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W. F. Krupke

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W. F Krupke

Lawrence Livermore Laboratory,University of California

Livermore, CA 94550

Abstrac:

Projections indicate that MJ/MW laser systems, operating with efficiencies in excess of 1 percent, are required to drive laser fusion power reactors. Moreover, a premium in pellet performance is anticipated as the wavelength of the driver laser system is decreased. Short wavelength laser systems based on atomic selenium (λ = 0.49μ), terbium molecular vapors (0.55μ), thulium doped dielectric solids (0.46μ), and on pulse compressions of KrF excimer laser radiation (0.27μ) have been proposed and studied for this purpose. The technological scalability and efficiency of each of these systems is examined in this paper. All of these systems are projected to meet minimum systems requirements. Among them, the pulse-compressed KrF system is projected to have the highest potential efficiency (6%) and the widest range of systems design options.

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Introduction

Significant scientific progress has been made [1] in the past half-decade toward the ultimate goal of producing commercial fusion power using inertial confinement techniques [2]. It is anticipated that achievement of the scientific milestones of the DOE Inertial Confinement Fusion (ICF) Program[1] will be attained during the next half-decade using laser systems and facilities currently operating (SHIVA)[3] and in construction (ANTARES[4], NOVA[5]). Looking beyond these milestones toward commercial power applications, it is clear that efficient, repetitively pulsed laser systems will have to be developed which can provide not only the high peak power pulses (as do today's single-pulse Nd:glass, iodine, and CO_2 fusion research lasers) but high average power as well. Reactor driver lasers may possibly utilize the active media of demonstrated research lasers but they must be reconfigured in device and systems geometries ameanable to average power operation; alternatively, they may use entirely new active media specifically identified for fusion applications on the basis of their relatively superior physical, technological and/or cost parameters. In this paper, the projected efficiencies of a number of driver laser systems based on selected new laser media and excitation techniques are given and key physical and technological scaling issues are identified. These systems are briefly compared with driver systems based on the more familiar (and more developed) laser media (Nd:glass, CO_2, Iodine, and HF).

Driver Laser System Requirements

In seeking to identify and develop entirely new laser systems for fusion power applications, it is well to define a set of system performance requirements which are likely to improve fusion pellet performance beyond that attainable using laser systems already known. A nominal set of laser system performance requirements for power plant service can be projected (Table 1) by combining the results of current implosion experiments[6] with LASNEX computer code simulations of high density implosions [7,8] and with preliminary analyses of fusion reactor concepts[9,10]. A determination of a precise set of parameters of an optimized laser system from within the ranges given in Table 1 will require detailed tradeoffs among all reactor subsystems that lie well beyond the precision of current technical knowledge. However, it is presently believed that operation at longer wavelengths[2,11] will require the laser system to deliver higher energies at higher system efficiency for constant reactor performance. The laser performance requirements given in Table 1 are expected to evolve with improved understanding of pellet physics and reactor design, particularly with respect to operating wavelength and efficiency. However, for now they serve as a useful guide for the identification and exploratory development of advanced laser systems for fusion applications. At this early stage, the most significant figure merit for differentiating between energetically scalable systems is the overall laser system efficiency. Of course, in the longer term, the total system cost will serve as the final figure of merit for systems capable of providing equal reactor performance.

Some New Laser Media/Concepts for Fusion

Laser media and systems concepts capable of the performance level called for in Table 1 have been addressed in terms of two basic types, 1) energy-storing media in which the electronic population inversion is radiatively and nonradiatively stable for times typically longer than a microsecond, and 2) highly radiating laser media in which the electronic population inversion decays radiatively on the time scale of a few nanoseconds. By early 1977, at least four new laser media/concepts with potential for meeting the requirements for ICF applications had been identified and explored in preliminary experimental studies[12]. These four generic media/concepts are listed in Table 2 along with a specific example of the active medium and the corresponding pump medium in each case. The concept of an energy-storage fusion laser based on the photolysis of simple polyatomic molecules containing Group VIa atoms (O,S,Se) has been discussed in detail by Murray and Rhodes[13] and recently demonstrated by Powell, et al.[14,15]. Energy-storing fusion lasers using molecular vapors containing trivalent rare earth ions and pumped by e-beam excited rare-gas halide excimer lasers have been described by Krupke[16] and observation of population inversions in such systems have been reported by Jacobs and Krupke[17]. The third energy-storing laser medium listed in Table 2 utilizes selected trivalent rare earth ions doped into transparent dielectric solids, pumped resonantly with the narrow band output from an e-beam pumped rare-gas halide excimer laser[18]. The fourth system listed in Table 2 is based on pulse compression of the long-pulse output (≥ 100 nsec) of a rare-gas halide excimer laser using combined techniques of sequential angle-code extraction and backward-wave Raman scattering.[19,20,21] Experimental studies of the latter technique in the context of fusion applications have been reported by Murray, et al.;[22,23] and analyses of concepts in the context of fusion applications have been recently given by Murray, et al.[24] and by Ewing, et al.[25]

