

1) nominal wavelength
2) optical cross-section for stimulated emission
3) spectral gain-bandwidth and type of saturation (homogeneous, inhomogeneous)
4) saturation fluence or flux
5) radiative and kinetic lifetimes of upper and lower laser levels

Variable parameters associated with power "scaling laws" are:

1) population inversion density

2) small-signal gain coefficient

3) input and output power (energy) densities (M. J. Weber, [Ref. 14])

Although an exhaustive analysis of all of these interconnected variables is beyond the scope of this thesis, an in-depth trade-off study involving each of these parameters is an essential preliminary step to the selection of an optimum laser system for the desired mission.

Regardless of the individual variable characteristics which are inextricably linked to the specific mission selected, there are certain "across-the-board" requirements which are common to <u>any</u> space-based HEL system. These are:

1) high power output requirements

2) size and weight restrictions due to limited launch and servicing capacities

3) high reliability and high degree of autonomous operation due to maintenance and replenishment restrictions

4) cost effectiveness

Three promising concepts under investigation by DARPA (Defense Advanced Research Projects Agency) and the Air Force, the primary agencies responsible for the space-based laser program initiated by the President's Strategic Defense Initiative (SDI), are:

1) <u>chemical infrared</u> space-laser

2) <u>free-electron</u> space-laser

3) <u>nuclear pumped x-ray</u> space-laser, [Ref. 15]

All three of these concepts appear to have the potential to satisfy, at least in theory, the first three "across-the-board" requirements to varying degrees. The cost effectiveness question, however, remains, as yet, unanswered and will be under continuous and intensive investigation.

C. CHEMICAL INFRARED SPACE-LASER

The maturation of the chemical laser as a promising HEL device for space-based application was expedited by the early investigations of the gasdynamic laser (GDL).

> "The problem limiting the power levels of early (pre-GDL) lasers was that the process which excited the population inversion within the laser device simultaneously generated considerable waste heat that was difficult to dissipate. Because the optical medium is greatly affected by the resulting heat, this waste energy posed a fundamental limitation on the attainment of high average power output of early lasers. Removal of waste energy could be achieved through conduction to the walls of the laser device or through diffusion to the gas--but not without limits. Hence, high power output was achieved only through lengthening of the device." [Ref. 16]

Practical limits on length, weight and volume would have precluded the use of any of these devices for space applications. However, it was discovered that a population inversion could be created by rapidly expanding CO_2 gas through a supersonic nozzle. This process (termed "vibrational freezing" since certain vibrational energy levels of the CO_2 molecule "freeze" or remain in an elevated energy state while the remaining ones "relax" as the medium is cooled through expansion) not only created a population inversion, but also provided high-speed medium flow which facilitated the rejection of waste heat by convection processes. Initial high-power chemical laser designs suffered from similar waste-heat rejection problems. However, application of "flowing medium" concepts to these devices efficiently rejected the waste heat and facilitated the successful transition to high-power chemical lasers with weapons potential. Consequently, most current atomic, ionic or molecular high-power laser designs utilize a flowing lasing medium for waste heat rejection and for the supply of fresh lasing medium at high speed to the laser generation system.

1. Concept Description

The chemical laser is potentially a high-power, flow-laser device which utilizes an exothermic chemical reaction as the "pumping" mechanism for the creation of a population inversion primarily by molecular vibrational excitation (although certain rotational excitations are involved). The "chain" reaction between hydrogen and flourine is the chemical laser system holding the most promise for space applications. The two reactions are:

a) $F + H_2 \rightarrow HF^* + H$ (cold reaction)

b) $H + F_2 \rightarrow HF^* + F$ (hot reaction)

(HF^* = "excited" molecule)

The "cold reaction" is so named because the exothermic chemical reaction provides energy to populate only to the third vibrational level of the hydrogen flouride molecule. The "hot reaction" utilizes the dissociated H_2 created by the "cold reaction" and populates up to the tenth vibrational level. Both reactions create excited molecules in various upper energy levels all of which contribute to the cumulative population inversion. Also, since each reaction does populate different energy levels, the HF chemical laser operates at a number of characteristic wavelengths ranging from 2.7 to 4.0 micrometers (μm). These infrared frequencies are dominated by the 2.7 (μm) wavelength. All of these lasing frequencies individually contribute to the total power output of the system.

The HF chemical laser is a strong contender for first generation space-based applications for three primary reasons:

a) The amount of energy required to initiate the chemical chain reaction (the initial F_2 dissociation energy) is comparatively small, and since the "pumping" power required for population inversion creation is completely self-contained within the chemical reactants, weight and volume penalties paid for alternate high-external-power requirement systems are greatly reduced. Therefore, the system has the potential to be relatively small and powerful.

b) Studies indicate that an unusually large amount of the reaction energy (57% of "cold reaction"; 45% of "hot reaction", [Ref. 17]) appears as excited vibrational energy, indicating that it should be able to extract approximately 10% to 15% of the total reaction energy as laser energy. This is an efficient system in terms of present state-of-the-art technology.

c) The HF chemical laser is one of the most thoroughly studied and understood HEL devices; several successful high-power lasers have been constructed and tested. Therefore, the confidence in system design and reliability is high.

Figure 8 is a schematic of a generic Combustion-Driven, Supersonic-Diffusion HF Chemical laser, operated in a continuous wave (CW) mode. For simplicity, this example is a "non-chain reaction" ("cold reaction" only) laser, which depicts only the basic laser components.

2. <u>Combustion Chamber</u>

The purpose of the combustion chamber is to produce the required amount of atomic flourine (F) through thermal dissociation which will subsequently be supersonically accelerated into the laser cavity for the reaction

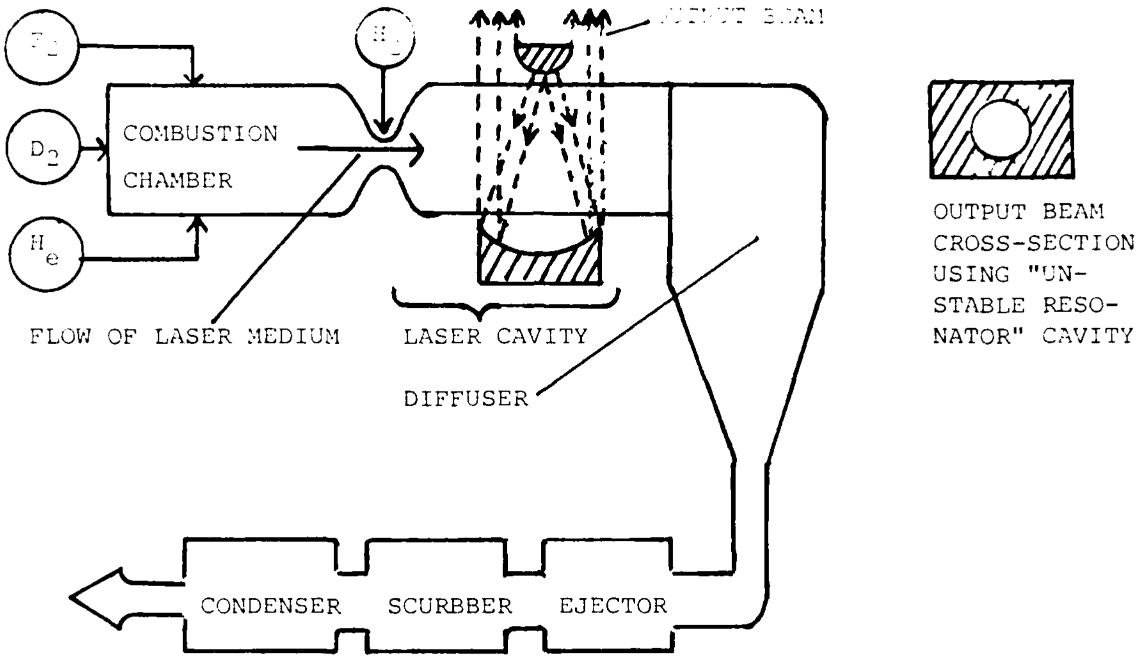


Figure 8. Combustion-Driven, Supersonic-Diffusion HF Chemical Laser System [Ref. 18].

with H_2. This combustor is designed to be a self-contained device requiring no external power (other than for control). Two general methods exist for the production of dissociated flourine; "thermally-driven" methods (including: shock tubes; regenerative and resistance heaters; chemical and combustion); and "electrical-discharge driven" methods. All electric-discharge driven chemical lasers, however, have characteristically low output powers and are relatively inefficient (R. W. F. Gross and J. F. Bott, [Ref. 19]). The most promising "thermally-driven" method for the production of dissociated flourine in a space-based chemical laser system is the combustion-driven type. The major advantage of this method is that it is a spontaneous combustion process requiring no external application of energy to initiate the reaction. Figure 9 is a more detailed schematic of the combustion chamber and laser cavity of a similar HF chemical laser under development by TRW.

