Novel Design of Ultrashort Pulse Excimer Laser Amplifier System I
(Energy Characteristics)

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Abstract—The technology required to advance the state of the art of ultra-high-intensity excimer amplifier construction to the 100 J/100fs output pulse level is identified. The preliminary design work for very large final amplifier pumped by electron beam module is described, and key design problems and approaches are presented and discussed in detail based on the recent experimental and theoretical results.

Index Terms— excimer laser, wide-aperture amplifier, high power KrF laser, ultra-short high intensity laser.

I. INTRODUCTION

EXCIMER lasers have proved themselves as very suitable for the production of extremely high-brightness outputs in the ultraviolet spectral region[1,2]. The availability of very high focussed power of more than 10^{21}W/cm^2 is stimulating many new applications like X-ray laser pumping, atomic physics, quantum electrodynamics, etc.(these new applications are sometimes referred to as strong field physics). In order to realize an X-ray laser excited by a high-intensity petawatt KrF laser pulse of subpicosecond pulse duration, the ultra-high-intensity UV laser system was recently proposed by the X-ray laser groups in Europe and Japan.

Several considerations on the rare gas halide laser amplifier physics and technologies indicate a new operational mode of the electron beam pumped buffer-free medium as the ideal one for this high brightness laser amplifier[3,4].

For high efficiency the pumping should occur in the form of a travelling-wave pumping. This could be alone by proper delays between the manyfold of diodes. The pressure in this two amplifiers should be reduce as much as possible in order to be able to use very thin windows for the suppression of nonlinear processes in the windows. It seems possible to use a KrF pressure of no more than 200 Torr, so that this is also the pressure differential between inside and outside, since the laser beam has always to be guided in evacuated pipes to preserve the optical quality of the beam.

In this paper, the wide-aperture amplifier design considerations are described from the point of the total system architecture. We first discuss the constraints on energy, in the wide aperture-beam pumped KrF amplifiers, sometimes citing referred to the experimental and numerical results performed before time. A proto-type of the amplifier is described to give a general guideline of the design and demonstrate the feasibility of the device.

II. REQUIREMENTS AND CONSTRAINTS

The "Rapier A" KrF laser of Lawrence Livermore National Laboratory(LLNL) is the first specially designed device for KrF pumping by the use of two opposed e-beam to excite the laser mixture[6].

The device was designed to have a 50ns laser pulse width, and to produce a 25J pulse from a 100 cm x 100 cm aperture for optical pulse compression experiments. The first priority was given to proving the overall efficiency in this laser-fusion oriental study. Following the successful operation of the Rapier A amplifier, further extentions of apertures were achieved in a guiding-magnet-equipped two-sided pumping scheme or a guiding-magnet-free circular pumping scheme the "Sprite" system in Rutherford Appleton Laboratory(RAL)[7]. The third approach was the longitudinal pumping scheme which has the origin in Sandia National Laboratory[8] and employed in a high-intensity pumping scheme of KrF. Each geometry has its own characteristics, and in this design proposal the most commonly employed guiding-magnet-equipped two-sided pumping scheme is taken for study purposes. The deposition of e-beam energy is easily estimated for the care of a guiding magnet, and the overall conceptual work is relatively straight forward.

III. ENERGY CHARACTERISTICS

For the pre-amplifier and the main amplifier the total system design requires primarily to achieve single-pass small-signal stage gains of 10(g_0l = 2.3). A double-pass optical arrangement is assumed in each amplifier but a saturated amplification is assumed only for the second pass in the final amplifier. From the maximum achievable fluence of 3×E_{sat}(E_{sat} : saturation energy), a clear square aperture of 1.3m×1.3m is required for 100J output with the maximum fluence at the exit window of 6mJ/cm2. For the conceptual design purpose, it is better to assume

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the active aperture as 1.5m × 1.5m to compensate edge loss in the real situation. The length of the pumped region is assumed to be the same as the side length of the active aperture, i.e. l = 1.5m. In this geometry, the total active volume is V = 33751, and the small signal gain coefficient is $1.5\%/cm^{-1}$. A relatively long time lag(~50ns) was measured for the ASE flux to build up inside the amplifier. One possible way to reduce this effect is to limit the pumping power and the pumping time in order for the ASE flux not to grow up significantly. Timing control of the input coherent flux may help to control the temporal gain behavior to limit the ASE loss effect. In the case of electron-beam pumping, the ion channel for the KrF upper-state formation is dominant and the g_0 / α ratio is relatively lower (~10) than in the case of discharge pumping (~20). Judging from the previous data in these 10 years, a small-signal gain coefficient of 2%/cm is obtainable at 200 kW/cm^3 pump power. As long as the expected small-signal gain coefficient of 2%/cm is achieved for the ultrashort pulse, lower pressure operation of the KrF medium is preferable to reduce the window thickness and distortion effects of the medium on the amplified pulse. A low-pressure operation of the KrF medium was successfully employed in microwave - discharge - pumped excimer lamps. In a low pressure environment around 100 Torr, collisional quenching of KrF upper state is low effective and the upper state lifetime is close to its radiative lifetime of 6.7ns. Recent experimental work is the SPRITE amplifier of the Rutherford Appleton Laboratory(RAL) demonstrated that a small-signal gain coefficient of 2%/cm is obtained with 200 Torr pressure[9]. A numerical kinetics study was also made by ourselves in Max-Planet-institute to investigate the low pressure operation in which a good agreement was obtained with the RAL experimental data[5].