Note here, that all of the systems cited in Table 2 consist of an electron-beam excited source of "pump" photons (either coherent or incoherent) and a "converter" medium which transform the pump radiation into a pulse format suitable for delivery to a fusion pellet. However, the operating parameters of the e-beam excitation source and the system geometries or architectures may differ significantly from each other.

A Comparison of System Candidates

During the past year or so, preliminary systems assessments of these four laser concepts were carried out by the Advanced Quantum Electronics staff at the Lawrence Livermore Laboratory[12] in order to provide a quantitative basis for comparing the various systems, to identify high-leverage physics and technical areas of risk, and to prioritize future technical effort. To conduct this assessment, preliminary device and system models for each laser candidate were developed. These models were then exercised for a number of alternate device geometries in an iterative fashion in order to arrive at preliminary technical designs for a nominal kilojoule/terawatt laser system. Throughout these analyses, new experimental and theoretical data generated for these media in on-going parallel efforts were integrated into the comparative assessment. Each system was also examined for any major physics or technological breakpoints in scaling to energies of order of a hundred kilojoules per beamline. Particular emphasis was placed on projecting overall systems efficiency at the kilojoule/terawatt level on a basis of "comparable technical risk". Such analyses necessarily entail considerable technical judgment in projecting efficiencies of individual laser subsystems and processes (power conditioning, deposition, medium conversion, extraction, beam transport, etc.). A major effort was made to be equitable in these judgments through an advocacy process. It is submitted that the projected systems efficiencies are quantitatively significant relative to each other and, as a set, are the likely achievable efficiencies to within a factor of two. Achievement of the projected system efficiencies is predicated on the demonstration of assumed values for a few important physics parameters which have been identified in the various models but have not yet been directly measured.

In these comparative laser system studies, a total of seven kilojoule-level laser designs were analyzed. In the case of the photolytic Group VIa atomic laser media, three distinct multi-pass power amplifier designs were analyzed, each differentiated by the method of photolytic pumping.[12] In one design, the OCSe fuel is photolyzed using coherent 172 nm radiation produced in a xenon excimer pump laser. In the other two designs, the OCSe fuel is photolyzed using incoherent fluorescence radiation from xenon excimer molecules. In the "solid window" version, the fluorescing xenon gas is physically separated from but closely coupled to the photolytic laser medium through a solid window capable of transmitting hard (172 nm) ultraviolet radiation. In the "windowless" version, the fluorescing xenon gas medium is flowed in streams parallel and adjacent to the flowing laser medium with matched pressures and velocities, leading to the elimination of potentially troublesome solid ultraviolet transmitting windows. The assessment of photolytic Group VI laser media has strongly emphasized the use of selenium as the active species and operation on the visible-wavelength transauroral transition. This selection is based on the observation that operation on the infrared auroral transitions of either sulfur or selenium will lower attainable efficiencies inversely with the transition wavelength, other things being equal. In the case of sulfur, evidence suggests that the stimulated emission cross-section of the transauroral transition is about an order of magnitude lower than that of the auroral transition, precluding the ready development of large energy storing amplifiers for operation at the shorter wavelength. In the case of selenium, the two transition cross-sections are essentially equal and operation on the transauroral transition is anticipated in large, energetic amplifiers. In the face of these considerations, the utility of the Kr_2^* pump medium and the OCS fuel must be established on the basis of compensating factors associated with other dynamical processes. To date such compensating factors have not been identified.

Three specific designs of kilojoule class lasers utilizing trivalent rare earth ions as the active species were examined in the study. An XeF excimer laser pumped Tm^{3+}:glass laser system, characterized by a relatively low specific thermal loading of the glass medium(18) was explored. This system can be directly compared with the rare earth molecular vapor laser systems in which the average power-thermal loading problem is solved by flow cooling of the laser medium. Designs based on two different molecular carriers(26) of the optically active terbium (Tb^{3+}) ion were explored to illustrate the issues associated with the distinct chemical, physical, and kinetic properties of these vapors. As a final system, the performance of a backward-wave pulsed Raman stacker-compressor laser using the KrF excimer medium as a pump and methane gas (CH_4) as the Raman medium(21,22,23,24,25) was analyzed.