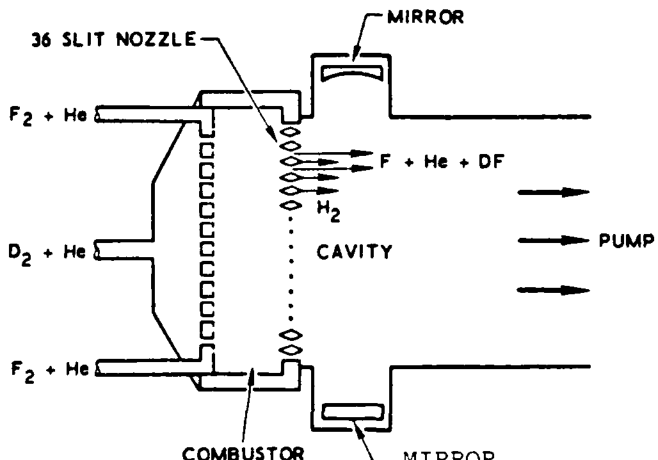


Figure 9. DF-Combustion Driven HF Laser Developed at TRW Systems, Inc. (R.W.F. Gross and J.F. Bott [Ref. 20]).

The reactants added to the combustor are D_2, He and an excess of F_2 (to maximize the mole fraction of atomic flourine) (R. W. F. Gross and J. F. Bott, [Ref. 21]). The chemical reaction of D_2 and F_2 ($D_2 + F_2 \rightarrow 2DF$; $\Delta H = -130$ Kcal/mol F_2) is a highly exothermic reaction and provides the energy required for the dissociation of F_2 into atomic flourine. The addition of He, called a "diluent," allows control of the combustion plenum temperature. Without the "diluent," the uncontrolled exothermic release of energy from the $D_2 + F_2$ reaction would cause thermal choking in the cavity. Since efficient lasing in the laser cavity is critically dependent upon a temperature and pressure substantially lower than in the combustor, supersonic flow in the nozzles must be carefully maintained to allow sufficient expansion of the gases and optimum downstream mixing conditions.

F, F_2, DF and added diluent are the constituents of the post-combustion hot gases which are supersonically expanded into the laser cavity. Additionally, H_2 is added to the supersonic flow through the perforated tubes of a bank of injector nozzles (Figure 10) for downstream mixing and reaction with atomic flourine (Figure 11) in the "reaction zone". The resultant is the chemical "pumping" of HF into vibrationally (and somewhat rotationally) excited energy states ($H_2 + F \rightarrow HF^* + H$).

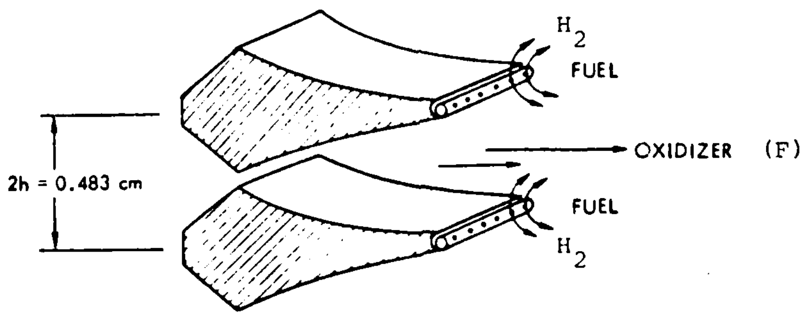


Figure 10. Injector Nozzles (R.W.F. Gross and J.F. Bott [Ref. 22]).

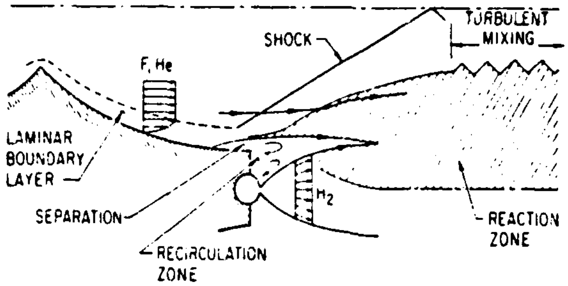


Figure 11. Chemical Laser Reaction Zone. (R.W.F. Gross and J.F. Bott [Ref. 23]).

3. Laser Cavity

Figure 12 depicts the laser cavity geometry of this device utilizing an unstable resonator design.

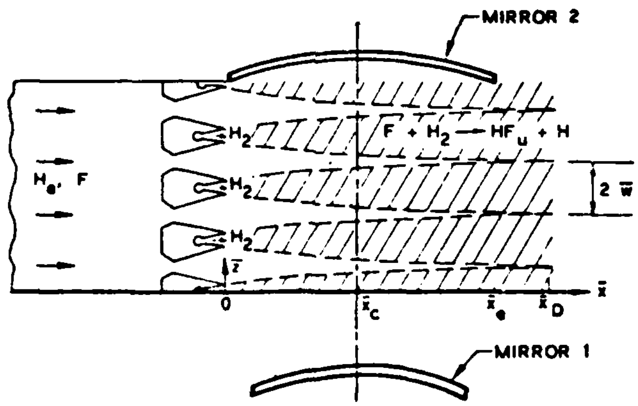


Figure 12. Laser Cavity with Unstable Resonator. (R.W.F. Gross and J.F. Bott [Ref. 24]).

The dynamics of the mixing and reaction regions of this design are complicated and are not considered in this discussion. Suffice it to say that the population inversion essential for the efficient extraction of laser power persists for only a short distance, about 15 cm (R.W.F. Gross and S.F. Bott, [Ref. 25]) downstream of the nozzle jets. Beyond this point, loss mechanisms destroy the population inversion and laser action is precluded. Consequently, the accurate placement of the resonant cavity mirrors is essential for the most efficient utilization of the available excited active medium.

The primary difference between a "stable" resonator and an "unstable" resonator (Figure 13) is simply that in a stable resonator the coherent radiation (generated by stimulated emission) is continuously maintained within the confines of the resonator geometry and power extraction must be accomplished by the use of a partially transmissive mirror.

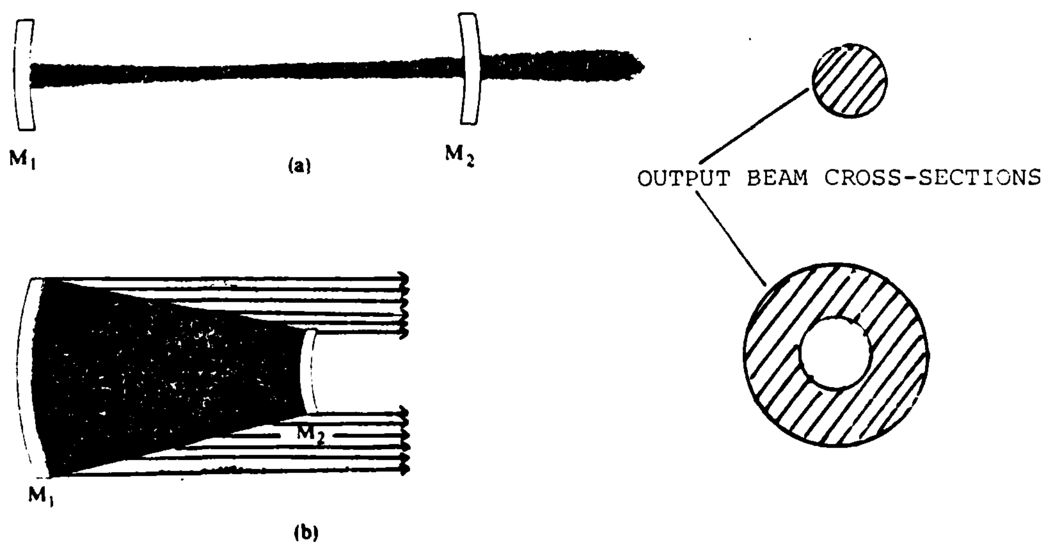


Figure 13. Stable (a) and Unstable (b) Resonators.

(D.C. O'Shea, R.W. Callen and W.T. Rhodes [Ref. 26]).

In an unstable resonator, however, the photon path (unless it exactly coincides with the centerline axis of the cavity) eventually "walks" out of the volumetric confines of the mirrors. The "confocal" unstable resonator of Figure 13 generates an annular collimated beam with center obscuration.

Unstable resonators are attractive for use in space-based HEL systems for two primary reasons:

a) As illustrated in Figure 13, an unstable resonator (unlike a stable resonator) utilizes the entire volume of the active medium and, therefore, generates more "stimulated emission" photons which will eventually add to the total power output. That is, the annular laser beam generated by an unstable resonator (given the same cavity geometry) will have more power in its side lobes, than a stable resonator ("gaussian" beam) has in its circular distribution.

b) The annular output beam is convenient for use with a "Cassegrain" telescope for optically focusing the laser beam on a distant target.

Arrangement of the laser cavity components for maximum power output and efficiency requires the simultaneous analysis of a large number of interconnected parameters. The primary variables are the chemical composition, pressure, temperature and velocity of the gas entering the laser cavity, the resonant cavity optics chosen for amplification and power extraction, and laser-cavity flow field configurations. Extensive computer modeling, coupled with experimental findings, are required to optimize the laser design.

