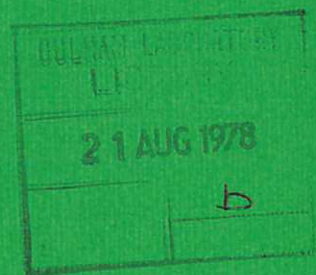UKAEA

Preprint

HIGH POWER LASERS AND THEIR APPLICATIONS

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ABSTRACT

Most high power lasers are either energised or initiated, directly or indirectly, by means of gas discharges. The paper first summarises the diverse operational characteristics desired for some existing and potential (civil) laser applications, and then examines how these requirements influence laser design. The applications include alignment, anemometry, holography, pollution monitoring, surface-hardening, welding, cutting, photochemistry, isotope separation, thermonuclear fusion, etc. and span a laser power range of $\sim 10^{20}$. For many, but not all, of these applications the CO_2 laser proves to be particularly convenient, powerful and efficient.

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INTRODUCTION

Most high-power lasers are either energized or initiated, directly or indirectly, by means of gas-discharges. (Gas-dynamic lasers pumped purely by thermal or chemical methods (1), and electrically-pumped solid-state diodes (2), present the major exceptions. Devices pumped by nuclear charged-particle emission are less simple to classify, but at present are merely of academic interest.) In constructing an optically-pumped laser such as ruby or Nd-glass one tends of course to use mass-produced gas-discharge components whenever these are available, so that the gas-discharge aspects of the flash-lamp, thyratron, spark-gap, etc. can often be overlooked. In contrast, typical industrial multi-kilowatt continuous lasers utilize stable, volumetric, electrical excitation of a gaseous $He/N_2/CO_2$ lasing medium, and an understanding of the relevant gas-discharge physics and plasma-chemistry is a sine-qua-non of their design (3).

On the one hand, then, the rapidly-expanding laser R&D market is a demanding consumer of gas-discharge devices and on the other hand the resulting lasers may also compete with (or sometimes improve and complement) existing gas-discharge applications. Typical examples are the competition between deep-penetration welding/cutting by CO_2 laser and plasma-arc techniques, and the use of lasers for fast-triggering of high-voltage spark-gaps. To reduce the scope of this paper to manageable levels, therefore, it will be convenient to limit discussion of such lasers and their applications primarily to civil uses of general interest within the UKAEA. However, state-of-the-art developments elsewhere will also be summarized where this seems necessary to provide a better picture of over-all trends.

LASER APPLICATIONS

High-power lasers are rarely developed for fun; they are developed to fulfil a requirement. Table 1 summarizes the diverse operational characteristics desired for some existing (and potential) civil laser applications. Note that, with rare exceptions, gas-discharge-excited lasers can fulfil most of these needs. Exceptions are the tunable-infrared 10^{-6}-10^{-5}W CW diodes used for molecular-spectroscopy, pollution and photo-chemical investigations (where a combination of narrow line-width and wide tunability currently confers a unique advantage), and the light-emitting diodes (LEDs) used in optical communications (here the ability to fully miniaturise the equipment, together with long-life and convenience, is the prime advantage). Let us look at a few of these applications in greater detail, so that we can determine how the end-use affects laser design philosophy.

Alignment, Laser Anemometry and Holography

For many industrial alignment problems a He-Ne laser operating at a power of up to 1 mW, often expanded through a telescope attachment to about 30 mm diameter, provides a cheap conveniently visible, straight-line alignment aid requiring minimal safety precautions. (An interesting example of the technique is the measurement of deck deflections to an accuracy of $\pm$ 0.5 mm on the 253,000t supertanker Esso Northumbria, during trial loadings at sea.) For such applications higher light intensities are unnecessary and could present a hazard to the retina of the eye. Powers of 10-30 mW are often necessary, however, for light scattering techniques, such as laser photon-correlation, anemometry and spectroscopy (4). These methods essentially measure Doppler shifts by counting the time of arrival of individual photons in an appropriate detection system, which incorporates on-line digital data-correlation to extract the maximum information from the weakly scattered light. Flow velocities ranging from micrometres per minute to 500m s^{-1} can be routine measured to accuracies of order 1% in this way, whilst analysis of the Brownian motion of complex organic suspensions has permitted the determination of diffusion coefficients and molecular weights to similar accuracy in times of one minute and one hour respectively. It is obviously important that the laser light source used in such work be reasonably monochromatic (although the exact wavelength is arbitrary), in order that the frequency shift should be well defined. Many gas lasers (including, for example, the He-Ne and He-Cd lasers) satisfy this requirement of temporal coherence, and are therefore suitable for laser-Doppler work. Much higher powers are normally required to provide the adequate exposure needed for holographic applications, particularly when time-varying interferograms are required, and so the long coherence length and compactness available from ruby lasers make them a convenient (but not unique) source for such work.