Since the system efficiency is such a singularly important parameter in comparing the potential of various systems, definition of this parameter is given here. The total laser system efficiency ($\varepsilon/_L$) is defined as a hundred times the ratio of the optical power delivered to the target (P_L) to the total power consumed (P_{IN}) in generating the delivered power

$$\varepsilon_L = \frac{P_L}{P_{IN}} = \frac{P_L}{P_{EC} + P_{FC}} \tag{1}$$

where P_{EC} is the total electrical power inputed to the laser pump medium and P_{FC} is the power consumed in flowing and reconditioning the spent laser and pump media. P_{FC} must be made sufficiently large so as to achieve a beam quality at the exit of the laser adequate for further transport to the target, as well as to recycle the laser media for reuse on a closed-cycle basis. The efficiency ε_T with which the laser output power (P_O) is transported to the target will, in general, be a function of the optical quality of the beam and therefore a function of P_{FC}.

$$\varepsilon_T = \frac{P_L}{P_o}$$

The efficiency of the laser system evaluated up to the laser exit aperture (ε_o) is therefore

$$\varepsilon_o = \frac{P_o}{P_{EC} + P_{FC}} = \frac{1}{\frac{1}{\varepsilon_{EC}} + \frac{1}{\varepsilon_{FC}}} \tag{2}$$

where $\varepsilon_{EC} = P_o/P_{EC}$ is the laser electrical efficiency, and $\varepsilon_{FC} = P_o/P_{FC}$ is laser flow factor of merit. (Since ε_{FC} may exceed unity, it is improper to refer to this quantity as an efficiency.) In the analyses to be discussed below, the beam transport efficiency factor, ε_T, has not explicitly been evaluated, however the beam transport issue has been recognized by estimating the ratio of $\varepsilon_{FC} = P / P$ required to produce optical beams such that ε_T will be sufficiently near unity so as not to significantly degrade the total laser system efficiency. By and large, it turns out that the flow cooling power for these systems is not excessive and does not appreciably lower systems efficiencies. Even these modest efficiency penalties due to flow cooling might be reduced by application of efficient phase-conjugation techniques[27,28] to correct for beam abberations.

Results of the System's Analyses

The major conclusions of the analyses of the seven laser systems can be drawn from the summary data presented in Table 3. In this table the laser efficiency (ε_0) has been divided into two main parts - that of the optical pump source and that of the laser medium which converts the pump radiation into a format useful for target irradiation. These two subsystems blocks are further broken down into several constituent efficiencies or factors in order to display which processes or subsystems dominate the reduction of the overall system efficiency and thereby command our future attention. For each system an approach to significantly improve on the most limiting process or subsystem efficiency has been identified; these items are identified by the use of a square containing a higher projected efficiency in order to flag it as a higher risk situation.

The first conclusion to be drawn from this data is that, based on information available to date, all of the analyzed systems have the potential for meeting or exceeding the minimum efficiency requirement of 1%, cited in Table 1. All systems also appear to be technologically scalable in energy to reactor class systems, albeit with differing technological issues. The second major conclusion to be drawn is that, on an "equal risk" basis, the KrF/CH_4 Raman stacker/compressor laser system concept is projected to offer a system efficiency signficantly higher than the others, possibly reaching as high as 4-6 percent. When coupled with the fact that this laser system operates at the shortest wavelength (0.27μ) and enjoys an intrinsically large range of systems architectures and technological options for implementation[25], it is concluded that this system concept has the highest potential of those reviewed here to meet anticipated fusion application needs.

The third major conclusion to be drawn from this analysis is that the projected system efficiencies are as low as they are (1-6%) primarily due to basic inefficiencies of the pumping sources when they are coherent. The medium which converts this coherent pump radiation into a useful format for fusion applications is by comparison, relatively efficient. One is therefore impelled to seek and identify intrinsically more efficient coherent pump sources, find more efficient processes for utilizing efficiently produced radiation from incoherent pump sources, or develop laser media which operate in a fusion pulse format using conditioned electrical energy directly. (The discharge-pumped metal excimer lasers, such as Hg_2^* [29] and $HgCd^*$ [30], are of interest for fusion applications because of their potentially high efficiencies.[1] Since net optical gain has not yet been established for these media, no scaling or efficiency assessments have yet been made for them.)