4. Diffuser; Ejector; Scrubber; Condenser

The diffuser serves the purpose of converting the kinetic energy of the flow into pressure recovery. However, the diffuser required for a chemical laser has one significant difference than that of a standard diffuser; that is, the low entrance Reynolds number of the flow into the diffuser causes the development of thick boundary layers. If the diffuser is not sufficiently isolated from the laser cavity by a compatible cavity-to-diffuser shroud configuration, the shock system developed by the diffuser-boundary layer interaction can extend into the laser cavity region causing a severe reduction in laser power. It has been determined that optimum pressure recovery of the diffuser occurs when the shrouds have a minimum positive angle consistent with good laser efficiency, and the diffuser inlet area is at a minimum (R. W. F. Gross and J. F. Bott, [Ref. 27]).

The purpose of the ejector is to maintain the required fluid flow rate through the device when working against some nominal atmospheric pressure. This device, therefore, would not be required for space-based systems operating in a vacuum where fluid flow rate requirements would be maintained by appropriate diffuser design.

The remaining elements (scrubber and condenser) are required for toxic gas processing so as not to contaminate the environment. Here again, exoatmospheric placement of this system would significantly reduce or even eliminate the need for these components.

D. FREE ELECTRON LASERS (FEL); SYSTEM CONCEPT

Free electron lasers operate differently than conventional lasers. The active lasing medium is not a collection of "excited" atoms or molecules confined within a resonant cavity but a high energy electron beam traveling through an evacuated resonant cavity. The term "FREE ELECTRON" refers to the fact that the high energy electron beam is composed of unbounded or "free" electrons. The fundamental lasing principle of the FEL is that when a "relativistic" electron (one that is traveling near the speed of light) experiences acceleration, it will radiate short-wavelength electromagnetic radiation according to the following relationship:

$$\lambda_L = \frac{\lambda_w}{2\gamma^2}$$

λ_L = radiated energy wavelength

λ_w = wavelength of "wiggler field which causes the electron beam acceleration in the resonant cavity

γ = relativistic gamma factor (a measure of the electron energy in the beam) (P. Sprangle, et al., [Ref. 28]).

A primary advantage of a FEL is that the output frequency is not a fixed function of the laser medium but can be varied or "tuned" by either adjusting the incoming electron beam energy (factor "γ") or by altering the wavelength of the "wiggler" field (λ_w). The ability to "tune" the laser beam would allow one to take advantage of certain "atmospheric windows," and propagate greater energy densities farther distances within the earth's atmosphere. Additionally, the lasing medium (the electron beam) is a pump field and cannot "break down" at very high power levels, as conventional molecular or atomic lasers have a tendency to do. "Break down" refers to a sharp change in the refractive index of conventional molecular or atomic laser mediums at very high power levels. This change in refractive index significantly limits the lasing capability of the medium. Therefore, in principle, higher power levels are expected from free electron lasers.

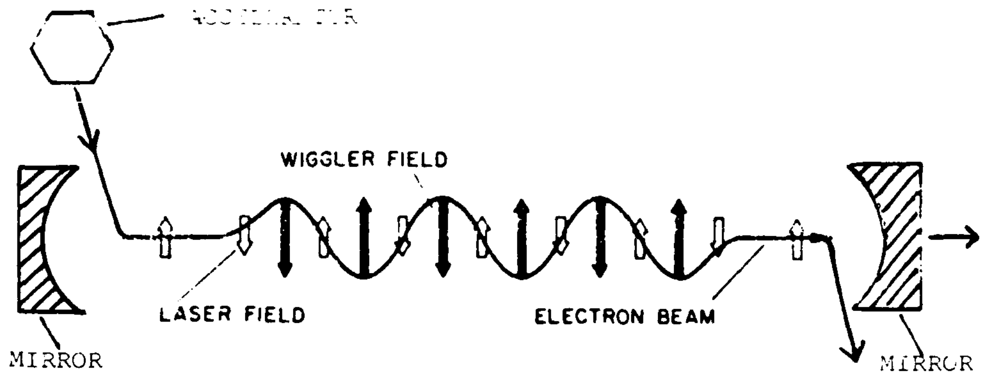
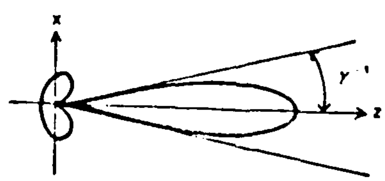


Figure 14. Basic Principle of a Free Electron Laser. (H. J. Schwarz, et al. [Ref. 29]).

Figure 14 illustrates the basic principle of a free electron laser.

A relativistic electron beam, a spatially periodic, static, magnetic "wiggler" field and an optical radiation field (laser field) propagating in the direction of the electron beam (all within a mirrored resonant cavity) are the three basic components of a free electron laser. The incoming electrons have been accelerated to relativistic speeds by an electron accelerator prior to entering the cavity. The electron beam avoids mirror contact and propagates along the cavity axis by appropriately applied magnetic forces. The alternating "wiggler" field is normal to the electron beam and causes the electrons to experience forced transverse oscillations while propagating through the evacuated laser cavity. During oscillation, the electrons spontaneously emit "magnetic bremsstrahlung" peaked in the direction of propagation. "Bremsstrahlung," or literally "braking radiation," is a broad term used to describe the response of a charged particle that is accelerated. This response is to radiate energy in the form of an electromagnetic wave. If the acceleration has been magnetically induced, the radiated energy is termed "magnetic bremsstrahlung". Furthermore, if the acceleration is transverse to the direction of propagation, the radiated energy contains only odd harmonics and has a peak intensity in the forward direction (as depicted in Figure 15).



γ^{-1} = natural emission angle of synchrotron radiation.

Figure 15. Magnetic Bremsstrahlung Caused by Transverse Acceleration of Relativistic Electrons. (H. Winick, et al. [Ref. 30]).

As shown in Figure 15, magnetic bremsstrahlung (also called "synchrotron radiation" if generated by relativistic electrons) causes the spontaneously emitted photons to be radiated along the cavity (z) axis. However, these photons are incoherent at the point of injection of the electron beam due to the initial random phases of the electrons in the beam and do not immediately contribute to amplification.

Coherence of magnetic bremsstrahlung is achieved by superimposing a laser field on the oscillating electrons and wiggler field. If the frequency of the laser field is nearly resonant with the electron oscillations, the wiggler field and laser field combine to produce a "pondermotive" or "trapping" wave illustrated in Figure 16.

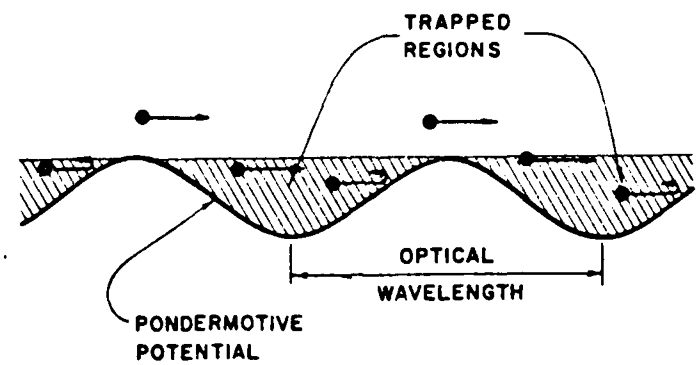


Figure 16. Electrons Moving in a "Trapping" Wave. (H. J. Schwarz, et al. [Ref. 31]).

Upon initial injection into the laser cavity, the random phased relativistic electrons experience a (V X B) force involving the electron velocity (V) and the combined laser radiation and "wiggler" magnetic fields (B).

Some electrons are accelerated and others are decelerated. As the accelerated electrons overtake those that have been decelerated, "electron bunches" are formed which eventually travel at the same frequency as the trapping wave. The originally random-phased electrons now acquire an increasingly uniform phase relationship at the optical wavelength, and these traveling "electron bunches" are in a position to collectively radiate or absorb energy. If the injected electrons have a velocity slightly greater than the resonant velocity of the cavity, an average deceleration of the electron beam results as the electrons settle into the "trapping" wave and a net resultant energy is radiated into the cavity. The laser, therefore, experiences net gain.

It is important to note that the "trapping" wave is most efficient at capturing electrons which are <u>only slightly</u> faster than the resonant energy. Studies have shown that an excessive spread in the velocity of the injected electrons can greatly reduce the bunching and the extraction of energy, especially at shorter wavelengths, (H. J. Schwarz, et al., [Ref. 32]).

1. High Power FEL Systems

The previous FEL discussion dealt with the behavior of individual electrons in the laser and wiggler fields. This analysis is a satisfactory approximation for relatively low electron beam current densities. Free electron lasers operating at these densities are said to be operating in the "Compton" regime where single particle interactions are the dominant lasing mechanisms. However, lasers operating in the Compton regime typically achieve a radiation gain per pass of only 0.1 and an intrinsic efficiency of only 1.0% (P. Sprangle and T. Coffey, [Ref. 33]). These lasers, which are normally based on low-current beam sources such as linacs (linear accelerators), microtrons or storage rings, can operate at optical or ultraviolet wavelengths and are primarily utilized as oscillators.