Pollution Monitoring

Remote measurements by laser radar (LIDAR) of stack plume velocities at power stations, etc. are now becoming almost routine (5). When localised samples are available, e.g. for on-line pollution monitoring in factory environments, acousto-optic ('spectraphone') techniques provide very high sensitivities (6); for example, the CO_2 (λ = 10.5321 μm) and CO (λ = 6.1493 μm) gas laser lines have been used to detect ethylene (0.0002 ppm) and NH_3 (0.0004 ppm) respectively. Tunable systems such as $Pb_{0.88}Sn_{0.12}Te$ diode lasers, permit absorption measurements with sensitivities of $\lesssim$ 1 ppm (2).

Thermo-mechanical Materials Processing

For many engineering applications one is not particularly interested in the precise wavelength or band width of the laser; what matters is the total power absorbed (at least 1-2 kW for welding steels a few mm thick) and the intensity distribution/dwell time of that power, cf Fig. 1. Phase-transformation hardening, surface alloying, deep-penetration welding and drilling by laser have already been discussed in various reviews (3,7,8); the subject of 'splat-quenching', or 'laser-glazing' is perhaps less familiar. By traversing laser beams focused to intensities of $10^4 \sim 10^7$ W/cm^2 across metallic alloys, it is possible to melt a thin surface layer, which then cools rapidly (by conduction to its substrate) at rates averaging some $10^5 \sim 10^{10}$K s^{-1}. Liquid metals are usually homogeneous; the ultra-fast cooling should ensure that segregation and phase-separation during solidification is very fine-scale, so that grain sizes, etc. are refined. Moreover, metastable structures and glassy-phases may be formed, so that unusual properties can be 'engineered'. Splat-quenched alloys exhibiting enhanced hardness, fatigue life, seawater corrosion-resistance, abrasion resistance, novel magnetic properties, etc. have been described (9).

Intense shock waves can also harden and strengthen metallic alloys and improve their resistance to stress corrosion and fatigue. It has recently been shown that stress waves of sufficiently high amplitude can be generated in solids using pulsed high energy lasers. In particular, Clauer et al (10) have investigated potential applications for the hardening of stainless steels, weld homogenization in aluminium alloys, etc., etc.

Photochemistry and Isotope Separation

Laser photochemistry is discussed in reference (11); some possible laser requirements for isotopic separation of atomic uranium have been summarized by George and Krupke (12), and for molecular UF_6 by O'Hair and Piltch (13). Higher mean and peak powers than are available from existing narrow-band tunable-sources (such as ir laser diodes, for example) are required for bulk demonstration of photochemical or isotope-separation techniques. Fortunately a very wide range of uv, visible and near ir wavelengths can be conveniently selected and generated using diffraction-grating or other wavelength-specific optical cavity elements in conjunction with wide-bandwidth dyes and appropriate optical-pumping devices (argon-ion, Cu-vapour lasers, etc.). In this way, wavelengths over the range 275-300 nm, and continuously from 400 ~ 1000 nm, can be generated using a variety of commercial (14) devices; pulsed output powers of order 1W are typical. Using wide-band optical feed-back loops, cw dye-laser frequency-jitter can be reduced to ~ 60 kHz (RMS), and in ion-lasers to $\lesssim$ 10 kHz (15). In the 'wavelength gaps' one is forced to either

(a) specially develop fully tunable sources such as multi-atmosphere (pressure-broadened) gas lasers, non-linear optical-parametric-oscillator/mixers (16) etc., etc., or

(b) search for chance coincidences between narrow laser lines (such as those emitted by low-pressure ir gas lasers) and the wavelengths of specific interest and/or

(c) frequency shift suitable laser-lines to full coincidence.