Of course, efficiency projections such as those given in Table 3 do not tell the entire story. Each system offers its own and generally distinct technological advantages and challenges; and each carries with it a presently incomplete description of all important physical processes. This aspect of system assessment is briefly summarized in Table 4 which lists the principle physical and technological issues for these systems.

Physics and Technology Issues

In the case of photolytic Group VI lasers the highest leverage items are associated with the pump source. The efficiency of a xenon rare gas excimer laser pump is strongly dependent on the photoionization cross-section of the Xe_2^* excimer, on the mixing rate of the two populated excimer excited states ($^1\Sigma$ and $^3\Sigma$), and on nonsaturable losses present in the electrically excited medium. The cross-sections (rates) characterizing these processes are insufficiently known at this time to definitively project the ultimate efficiency of an optimized xenon excimer laser pump. In constrast, the fluorescence dynamics of the e-beam exciteo xenon excimer medium are fairly well understood and characterized; the major leverage to be gained in this case is to develop concepts for more efficient coupling of the fluorescence radiation to the Group VI fuel.(12)

In the efficiency projections for Group VI selenium lasers, long storage times ($>\mu$sec) have been assumed. This assumption appears technically warranted,(14,15) although deleterious quenching of excited Group VI atoms due to photo-generated electrons and heavy-particle minority species requires additional study to optimize energetic amplifiers with microsecond long storage times. The major technological risks associated with Group VI lasers center on the development of VUV optics able to withstand the intense pump fluxes at 170 nm. In the case of coherent pumping, high-reflectivity, large aperture mirrors and windows need to be developed. In the case of fluorescence pumping with a solid window geometry, the VUV transmitting windows must stand-up to large cumulative doses of both VUV radiation and relativistic electrons. In the "windowless" geometry, the VUV optics problem is largely obviated but the added problem of mixed pump and fuel gases arises and systems efficiency may be decreased due to increased flow power requirements. In the analyses to date, no consideration of efficiency reduction due to pump and fuel medium reconstitution has been included. While this factor is not expected to dominate the overall system efficiency, it must be treated quantitatively if this design concept is to be pursued further.

Consider next the Tm^{3+}:glass hybrid system (excimer laser pumped solid state laser). The high leverage areas include use of a pump laser with substantially higher efficiency than projected for the XeF excimer laser (3-5%),[31] and the identification and use of host materials with lower nonlinear refractive index and higher thermal conductivity than glasses. As a class, crystalline materials offer considerably higher thermal conductivities and in some cases very low nonlinear refractive indices. In terms of physics issues, estimates of nonradiative decay rates due to multiphonon and ion-ion interactions have been made for the Tm:glass system. Experimental documentation of the important nonradiative (thermal) rates would have to be in hand prior to the selection and development of such a hybrid laser system. Preliminary analyses suggests that axial gradient cooling techniques can be implemented to achieve useful high average power from a solid state laser.[18] The optical quality of radiation extracted from such a system and the system efficiency will depend largely on the degree to which one can control transverse temperature gradients. While it is judged that adequate temperature control can be achieved in principle, design solutions depend on the specific details of the pump deposition and laser medium dynamics. Given the projected performance of the Tm^{3+}:glass system and others using a XeF excimer pump in comparison with alternative systems, it is felt that this specific hybrid laser system does not warrant such a detailed analysis. Rather, effort in this system area will likely center on identifying intrinsically better pump and medium combinations.

Consider next the rare earth molecular vapor laser systems. Again we are forced to recognize the leverage in identifying more efficient pump sources. Although laser (coherent) pump sources alone were considered for the Tb based systems analyzed to date, the long population inversion lifetimes possible in selected rare earth molecular vapors (particularly for the aluminum halide complexes) appear ameanable to the use of incoherent pump sources such as flashlamps,[32] provided efficient spectral coupling can be achieved. At the same time, laser amplifiers based on aluminum halide complex vapor media must operate at a relatively high total pressure (2-4 atm of Al CL) as a result of a two-component chemical nature. This is expected to lead to significant design issues with respect to maintaining adequate beam quality of the extracted radiation. A premium is therefore placed on use of single component rare-earth ion carriers such as the thd-chelates when suitably buffered with a rare gas.