If high electron-beam current densities (produced by induction linear accelerators or pulsed transmission-line accelerators) are used, electron-electron interactions are induced in the cavity and the electron beam acquires the capability of responding to the FEL magnetic fields as a coherent plasma entity. The resultant electron-electron interactions are called "collective" oscillations, and the process which increases the amplification of the laser is termed "stimulated Raman scattering," (D. B. McDermott, et al., [Ref. 34]).

"Collective" oscillations refer to the sympathetic oscillations of counterpropagating "scattered" electromagnetic waves which can exponentially amplify the oscillations of the resonant cavities. If the incident electron-beam pulse has sufficiently high electron-beam current densities, electron-electron interactions cause radiation to be diffusely reflected in all directions, initially reducing the energy intensity in the direction of propagation. This incipient "scattered" electromagnetic wave, however, couples with the resonant electromagnetic wave and leads to a low frequency density modulation of the electrons in the cavity. Eventually, the growth of the electron density modulation increases the coherence of the scattering process, which in turn increases the density modulation still further. If the incident accelerated electrons are sufficiently dense and "cold," a synergistic growth of the "scattered" electromagnetic wave results as the incident electromagnetic wave is amplified, and both tend to oscillate at the frequency of collective oscillation. Theoretically, FEL amplification employing stimulated Raman scattering techniques have potential efficiencies of 30 - 40% (M. J. Schwarz, et al., [Ref. 35]).

Figure 17 illustrates an experimental FEL using collective interactions and Raman scattering principles. Experiments indicate that devices of this type could generate from 1 MW to 35 MW of output power (M. J. Weber, [Ref. 37]).

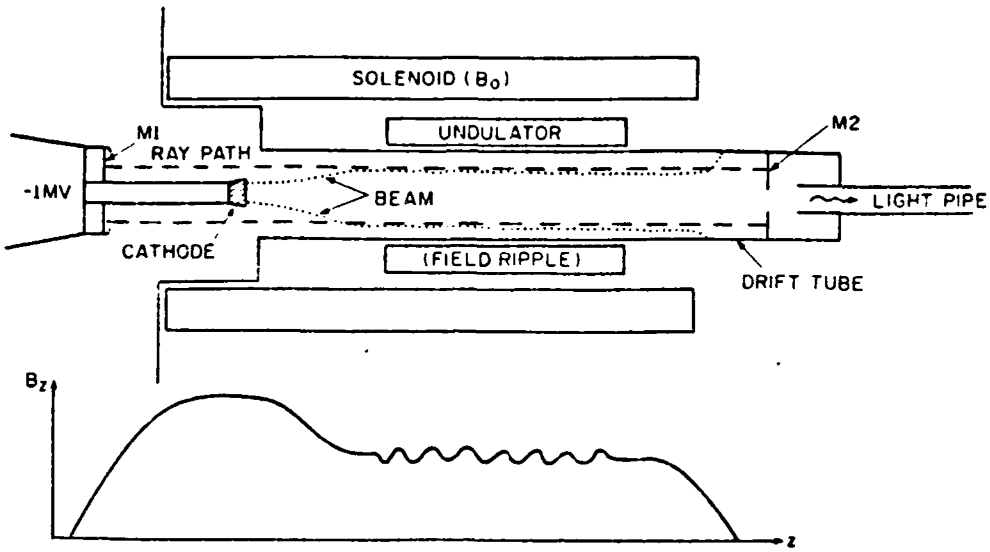
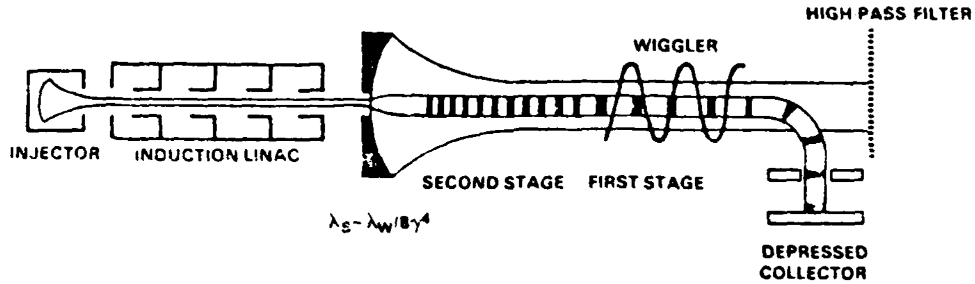


Figure 17. FEL Design Utilizing Collective Interactions. (M. J. Weber [Ref. 36])

Figure 18 represents an advanced two-stage Raman free electron laser. By superimposing the collective oscillation output of the first stage onto the incident electromagnetic pump wave of the second stage, it is theorized that up to 200 MW of output power are possible (M. J. Weber, [Ref. 38]).

An additional advantage of a two-stage Raman FEL is that the output wavelength is approximately $\lambda \approx \ell/8\gamma^4$ instead of $\lambda \approx \ell 2/\gamma^2$, as is the case with a single-stage device. Therefore, in principle, far shorter output wavelengths can be realized for the same electron kinetic energy (M. J. Weber, [Ref. 40]).



λ_s = output wavelength of second stage (laser output wavelength)

λ_W = "wiggler" wavelength

Figure 18. Two-Stage Raman FEL. (M. J. Weber [Ref. 39]).

2. FEL Advantages/Disadvantages

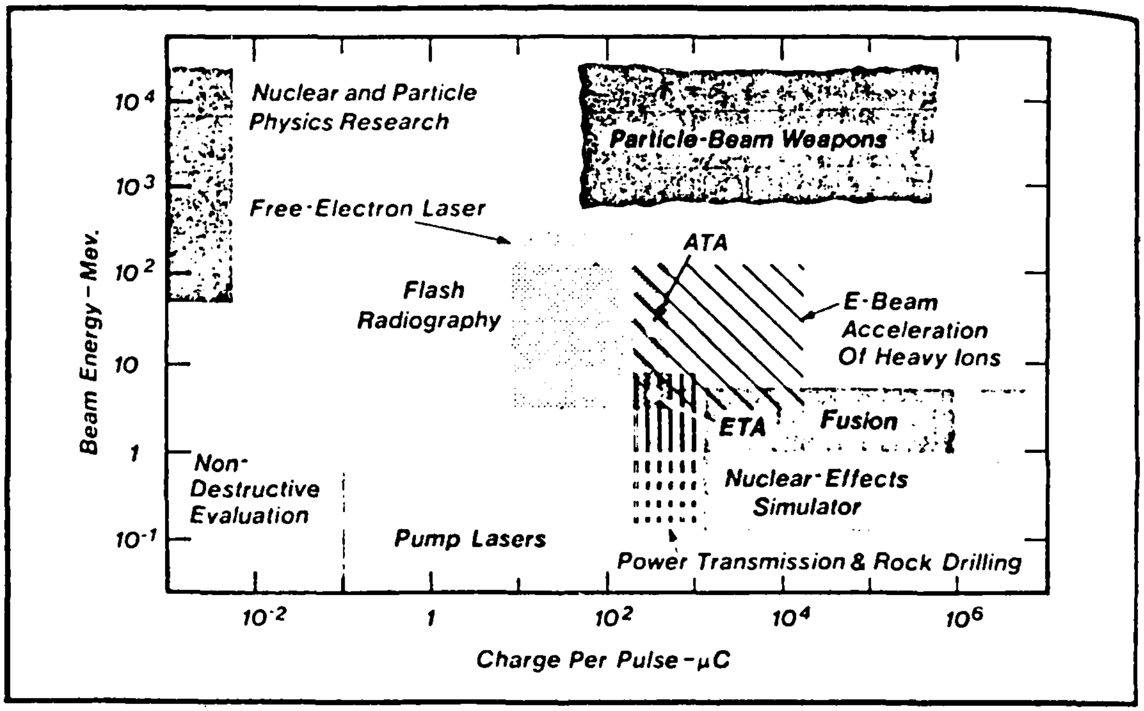
Free electron lasers have three significant potential advantages compared to conventional atomic or molecular lasers:

a) continuous frequency "tuneability"

b) large expected output power levels

c) very high predicted efficiencies

At present, however, the size and weight of appropriate electron accelerators loom as major disadvantages. The key to whether or not free electron lasers will compete successfully as viable space-based HEL weapon systems is the development of a relatively lightweight accelerator capable of providing the electron velocities required. Figure 19 relates the "Beam Energy" power requirements of space-based FEL to various other systems.



Beam energy and charge-per-pulse capability of new Advanced Test Accelerator (ATA), and its predecessor Experimental Test Accelera... (ETA), relative to those required for particle-beam wea... ns and for free-electron laser as well as other accelerators, are shown in cha...