Thermonuclear Fusion

Monochromatic lasers are particularly useful for making non-perturbing interferometric and scattering measurements on plasmas. For both applications the high spectral brightness helps to discriminate against background light emitted from the plasma. For time-resolved measurements incident powers typically $\gtrsim$ 1 MW are required to produce statistically-significant scatter-signals, and ruby lasers have therefore been traditionally used for Thomson-scattering diagnostics (17). Recently, however, powerful submillimetre gas-lasers have been developed to provide a closer wavelength match between the diagnostic beam and the Debye length of the hot tenuous, Tokamak plasmas of current interest (18), thus facilitating measurements of co-operative (as distinct from free-electron) scattering in such plasmas.

At higher plasma densities and laser intensities, efficient heating of isolated solid-state targets is also possible. The resulting plasmas may simply be used for filling (magnetic) toroidal-confinement devices such as Stellarators (19), or by suitably symmetric (eg spherical) illumination may be used to isentropically compress DT fuel at the centre of the target. The latter approach has been shown to generate measurable thermonuclear burn in the compressed core (20) during the inertially-confined micro-explosion which follows heating of the DT to temperatures of a few keV (with consequent ignition). Whilst laser-filling experiments may provide an interesting alternative to electrical-discharge heating within a gas-filled torus and neutral atom injection, etc., the reactor prospects for such an approach are clearly governed by the effectiveness of the magnetic confinement and related engineering consequences (divertors, superconducting coils outside T breeding blanket, relatively large modular size, servicing access in toroidal topology, etc.). Many of these engineering constraints are different in conceptual inertial-confinement reactor scenarios (21,22), but nevertheless they may prove to be quite demanding. Illustrative problems for laser-fusion are the design of the high-mean-power, high-peak-power, optical (or aerodynamic) window, and the long-term reliability and capital cost of the pulsed laser power supply (21). At present, however, the prime challenge lies in the physics; can the target gain A (thermonuclear energy out/laser energy incident on target) be proved experimentally to approach the values of 100-1000 which have been discussed theoretically (23,24), and will the efficiency η (focusable energy from laser/pumping energy in) of the associated 1 MJ, ~ 100 TW driver be sufficiently high for the product Aη to approach values $\gtrsim$ 10 which are of civil reactor interest (24,21)? For economic power generation it is the optimisation of (Aη) against available laser wavelengths, pulse-shapes and feasible target designs that is important. It should be remarked particularly that wavelength optimization of A by computer-modelling is not a simple issue, since an accurate description of highly non-linear laser-plasma interactions is required; recent experiments have shown that the behaviour of targets irradiated at ~ 10^{15}W cm^{-2} by λ = 1 and 10 μm radiation is remarkably similar (25), due to intensity-dependent density profile modifications in the corona (26-28). This result is encouraging for the CO_2 gas laser, and should have important consequences in the evaluation of alternative 'Brand X' fusion drivers.

LASER TRENDS

Space does not permit an extensive treatment of the way in which these various applications influence laser design; however, some general trends can be illustrated. Firstly, for many actual and potential uses (such as industrial heat-treatment of metals using multi-kilowatt CO_2 lasers, bulk photochemical processes, possible laser-fusion reactors) a high mean-power requirement will imply a significant waste-heat removal problem. This is normally solved by employing a gaseous laser medium, with forced convection through the optical cavity/pump region and subsequent cooling in heat exchangers before recirculation, as illustrated schematically in Fig.2. Secondly, for economic (bulk) applications the efficiency of the laser is usually very important - as we have seen in our discussion of inertial - confinement fusion (ICF) driver requirements. Table 2 summarizes the present state, and typical efficiencies of some ICF drivers in the USA. (Planned performance is given in parentheses. It should be noted that the associated DoE budget is of order $130M pa, compared to their CTR budget of ~ $400M pa.)

The relatively high efficiency of the CO_2 laser over optical energy-extraction times of 1 ns - 1 μs (19) makes it not only very attractive for present laser-filling experiments (where, for example, the discharge-efficiency of the Culham TROJAN laser is $\lesssim$ 20%), and potentially for laser-fusion, but also as a pump to generate alternative wavelengths for diagnostic lasers or photochemical applications. Some typical CO_2 laser-pumped line-tunable systems at Culham are listed in Table 3; other pump-lasers are also finding similar application - for example an HBr chemical laser having an (electrical-initiation) efficiency $\gtrsim$ 0.5% and a 4 μm output $\gtrsim$ 0.2J is now being operated routinely at a repetition rate of 1 Hz (29).