The electron beam source must be designed to achieve an uniform pumping in the whole active volume to yield the needed pump-power deposition for the given operational pressure. Differential energy loss -dE/dx (eV/cm) is given in Fig.1. For Kr and Ar as functions of electron energy and pressure. The energy loss (ev/cm) multiplied by the e-beam current density (A/cm2) yields the pump-power density(kW/cm3). However, a Monte-Carlo electron-transport and deposition code is necessary to determine the energy loss of the electron beam due to relatively high side-and back- scattering.

As the result, a few times the value calculated from Fig.1 is obtainable in a magnetic guided electron geometry, It is seen that to achieve the expected 200 kW/cm3 pump-power density in 200 Torr Kr operational pressure, $50A/cm^2$ current density is needed. Although the differential stopping power dE/dx is less sensitive to the acceleration voltage, higher voltage is desirable to achieve higher current in a constant-impedance module in the design work of the PAM module of Los Alamos National Laboratory in United States[10], 1MV, $20A/cm^2$ e-beam pumping in 585 Torr gas is expected to give $250kW/cm^3$ pump-power density. These parameters are the main subjects to be studied in the detailed design phase before construction.

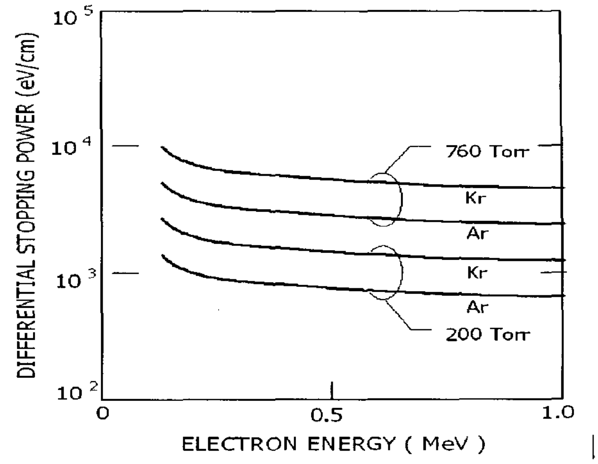

Fig.1 Differential energy loss dE/dx of Ar and Kr as a function of acceleration

The other requirement in the design work of ultra-intensity UV laser system is to achieve a moderate repetition-rate operation of the whole system. The major factor that limits the repetition-rate operation is the accumulated heat loading at some-heat-sensitive parts such as the capacitors, spark gaps, vacuum interface and foils. Surface discharge on the vacuum interface and pinhole formation at the foils are often observed often repeated operation. The physics of surface flashover is still poorly understood, but the equation below is the only one reliable benchmark on this phenomenon-charged particle. This is taken from a study of small area, +45° insulators done by J.C.Martin.

The equation is written as

$$\left[\frac{F}{kV/cm}\right]\left[\frac{t}{\mu s}\right]^{1/6}\left[\frac{A}{cm^2}\right]^{1/10}=175$$

Where f is the flashover field, t is the time during which the field on the insulator exceeds 0.89 of the peak field, and A is the surface area of the insulator. In a large scale system, the area tends to be large, so that this time t should be smaller in order to suppress the flashover probability. Damage is caused by accumulated heat at some parts, normally insulators or small metal connectors/ electrodes. To limit the damage effect from being catastrophic, the total energy that passes through each module must be reduced. One of the common defects in the e-beam device is a pin hole formation at the pressure foil. The resulting vacuum degradation in the diode section prevents.

further operation.