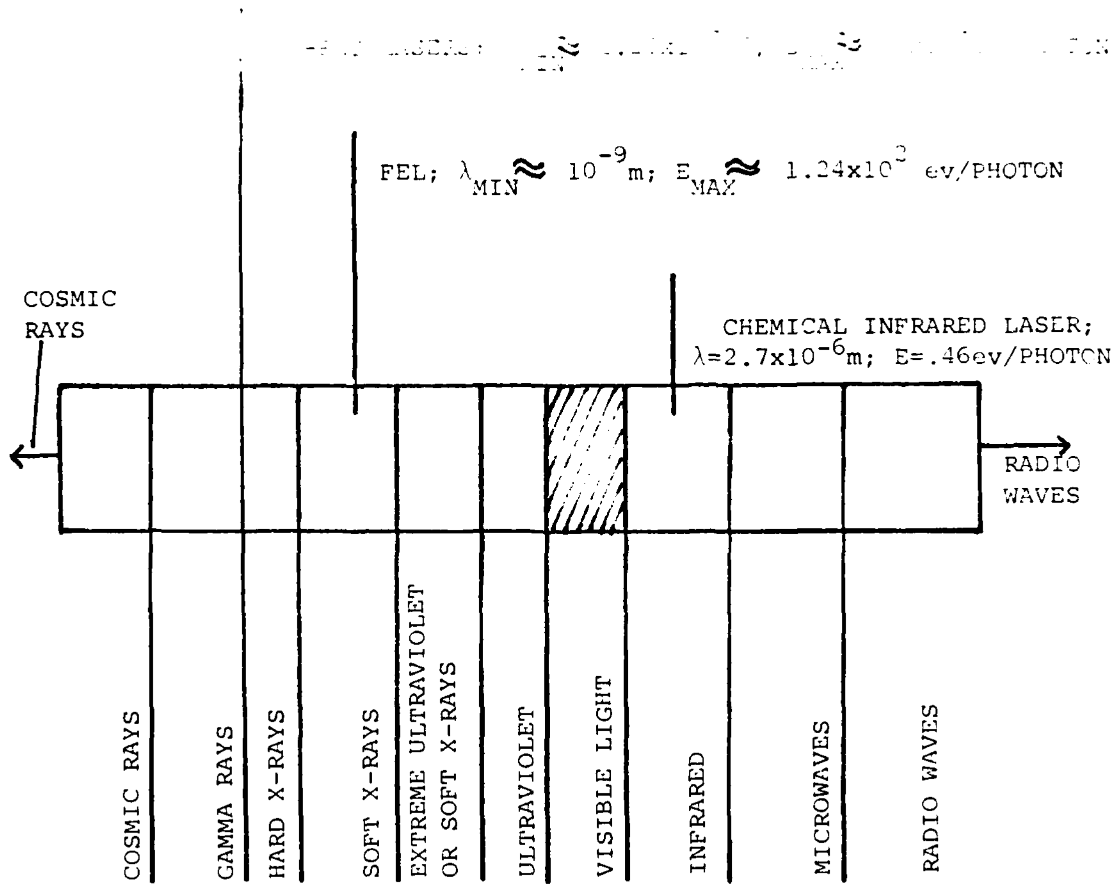
Figure 19. FEL Electron Beam Energy Requirement Comparisons.

A possible solution to the FEL accelerator problem is a very compact radial pulse line accelerator (RADLAC) under development at Kirtland Air Force Base in conjunction with particle beam weapon research, [Ref. 42]. This accelerator, which has demonstrated 10 Mev and about 50-Kiloamp current, is a closed system capable of higher accelerating gradients and currents than linear accelerators and is inherently lighter due to a "coreless" design.

E. NUCLEAR-PUMPED X-RAY LASERS

Both of the laser systems previously examined (chemical infrared and free electron lasers) are capable of producing high-power, coherent electromagnetic radiation at wavelengths which are relatively "long to medium" in comparison to X-ray or gamma-ray wavelengths. Figure 20 illustrates approximately how the characteristic wavelength photons of these lasers compare with each other within the entire electromagnetic spectrum in terms of wavelength (or wavelength range) and photon energy.

It is obvious from Figure 20 that the energy per photon of an X-ray laser potentially exceeds that of either of the previous systems by almost three orders of magnitude. Furthermore, the damage mechanisms of X-ray lasers differ markedly from those of longer wavelength systems. The primary damage mechanism of a chemical infrared or free-electron laser is thermal in nature in that energy deposition causes surface melting and burn-through. The primary lethality mechanism of the X-ray laser, however,



$$1\,ev = 1(\text{electron volt}) = \frac{hc}{\lambda e}$$

E = energy per photon in ev's

where: h = Plank's constant = $6.626X10^{-34}$ Joule-second

c = speed of light in a vacuum = $2.9979x10^{8}$ m/s

e = charge of one electron = $1.602x10^{-19}$ coulomb

λ = characteristic photon wavelength

Figure 20. Characteristic Photon Wavelength and Energy Comparisons.

would be an "impulse kill," which refers to the deformation or crushing of the target by a "LASER SUPPORTED DETONATION WAVE" (LSD) or shock wave generated by rapid deposition of energy at the surface. The "impulse kill" mechanism carries the additional advantage of requiring little (if any) dwell time on target. Also, the unique penetrating characteristics of X-rays would make these lasers extremely difficult to defeat through countermeasure applications.

Although X-ray lasers are only potentially appropriate for use in the vacuum of space because of high X-ray absorption within the atmosphere, the previously stated advantages (among others) have prompted DARPA to pursue a parallel X-ray laser development program (along with the chemical and FEL lasers) even though nuclear-pumped X-ray laser technology is far behind the other two.

> "The development of directed-energy weapons technology is structured on the premise that the most needed technology is usually the least mature, and that there are associated technical uncertainties. The program (Strategic Defense Initiative) is designed to focus on the early resolution of fundamental feasibility issues, emphasizing those key activities that have the longest development lead time ... the plan calls for continual investment of approximately 5% of available resources in high-risk, innovative approaches that offer high payoff." [Ref. 43]

The payoff for the successful development of X-ray lasers appears to be very high. However, significant difficulties arise with the attempt of lasing at very short wavelengths that are not present at longer wavelengths. Three of the major difficulties are:

a) Firstly, matter in any solid, liquid or vapor state has a high opacity at short wavelengths ($\lambda < 10$ A°) (B. Kursunoglu, et al., [Ref. 44]) which essentially means that the absorption and scattering coefficients are very high whereas the transmission coefficient is very low. This limitation precludes the use of most (if not all) conventional atomic or molecular lasing media, since most of the X-rays generated by stimulated emission would be absorbed or scattered prior to reaching the exit plane of the laser generator. Therefore an alternative active lasing medium must be identified.

b) Secondly, the utilization of conventional laser cavity oscillators with mirrors at either end of the cavity would be ineffecitve in terms of intracavity energy amplification for the same reason stated above. Furthermore, even if a mirror material could be found which would reflect enough energy for cavity amplification, the intense energy flux levels within the cavity would destroy the mirrors. Therefore, an alternative method for intensifying the energy produced by stimulated emission (while simultaneously maintaining a high degree of electromagnetic coherency) must be developed.

c) Thirdly, the "pumping" power required to create an X-ray laser medium population inversion is very high, and the excited state lifetimes of X-ray transitions are extremely short (i.e., on the order of femtoseconds (Fs); 1 Fs = 10^{-15} seconds) [Ref. 45]. Consequently, maintaining a population inversion in such a system implies the expenditure of vast amounts of energy in very short periods of time. Studies have indicated that these power levels could equate to a minimum of 1 watt per atom of active medium [Ref. 46]. Therefore, a relatively lightweight pumping mechanism capable of generating extremely high power levels must be developed.

These are three major feasibility issues presently under evaluation by DARPA in the attempt at clarifying the viability of space-based X-ray laser technology. Since virtually all information concerning DARPA'a X-ray laser effort is classified, no attempt is made here to describe (or even reflect) any or part of this work. However, the remainder of this section does focus on clarifying the physical processes involved in lasing in the X-ray spectrum and the possible solutions to the aforementioned major feasibility issues.

1. Production of X-rays

The classic way to obtain X-rays is to accelerate electrons to relativistic speeds (which imparts the required energy to the electrons) and allow these electrons to collide with a sample of atoms. Figure 21 illustrates this process.