CONCLUSIONS

Gas-discharges play an important role, directly or indirectly, in the operation of most lasers. This role is particularly obvious in the relatively-efficient

electrically-excited CO_2 laser, which is finding increasing use in laser-machining, laser-plasma filling experiments, and as pumps, etc. for other laser systems. Its proven ability to operate at high peak intensities, at peak powers $\gtrsim 10^{13}$ W, at high mean-powers, and at 'wall-plug' efficiencies which range between 1.5 and $\sim$ 15% depending on pulse duration, etc. make this a potentially promising candidate for laser-fusion demonstration and possible ICF reactor application. For this application its efficiency is at present unique, although longer-pulse discharge-efficiencies of 40-60% have been reported for 5-6 μm CO systems, and efficiencies of a few per cent are now relatively common for pulsed visible (Cu) and excimer (uv) lasers respectively. We may therefore expect gas-discharge physics (and related engineering developments) to play a continuing role in the increasingly rapid evolution of high-power lasers and their applications.

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TABLE 1 - Operational characteristics required for some actual (and potential) laser applications

Application	Typical λ (μm)	Spatial Mode Control?	Narrow Line Width?	Tunable λ?	High Peak Power (W)	Mean Power (W)	Temporal Pulse Shaping?	Typical Efficiency %
INDUSTRIAL								
Fibreoptic communications*	0.82 (LED)	√	X	X	X	5×10^{-3}	$\sim 10^{-9}$ s	0.5
Alignment	0.63 (He-Ne)	√	X	X	X	X	CW	Low
Holography	0.69 (Ruby)	√	√	X	$\sim 10^{7}$	X	$< 10^{-7}$ s	"
Raman Scattering	Argon/N_2 etc.	√	√	Preferably	?	√	X	"
Doppler Velocimeters	0.63, 10.6	√	√	X	X	X	CW	"
Pollution Monitoring	CO_2/CO/Dye/Diode	√	√	Preferably	X	$> 10^{-6}$	X	
Materials Processing								
Transformation Hardening	CO_2 (10.6)	Preferably	X	X	X	√	CW	4-10
Cutting	CO_2/Argon/Xe/NdYAG	√	X	X	X	40W to > 20kW	CW	NdYAG $\lesssim$ 3
Welding/Laser Glazing	CO_2/NdYAG (1.06)	√	X	X	X	40W to ~ 20kW	X	-
Drilling	CO_2/Argon/NdYAG/Ruby	√	X	X	√	?	?	-
Shock Hardening	Nd/glass	√	X	X	$\sim 10^{9}$	√	√	0.1
PHOTOCHEMISTRY	UV → IR	?	√	√	Sometimes	√ (for bulk)	X	-
ISOTOPE SEPARATION	UV → IR	?	Essential	√	Sometimes	? (" ")	X	1?
THERMONUCLEAR FUSION								
Diagnostics	1 nm - 1 mm	√	√	√	√	X	X	-
Heating (Magnetic Confinement)	$\gtrsim$ 10 μm	Preferably	?	?	√	X	Possibly	$\gtrsim$ 10
Inertial Confinement	0.1 μm < λ $\lesssim$ 10 μm	Essential	Control important	X	$\sim 10^{14}$	~ 10-50 MW for reactor √	Essential $(10^{-10}-10^{-8}$ s)	$\gtrsim$ (1-10)

* Eg. 140 Megabit/s optical telephone link - Ref.(30).

TABLE 2 - Actual (and planned) performance of ICF drivers in the USA

Name	EBS	Argus	Shiva	Shiva-Nova	Antares	Proto II	EBFA 1
Laboratory	LASL	LLL	LLL	LLL	LASL	Sandia	Sandia
Driver	CO_2	Nd	Nd	Nd	CO_2	eb	eb
Power (TW)	3, 16,* (20)	4.6	1.8, 10,+ (30)	(200-300)	(100-200)	8-3.5	(30)
Pulse (ns)	0.4-1	0.1	0.1-1	0.1-3	(1-0.25)	22-90	45
Energy (kJ)	1.2, 8,* (10)	2	0.18, 10+ (10)	(200-300)	(100-50)	-	(1000)
No. beams	1, 8,* (8)	2	1, 20,+ (20)	40	6 x 12	2	36
Cost FY76 $M	5?	~ 3	~ 19	(< 195?)	(< 54?)	-	(8)
Op. date	1978	1977	1977-1978	1984?	1983?	1977	1980?
η driver	1.5%*	-	0.04%	-	2%*	~ 50%	~ 50%

* Not yet fully optimized. Efficiencies of 3 ~ 15% in principle achieveable by more sophisticated engineering and multi-passing optical pulses at 1/10 μs.