The reason for the pin hole formation is mechanical : material degradation by fast electron attack and strong radiation, explosive pressure jump in the laser channel and excessive heating due to absorbed energy and vibration. The equation for maximum stress in the center of the foil is given in a static condition [11]:

$$\sigma_x = \left(\frac{p^2 E a^2}{t^2} \right)^{1/3}$$

where

σ_x = tensile strength in the center of the foil (N/m^2),

k_2 = coefficient based on the length/width ratio of the slot,

p = pressure (N/m^2),

E = elastic module of the material (N/m^2),

a = length of the slot (m),

t = material thickness (m).

This equation implies that in a reduced pressure condition a safety factor for the foil increases as $p^{-1/3}$ or the thickness t can be reduced linearly as p which in turn results in higher electron beam transmission efficiency through the foil. A current density(~50 A/cm^2) must be achieved at the pressure foil to get the necessary pump power in the laser chamber, but the pulse duration should be minimized to avoid pinhole formation due to excessive heat pile-up in the foil. A ions electron-beam source was successfully employed by Maxwell to pump XeF(C→A) beam at 1 Hz operation[12]. Though the necessary pump power for XeF is relatively and the peak voltage and current density are 650 kV and 250 A/cm^2 the transmitted charge per unit area is as low as 2.5 μ C/cm^2 due to the limited pumping time. A detailed study on these issues is expected to determine the design voltage, current density, the pump time, and active pressure for optimum spatial and temporal deposition by experiments and numerical analysis. Table I summarizes these parameters based on the previous experimental data.

TABLE I 100J AMPLIFIER PARAMETERS

single pass stage gain	10($g_0 l$=2.3)
aperture	1.5×1.5(m_2)
output fluence	6mJ/cm_2(A=1.7×10^4 cm^2)
active length	1.5m
active volume	33751
small-signal gain coefficient	1.5%cm^{-1}

IV. PROTO-TYPE DESIGN OF THE FINAL AMPLIFIER

The construction of the final amplifier is one of the central issue in the ultra-high intensity UV laser system, because it occupies the main part of the finance and time schedule. A large-scale laser device is not easily modified after construction. A normal approach is a modular system achitecture, where the main amplifier is pumped by a number of moduled e-beam devices. Each pumping geometry, such as the opposed-sided square, the circular, or the longitudinal pumping is assembled by using the modular design. Only the laser vessel is common in this approach. For the design purpose, a magnetic-field-guided two-side pumping is the natural choice. This scheme can provide the most probable way for fast, uniform e-beam deposition with minimum window attack in a 1.5m aperture device. A low turbulence gas flow system can be easily installed perpendiculary both to the e-beam and optical axis. The required e-beam area is 1.5m × 1.5m, which can be constructed only by a combination of moduled diodes. Table II summarizes these parameters estimated for ultra-high intensity UV laser system.