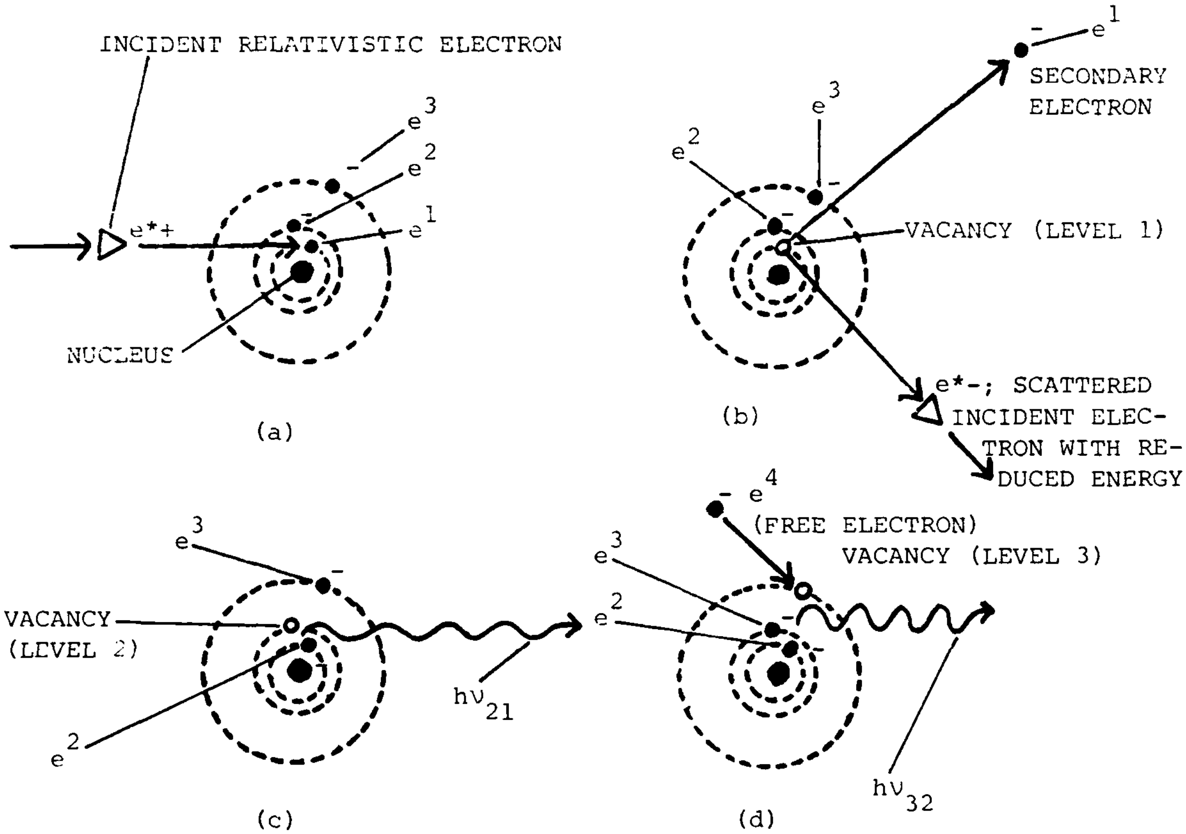


Figure 21. X-ray Production Sequence

In Figure 21(a), e^1, e^2 and e^3 represent electrons residing in successive orbits or "shells" of a theoretical atom. The innermost shell is occupied by electron e^1 which is the most tightly-bound electron of the three. Consequently, the "binding energy" of e^1 is higher than that of e^2 or e^3, whereas the total energy of electron e^1 is the lowest of the three since the orbital energy of e^1 is a minimum.

If an incident relativistic electron (which possesses energy equal to or greater than the binding energy of e^1) collides with e^1, e^1 is completely ejected from the atomic system (becoming a "secondary electron") and an electron vacancy (or "hole") is created in the innermost shell (LEVEL 1 Figure 21(b)). The atom now becomes an ion and is in an unstable or "excited" state because of its unsatisfied excess (positive) binding energy. As one moves further from the nucleus of the ion, the binding energies associated with each discrete energy level decreases accordingly in a nonlinear fashion. For instance, the binding energy of the innermost shell (K-shell) of a heavy element such as Cadmium (Figure 22) is of the order of 10^3ev while the binding energy for the outermost shells are no more than a few ev (A. P. Arya [Ref. 47]). As illustrated in Figure 21(c), therefore, the electron in level 2 (e^2) jumps to occupy the vacancy in level one.

In doing so e^2 emits a photon of energy according to the relationship:

$$h\nu_{21} = E_1 - E_2$$

E_1 = Binding energy of LEVEL 1

E_2 = Binding energy of LEVEL 2

$E_1 > E_2$

Since the difference between E_1 and E_2 for most inner-shell atomic transitions is very high, photons of energy in the X-ray spectrum are often yielded. Furthermore, this X-ray emission is characteristic for the emitting substance since the binding energies for any two levels of different atoms are never exactly the same. Therefore, these photon emissions are termed the "characteristic lines" which are unique to each X-ray lasing substance.

The remaining successive outer-shell electrons continue to "jump" in cascade fashion to fill the newly created vacancies until the "hole" has moved to the outermost shell where it is quickly filled by a "free" or "secondary" electron (Figure 21(d)). Each jump of an electron generates another photon of a different frequency. Whether or not the successive emission of photons are in the X-ray spectrum is dependent upon the binding energy variations between the specific energy levels taking part in the transition. Although most substances have several characteristic X-ray lines (0.1A° to 10A°), by the time the vacancy reaches the outer-shells the photons produced are primarily in the optical spectrum (4000A° to 6000A°) (A. P. Arya [Ref. 48]). Figure 22(a) illustrates the shells and subshells of the relatively heavy Cadmium atom, and Figure 22(b) depicts the associated energy levels.

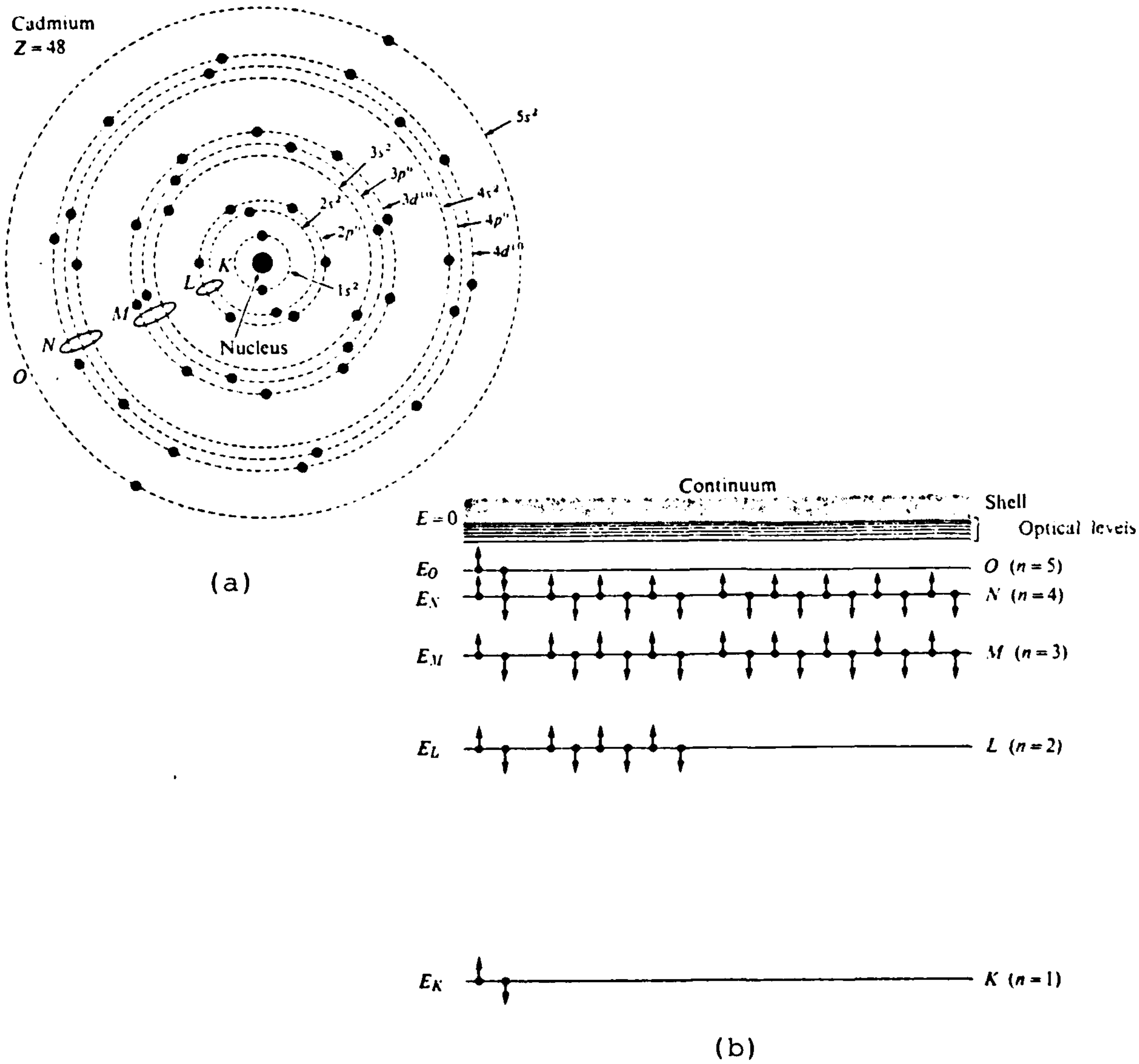


Figure 22. Shells, Subshells (a) and Energy Levels (b) of a Cadmium Atom (A. P. Arya [Ref. 49]).

"Besides the radiative X-ray emission process, the deexcitation of an excited atom can proceed through other channels like nonradiative Auger process, Coster-Kronig interband transition, or simultaneous emission of X-ray and Auger electron, the so-called radiative Auger process. The relative probability for decay into the different channels depends on the atomic number (Z) of the atom; nonradiative processes, for instance, dominate for $Z \leq 20$." (R. G. Lerner and G. L. Trigg [Ref. 50]) This is an important factor in the selection of an X-ray lasing medium where the maximization of radiative processes is desired.