In the efficiency analyses of the rare-earth molecular vapor systems, and in the absence of direct experimental measurements, unity quantum yields (one molecule in the upper laser level for each photon absorbed) have been assumed for the two Tb-vapor media. Due to the relative simplicity of the electronic structure of the Tb-Al-Cl molecule, this assumption can be technically rationalized.[12] However, such is not the case for the more complex thd-metallo-organic molecule and the true quantum yield is a more open issue. This situation represents a major remaining physics uncertainty for these vapor systems. Quantum yields much less than unity will lower projected efficiencies for these systems below the minimum level of interest. A secondary physics issue has to do with the spectral homogeneity of the gain medium transition for pulse extraction times of ≈ 10 nsec. To date there has been no quantitative characterization of the transition lineshape at the temperatures and pressures of interest for fusion amplifiers. While there is reason to assume an effectively homogeneous gain line due to collisional coupling of Stark and rotational states within the fluorescence envelope, this issue would have to be addressed experimentally prior to development of large scale devices.

Technologically, the principle issues associated with rare earth molecular vapor laser systems center on successful optical-mechanical designs of amplifier structures for the relatively high operating temperatures anticipated (300-500°C). The designs must also accommodate the flow of the working materials consistent with optical pumping requirements and maintenance of fuel purity. It would appear to be a particularly great challenge to devise successful design solutions for lasers using the two chemical component aluminum halide vapor medium.

Finally, consider the KrF/CH_4 Raman Stacker/Compressor laser system. Although utilizing the most efficient and energetically scalable excimer laser pump demonstrated to date,[33] the development of techniques to make the KrF [34,35] or other narrow-band excimer laser pumps more efficient is clearly desirable. Considerable effort is in progres- to fully understand the full kinetics of the KrF and other excimer lasers particularly at high excitation rates, in order to significantly improve the laser efficiency under narrow-band conditions. From a systems scaling viewpoint, development of techniques to suppress gain at the second-Stokes frequency will be profoundly advantageous.[24,25] Such techniques will allow a high compression ratio per Raman stage and greatly reduce system complexity. Several techniques to suppress second-Stokes gain have been proposed and will be the subject of considerable effort in the near future.

The major technological issues to be addressed for the Raman systems are clear. First, it is recognized that transmitting and reflecting optics at 0.27 m will have to be substantially improved over those presently available. Present conceptual designs of large systems call for optics capable of handling beam fluences up to 10 J/cm^2, or several times larger than presently available optics.[36] No significant effort has been expended to date to develop high damage threshold optics at 0.27μ; while optical materials suitable for service at 0.27μ are considerably fewer in number than those suitable for service at 1μ, it appears that adequate optics are likely to be developable using the methodology proved to be so successful in developing 1μ optics for Nd:glass systems. If an efficient hybrid compressor could be developed using XeCl as a pump medium operating at 308 nm and using methane as a Raman scattering medium (Stokes wavelength of 375 nm), the optical damage thresholds of available material may well be increased by a significant factor.[36] The control of the radiation extracted from an intrinsically high gain KrF pump amplifier medium is also rated a significant issue.

To date, KrF power amplifiers pumped by electrical discharges have been successfully presaturated.[34,35] These relatively small size ($\geq$ 1J) amplifiers have been demonstrated to be spectrally and energetically controllable with modest levels of injected radiation. Using this ir[illegible]ion together with a preliminary analysis of the stabilization of KrF power amplifier of large transverse dimensions ($\sim$ 40 cm), it is believed that adequate gain control can be achieved. However, this remains to be demonstrated experimentally.

All of the laser systems being discussed in this paper use large-area relativistic (1-2 MeV) electron beams to excite the optical pump sources. The energy storage laser systems favor microsecond long pulses with beam current densities of order 10 A/cm^2; the compressor laser systems favor shorter pulses (100-200 nsec) and higher beam current densities (100 A/cm^2). By in large, present experimentation is being carried out using cold cathode diodes to form electron beams of modest areas (1000 cm^2), driven by Marx-bank and pulse-forming-line power conditioning technology. The technical (and economic) success of all of the laser systems described here calls for significant development of both the power conditioning technology and the e-beam forming element, both with respect to scale (larger areas, higher total current) and shot lifetime in an average power mode of operation. In the case of the compressor laser systems, in which the excitation of several large power amplifiers must be synchronized with the arrival of propagating extraction pulses, special attention must be placed on the development of efficient low-jitter switching techniques.

On the basis of the information summarized here(12), it is concluded that the Raman stacker compressor laser system concept offers the highest performance potential of the systems studies. We project an efficiency for the KrF/CH_4 system in the 2-4% range, with a possible high of 6% using augmented discharge techniques: the short wavelength of operation (0.27μ) appears quite attractive from the point of view of pellet coupling; and the richness of systems architectures and technologies provides flexibility in tailoring system output parameters over a wide range. The projected efficiencies for the pulse compressor systems should be referenced to the projected efficiencies of comparable performance laser systems based on CO_2(5-10%), Nd:glass (1-2%), Iodine (0.5-1.2%), and HF (3.5-7%) laser media.