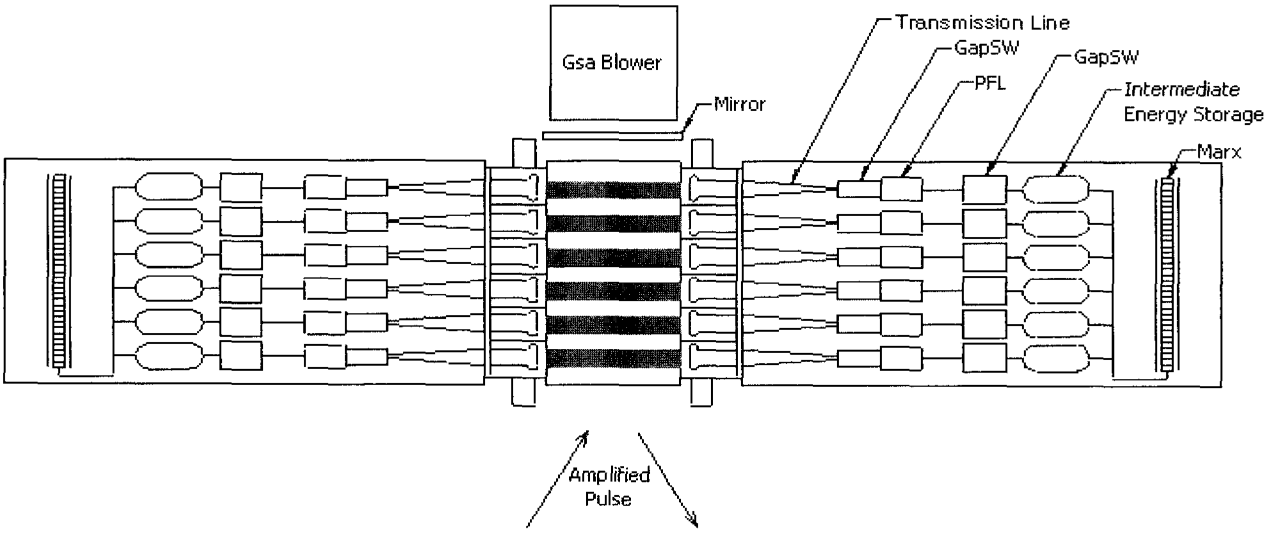

Fig. 2 The Proto-type design of the final Amplifier

TABLE II 100J AMPLIFIER / POWER MODULE PARAMETERS

e-beam boltage	1MV
e-beam current density	25A/cm^2
pumping power	200kW/cm^3
active length	1.5m
active volume	33751
pumping pulse with(FWHM)	10ns
deposition energy	6.8kJ
diode efficiency	30%
diode energy	24kJ
unit area of e-beam	150cm×25cm
number of e-beam module	6×2(=12)
diode energy	2kJ
diode voltage	1MV
diode current	200kA
diode impedance	5ohms
diode current density	55A/cm^2
guide magnet	2kGauss

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TABLE III SPECIFICATIONS

Marx Generator (×2)	
output voltage	2.0MV
capacitance	1.5nF
stored energy	3.0kJ
Power module (×6×2)	
peak voltage	2.0MV
capacitance	1.5F
stored energy	3.0kJ
Laser triggered spark gap(×6×2)	
peak voltage	2.0MV
jitter	-1ns
PFL(×3×6×2)	
peak voltage	2.0MV
stored energy	1.0kJ
impedance	15 ohms
Self-break down peaking gap	
peak voltage	2.0MV
impedance	15ohms
Transferred energy(×2)	18kJ(10ns)
Diode(×2)	
voltage	1.MV
current	200kA(10ns)
impedance	5ohms
current density	50A/cm^2

These parameter for each module are similar, except for the pumping time, with those of the next generation electron-beam gun test facility, for example the amplifier test unit(ATU) of LANL. The unit area of each diode module is determined as 150cm×25cm. The resulting total module number is 12 (6 for each side). A segmented planar diode with constant B-field approach is selected for the benefit of simplicity, fast turn-on of current and uniform deposition. The disadvantage is the excessive unpumped regions between modules as shown in Fig 2. The absorption coefficient for high-Intensity fs-pulses in the unpumped KrF gas mix is not known, but the total length of the unpumped region is nearly the same as that of the pumped region. This is almost the same ratio as in conventional discharge amplifiers. The aspect ratio increases from L/D=1 to L/D=2 at the expense of excessive light transit time. This is turn favors less gain depletion by self-generated ASE. Higher guide-magnet field is better for higher foil/Hibachi transmission efficiency, faster drift speed and uniform deposition, Related diode parameters are also listed in Table II, The current density in the diode is determined by the child-langmuir law.

$$J = KU^{3/2}/d^2$$

U : cathode voltage,

D : anode-cathod(A-K) gap,

K : constant $= 2.34\times10^{-6}A/V^{3/2}$

with J = 55 A /cm^2 and U =1MV, an A-K distance of d=6.5cm is obtained. The critical current in a rectangular geometry is expressed as

$$I_c = \frac{8500A\beta r}{1+\ln(2l/w)} l/d$$

where relativistic parameters are given as β=0.94, r =2.9. In this design, geometrical parameters are l=150cm, d=6.5cm, w=25cm. Thus the critical current is I$_c$=154kA. The self-generated magnetic field for I$_c$ is

$$B_c = \mu_0 \frac{I_c}{2l}$$

In this case, B_c=630 Gauss. For I=200KA current, B$_{self}$ = 840 Gauss. As the strength of the guiding magnet, 1.5 ~ 3 times B$_{self}$ is advisable. In the normal operation condition of 1 MV and 200 kA, 2 kGauss is an optimum parameter, Table III summarizes the specification of the final amplifier in ultra-high intensity UV laser system.

V. CONCLUSION

This design work is an optimization of the normal e-beam pumping technology for a short-pulse amplifier. Several estimations were made to determine the specifications. A small-side study is desirable to determine each of the final parameters. Relation between acceleration voltage, current density, guiding magnet strength, Kr/F$_2$ gas pressure, chamber structure for 200 kW/cm^3 pumping power and 1-2 % cm^{-1} small-signal gain coefficient by a 10ns e-beam pulse (1.0%cm^{-1} of small-signal gain coefficient is confirmed by our fs-KrF pulse amplifier experiment)[13-15]. After these issues are well studied, the pre- and main-amplifiers are flexibly assembled by the combination of the established e-beam module depending on the final optical arrangement.

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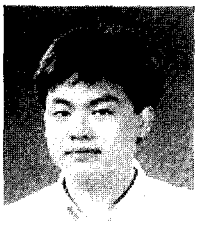

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