Although the generation of X-rays by the bombardment of neutral atoms by relativistic electrons is the classical method examined here, photons and charged particles other than electrons may equally well be used for the excitation process. The incoming velocities required of the specific "projectile" type are inversely related to the mass of the particles (R. G. Lerner and G. L. Trigg [Ref. 51]). for instance, heavier particles (i.e., protons) can be at a lower velocity to successfully "knock-out" an innershell electron. Therefore, pumping mechanisms, other than electrical, may be appropriate for the generation of X-rays in a space-based X-ray laser.

2. <u>Selection of an Appropriate X-ray Lasing Medium</u>

The active medium selected for use in any X-ray laser must indeed be unique in order to satisfy the following criteria:

a) The medium must allow adequate transmission of the X-ray energy generated by stimulated emission.

b) The medium must also amplify this energy to weapons level intensities without the assistance of conventional mirrored laser cavities.

c) The medium must somehow facilitate a high degree of coherency of this X-ray electromagnetic radiation. Theoretically, the nearest thing to a transparent optical medium (such as glass for a conventional molecular laser) for an X-ray laser, which might at least satisfy criteria a and b, is a hot, fully stripped plasma where the opacity is due only to Compton scattering. (B. Kursunoglu, et al. [Ref. 52])

A "plasma" has sometimes been referred to as "the fourth state of matter." (D. A. Frank-Kamenetskii [Ref. 53]) Unlike typical solids, liquids and gases within which the electrons are bound (in varying degrees) to the atomic nucleii and conform to the laws of quantum mechanics, the electrons in a plasma are liberated from the atoms and acquire freedom of motion. A plasma, therefore, is a gas consisting of positively charged ions and negatively charged electrons in such proportions that the total charge is equal to zero and in which the electrons can transport electric current.

If only some of the electrons are removed from the atom, the plasma is "partially stripped." If all of the electrons are removed from the atom, the plasma is "fully stripped." Also, the temperature unit applied to plasmas is the "electron volt," which corresponds to 11,600°C. (D. A. Frank-Kamenetskii [Ref. 54]) A "cold" plasma exists at temperatures of only "a few electron volts," or a few hundred thousand degrees. A "hot" plasma, however, is at a temperature of at least a few hundred electron volts, or millions of degrees. (D. A. Frank-Kamenetskii [Ref. 54])

Plasmas, in many aspects, behave just like gases except when subjected to a strong magnetic field. When this situation occurs, the plasma electrons (which initially exist without any order) are forced to move in a regular fashion. Plasma particles are constrained to circle around the lines of force of the magnetic field and eventually gyrate around the lines in a helical motion. Figure 23 illustrates the motion of plasma particles subjected to a strong magnetic field.

Actually, Figure 23 (or some magnetic confinement derivative) is only means of confining, for any length of time, a hot, fully-stripped plasma, because solid walls of

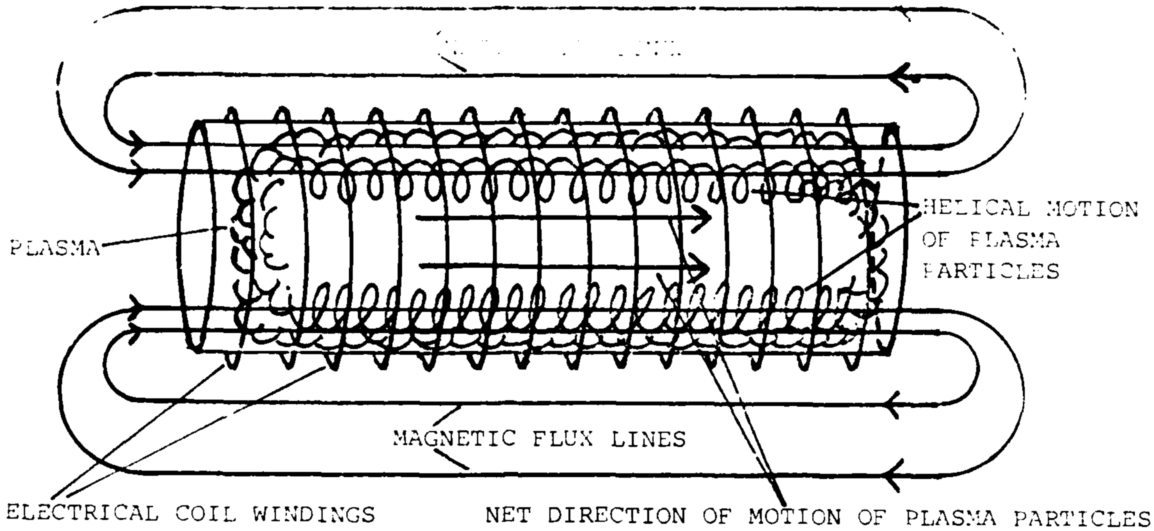


Figure 23. Plasma Particle Motion in a Strong Magnetic Field.

any known material cannot withstand these intense temperatures. The ordered helical motion of the plasma particles remains undisturbed and very predictable so long as the plasma is not allowed to contact the container walls. Fortunately, particle collisions in hot plasmas are very rare (the opposite is true for "cold" plasmas) and, therefore, the probability that a collision might knock particles from the magnetic field lines into the container wall is small compared to that of a "cold" plasma. Unfortunately, however, additional processes which are not fully understood commonly promote plasma instabilities which can lead to particle motion disorder and the breakdown of predictable motion.

Assuming that a hot, fully-stripped plasma can be contained by a strong magnetic field without the occurrence of serious plasma instabilities, one has the makings of an efficient X-ray lasing medium. The reason for this is that the transparency of a plasma to radiation is a function of the opacity of the plasma, which, in turn, is a function of the optical absorption of the medium (which is strongly dependent on the radiation frequency) and the electron scattering of the medium (which is essentially frequency independent).

> "The over-all coefficient, characterizing both the absorption averaged over all frequencies and the scattering is called the <u>opacity</u> of the plasma. Radiative diffusion (radiative thermal conductivity) depends only on the opacity of the plasma. By multiplying the opacity by the thickness of the plasma layer we can obtain a nondimensional quantity called the optical thickness. A plasma layer with large optical thickness is opaque to radiation. Radiation emerges from this layer only by the slow process of multiple reemission and scattering. This radiation is said to be trapped and is in thermal equilibrium with the material ... Conversely, a plasma layer with small optical thickness is transparent to radiation. The radiation emerges freely from such a layer and the concepts of radiative diffusion and radiative thermal conductivity lose their meaning. Thermal equilibrium is not realized either between the radiation and the material, nor between ions, electrons, and neutral atoms." (D. A. Frank-Kamenetskii [Ref. 56]).

A hot, fully-stripped plasma confined by a strong magnetic field is a rarefied "optically thin" plasma with a small opacity coefficient, and therefore a strong X-ray emitter. The specific substance under consideration by DARPA for use as an X-ray laser plasma medium is unknown. However, since radiative processes dominate in the de-excitation of innershell ionized, high-Z substances, a high-Z (Z>20) substance might be a good first guess.

3. X-ray Photon Amplification

Assuming that a hot, fully-stripped plasma performs well as an X-ray lasing medium with adequate radiation transmission characteristics, the next step will be to devise a means of amplifying the generated laser energy to required intensities. Preliminary investigations by DARPA have determined that the brightness required of an X-ray laser designed to destroy an ICBM booster at 3,000 Km is 10^{21} to 10^{22} joules/steradian/second, or a radiant intensity of 10^{21} to 10^{22} watts/steradian. [Ref. 57] Considering that the sun generates a radiant intensity of approximately 2.2×10^{6} watts/steradian, it is obvious that an appropriate amplification mechanism is of crucial importance in the successful development of this system.

As was stated previously, all materials are poor reflectors at very short wavelengths, and, therefore, significant difficulties arise if the conventional method of placing an inverted medium between mirrors which form an optical resonant cavity is employed for amplification purposes. Although no known method exists for the design of efficient resonant cavities for wavelengths between 1000A° and 10A°, at very short wavelengths of about 10A° or less it becomes possible to use Bragg reflection from the crystal planes of solids. (R. W. Waynant and R. C. Elton [Ref. 58]) Several designs have been proposed which would be theoretically suitable for the amplification of X-ray energy. Figure 24 illustrates one such design.

However, although the losses at each crystal reflection are less than 5 percent, the losses multiply as additional crystal elements are added and so does the difficulty of alignment. The utilization of single crystals with carefully fabricated internal crystal-plane alignments has also been contemplated to serve this same purpose. However, the projected difficulties in fabrication, stability and alignment of both designs are, at this point, prohibitive. Additionally, the flux levels required of a X-ray laser weapon would certainly destroy the crystals.