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Table 1. Laser Systems Performance Requirements for a Fusion Power Plant

Laser wavelength	250 - 2000 nm
Pulse energy	1 - 3 MJ
Pulse duration	~ 10 nsec
Peak power	~ 200 TW
Pulse repetition rate	a few Hz
Average power	~ 10 MW
Overall efficiency	> 1%

Table 2. Some Potential Laser Systems for Fusion Applications[12]

Generic Species/Concept	Active Species	Pump Source	Medium Type	Reference
Photolytic Group VI atoms	Sulfur (S), Selenium (Se)	E-Beam Driven Rare Gas Excimers (Kr_2^*, Xe_2^*)	Storage	12,13,14, 15
Rare Earth Molecular Vapors	Tb-Al-Cl, $TbThd_3$	E-Beam Driven Rare Gas Monohalide Excimer (KrF)	Storage	12,16,26, 32
Rare Earth Solid State Hybrids	Tm^{3+}:Glass, Crystal	E-Beam Driven Rare Gas Monohalide Excimer (XeF)	Storage	12,18
Raman Stacker/Compressors	Methane (CH_4)	E-Beam Driven Rare Gas Monohalide Excimer (KrF)	Non-Storage	1,12, 21-25

Table 3. Projected System Efficiencies of Several Potential Fusion Lasers(12)

	System / Subsystem	Xe_2^* Pumped OCSe			Rare Earth Ions			Raman
		Laser pumped	Fluorescence (windowless)	Fluorescence (window)	XeF pumped Tm^{3+}:Glass	KrF pumped Tb-thd_3	KrF pumped Tb-Al-Cl	KrF/CH_4 compressor
ϵ_1	E-beam generation, transport and deposition	65						
ϵ_2	Pump medium-electron to light conversion	5–10 [20]	45	45	5–7.5 [15]	10–15 [25]	10–15 [25]	10–15 [25]
ϵ_3	Pump electrical eff	3.2–6.5 (13)	29	29	3.3–4.9 (9.8)	6.6 – 9.8 (16)	6.6 – 9.8 (16)	6.6–9.8 (16)
	Total pump efficiency	3.2–6.2 (12)	23†	27	3.0 – 4.4 (8)	6 – 8 (12)	6 – 8 (12)	6 – 8 (12)
ϵ_4	Transport/coupling	90	20–40 [60]	20 – 40 [60]	90	90	90	80
ϵ_5	Fill factor	80						
ϵ_6	Extraction X Quantum	22	22	22	35	28*	28	55–75#
ϵ_{ec}	Laser system electrical	0.5–1.0 (1.9)	0.8–1.6 (2.4)	0.9–1.8 (2.6)	0.8–1.0 (2.0)	1.2–1.6 (2.4)	1.2–1.6 (2.4)	2.1 – 4 (6)
ϵ_o	Total system after flow	0.5–1.0 (1.9)	0.8–1.5 (2.3)	0.9–1.7 (2.5)	0.8–1.0 (2.0)	1.1–1.5 (2.3)	1.1–1.5 (2.3)	2.0 – 4 (6)

[ ] Percent efficiency with possible breakthrough

( ) *Total with breakthrough increment*

Requires cleaner pump medium – more flow

† Second Stokes gain suppression

* Assumes unit quantum efficiency

Table 4. Key Physics and Technology Issues for Several Potential Fusion Lasers[12]

System	Group VI	Solid State Hybrid	Rare Earth Molecular Vapor	Raman Stacker/Compressor
Efficiency after flow,%	0.5-1.9 (2.5)	0.8-1.0 (2.0)	1.1=1.5 (2.3)	2-4 (6)
Leverage items	Pump laser eff; fluorescence coupling eff.	Pump laser eff; low n_2 mat'l; high therm. cond.	Pump laser eff; single component vapors	pump laser eff.; second Stokes suppression
Physics risks	Storage time at high inversion density; minority quenchers	Nonradiative decay channels	Unit quantum yield; spectral homogeneity	High order nonlinearities
Technology risks	VUV optics gas reconstitution	Transverse temp. gradients; cyclical stress	High temperature opto-mechanical design; fuel integrity	UV optics gain control of pump medium