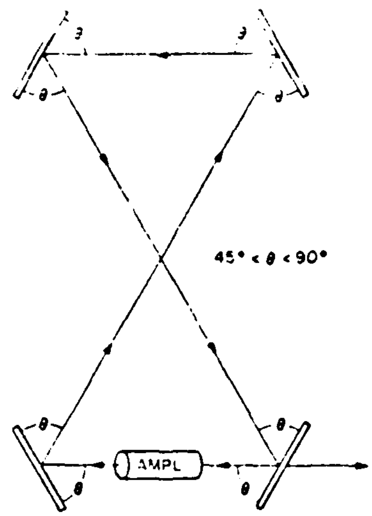


Figure 24. X-ray Resonator and Possible Amplifier Using Several Bragg Reflections. (R. W.Waynant and R. C. Elton [Ref. 59])

An alternative amplification concept has been proposed by Allen and Peters termed "Amplified Spontaneous Emission" or ASE. (R. W. Wynant and R. C. Elton [Ref. 60]) This concept provides for a high-gain mirrorless system which relies entirely on the ability of a judiciously directional, spontaneously emitted photon to induce the materalization of another identical photon at some critical distance through the cavity. The "threshold" condition for ASE to occur is defined as the condition when a spontaneously emitted photon at one end of the column (x=0) just induces another photon at the other end. Preliminary experiments using a He-Ne laser with and without a mirrored resonant cavity verified the existence of the ASE phenomena (Figure 25).

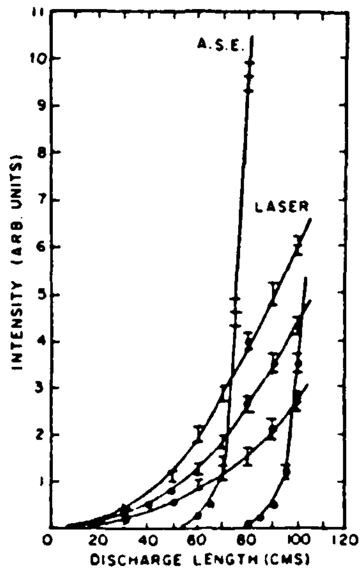


Figure 25. "ASE" vs. Resonant Cavity Intensity.

(R. W. Waynant and R. C. Elton [Ref. 61])

As illustrated in Figure 25, the resultant intensity profile of the ASE concept is very encouraging. Additionally, although the coherence of the energy was initially (and predictably) very low at the beginning of the cavity (x=0), improvements in the coherency did increase with gain length. However, evidence indicates that ASE devices may be fundamentally limited in coherence, (R. W. Waynant and R. C. Elton [Ref. 62]) and further investigation is needed to determine the possible impact of this limitation on the development of a space-based X-ray laser weapon.

Furthermore, the ASE theory has yet to be applied to pulsed systems employing traveling-wave excitation, which is a probable operating mode of DARPA's nuclear-pumped X-ray laser. (R. W. Waynant and R. C. Elton [Ref. 63])

4. X-ray Laser Pumping Requirements

High particle densities are necessary for achieving laser action at short wavelengths for two primary reasons:

a) First, since the lifetimes of excited states for allowed X-ray transitions are shorter than for transitions at optical wavelengths, a higher rate of production of excited states is required.

b) Second, since intense X-ray photon amplification will be required without the aid of conventional mirrored resonant cavities, extremely high inversion densities will be required to implement an ASE or similar amplification concept.

Table 1 compares the approximate pumping requirements (Q) and rates of particle excitation (q) for different wavelengths (λ). These values are the minimum values necessary to obtain a gain (k) of $k=1\ cm^{-1}$.

As reflected in Table 1, $q \sim \frac{1}{\lambda}$ and $Q \sim \frac{1}{\lambda^4}$, therefore, for very short wavelengths, the required pumping power for achieving only minimum gain is extremely intense. One way to generate these power levels might be to detonate a nuclear device and couple the resultant

TABLE 1

λ [A°]	1	10	10^2	10^3
q $[cm^{-3}s^{-1}]$	10^{31}	10^{28}	10^{25}	10^{22}
Q $[Wcm^{-3}]$	10^{16}	10^{12}	10^8	10^4

Q = power required for excitation per cm^3
q = particle rate of excitation
λ = wavelength

(for a gain of $K = 1 cm^{-1}$)

Pumping Power Requirements vs. Wavelength [Ref. 64]

fission products to an appropriately selected X-ray laser medium. If this medium were suspended somehow in a tube or waveguide and subjected to a strong magnetic field, one would have assembled all the fundamental elements required to construct a high-gain, nuclear-pumped X-ray laser. Figure 26 depicts a possible geometric configuration of such a system.

Ideally, upon detonation, the intense heat, radiation and fission fragments create a thermonuclear wave (or "pumping wave") which progressively traverses the waveguide from left to right. This thermonuclear pumping wave

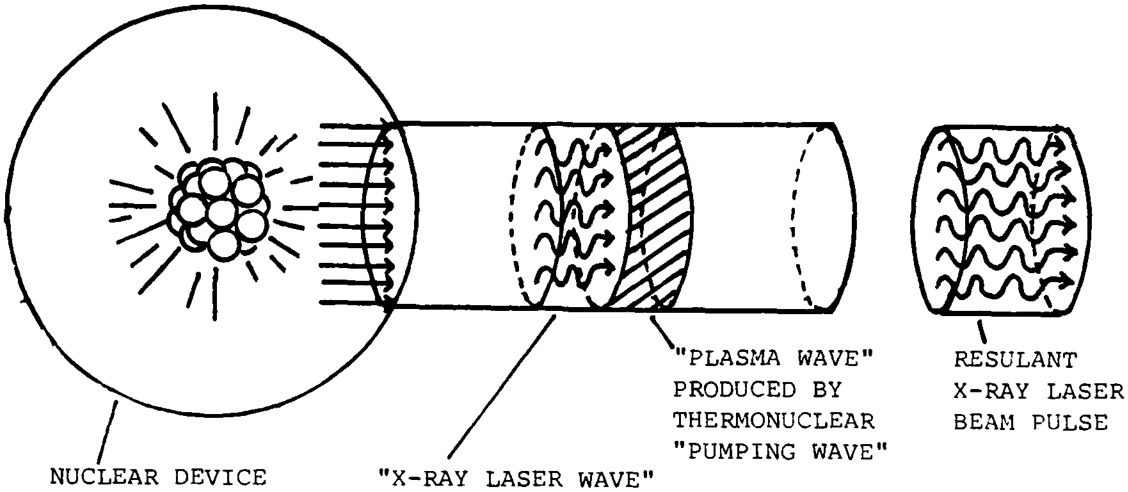


Figure 26. Possible Nuclear-Pumped X-ray Laser Configuration.

is sufficiently intense to transform the lasing media to a hot, fully-stripped plasma as it progresses down the waveguide. Since a strong magnetic field has been previously established in the axial direction of the waveguide, the "plasma wave" remains confined and represents a high-density inverted medium which is transparent to radiation. As the pumping wave moves beyond a freshly plasmatized volume of laser medium, recombination processes (i.e., deexcitation of fully ionized atoms by the predominantly radiative processes previously discussed) cause the spontaneous emission of X-ray photons (among others), some of which are coincident with the cavity axis. These photons, in turn, induce amplification by stimulated emission and the intensity within the cavity increases exponentially. Additionally, the coherency of the radiation also increases with the gain length. Finally, since the plasma freely transmits radiation, an intense X-ray beam pulse is emitted at the exit plane of the generator. If the pointing and tracking systems have functioned satisfactorily, the X-ray beam pulse impacts the target (at $\approx$ 3000 Km) approximately .01 seconds later, and destroys it by impulse mechanisms.

5. Unanswered Questions

Although this concept appears deceptively simple, many technological and engineering questions remain to be answered before such a system could be successfully constructed and demonstrated. These include:

a) The identification of specific coupling mechanisms between the fission products of the nuclear detonation and the lasing medium. These designs must ensure that the waveguide package remains intact as the energy transfer process is accomplished. Additionally, these designs should maximize the fraction of available fissionable material which is ultimately converted to the X-ray laser pulse in order to enhance system efficiency.

b) The verification of precise plasma wave versus X-ray laser wave sequencing as both waves travel along the waveguide. That is, the plasma wave and the X-ray laser wave must maintain a precise and constant physical orientation to ensure that the X-ray laser wave is continuously amplified by penetrating the newly created plasma material at the instant that the material is lasing. If the laser wave arrives too soon, the laser medium will not have attained the hot, fully-stripped state required to efficiently transmit the incident radiation, and absorption rather than transmission and amplification dominates. Conversely, if the laser wave arrives too late, the plasma will have already radiated its energy, and, again, the dominant mechanism will be absorption.

c) The refinement of extremely precise stabilization and pointing/tracking subsystems. DARPA anticipates a pointing and tracking accuracy requirement of 10 microradians (10×10^{-6} radians) for space-based X-ray lasers. [Ref. 66] In order to ensure these accuracies, a space-based X-ray laser stabilization subsystem must be capable of preventing (or eliminating virtually instantaneously) any nuclear-detonation-induced instabilities or jitter. Additionally, this problem will be complicated by the fact that if beam pointing adjustments are required, the quick and simple movement of an external mirror will no longer suffice. More complicated (and probably much slower) thruster or impulse-jet stabilization arrays will be needed to accurately point the entire waveguide "muzzle" at the target.

Although nuclear-pumped X-ray laser technology is approximately 10 years behind other conventional high power laser research, some officials predict that if appropriate funding becomes available, the nuclear-pumped X-ray laser will quickly become the primary focus for space-based high power laser weapons. [Ref. 67]

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