+ Not yet fully optimized.

TABLE 3(a) - Mid-infrared output from Culham OPML

Gas	$^{12}C^{16}O_2$ (9 μm) Pump	ν (cm^{-1})	O/P Energy (mJ)	λ (μm)	Notes
$^{16}O^{12}C^{32}S$	P (22)	524.7		19.06	Ref.34 (cf Schlossberg & Fetterman, Ref.35)
"	P (22)	526.9	0.60	18.98	Green (Refs.31 and 34)
$^{12}C_2D_2$	R (14)	489.2		20.44	NEW LASER, Rutt and Green Ref.32:(h)
"	R (12)	499.7	2	20.01	" (c)
"	R (20)	508.4		19.67	" (c)
"	P (38)	518.9		19.27	" (d)
"	P (36)	520.7		19.20	" (c)
"	P (26)	522.7		19.13	" (e)
"	P (38)	525.6		19.03	" (f)
"	P (26)	527.1		18.97	" (g)
"	P (24)	527.4		18.96	" (c)
"	P (24)	530.6		18.85	" (c)
"	P (38)	532.2		18.79	" (f)
"	R (14)	535.7		18.67	" (h)
"	R (12)	562.6		17.77	" (c)
"	R (20)	567.8		17.61	" (c)
"	R (14)	573.1		17.45	" (h)
$^{12}CF_4$	R (12)	615.07	1.2	16.258	Ref.31 (cf Tiee and Wittig, Ref.36)
$^{14}NH_3$	R (16)	780.6		12.81	Green and Rutt (see also Chang and McGee, Ref.37)
"	R (30)	828.5		12.07	Green and Rutt (private communication)

Notes References 32 and 33 discuss the following transitions: (c) $\nu_5 + \nu_4 \to \nu_4$, (d) $2\nu_5 + \nu_4 \to \nu_5 + \nu_4$, (e) $2\nu_5 + \nu_4 \to 2\nu_4$, (f) $2\nu_4 + \nu_5 \to \nu_5 + \nu_4$, (g) $2\nu_4 + \nu_5 \to 2\nu_4$, (h) hot band?

TABLE 3(b) - Summary of far-ir CO_2-pumped diagnostic lasers at Culham (Ref.18)

Gas	λ (μm)	P_{av} (MW)	P_{peak} (MW)	Bandwidth (MHz)
CH_3F	496	0.25		55
		0.7	~ 1.0	> 200
D_2O	385	1.5	4.5	
	94/114	4.8	12 (25)	> 200
	66	6.6	15 (45)	

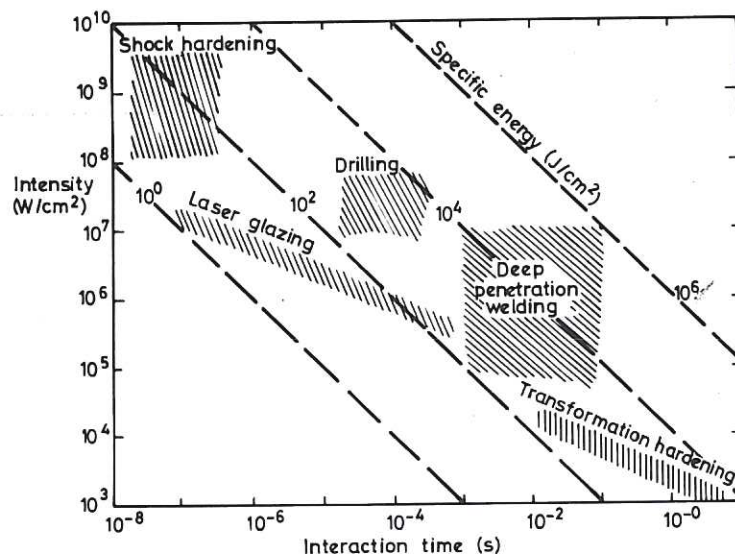NB Numbers in brackets are corrected for attenuation in TPX window.

Figure 1 Typical CO_2 laser intensities and dwell-times for
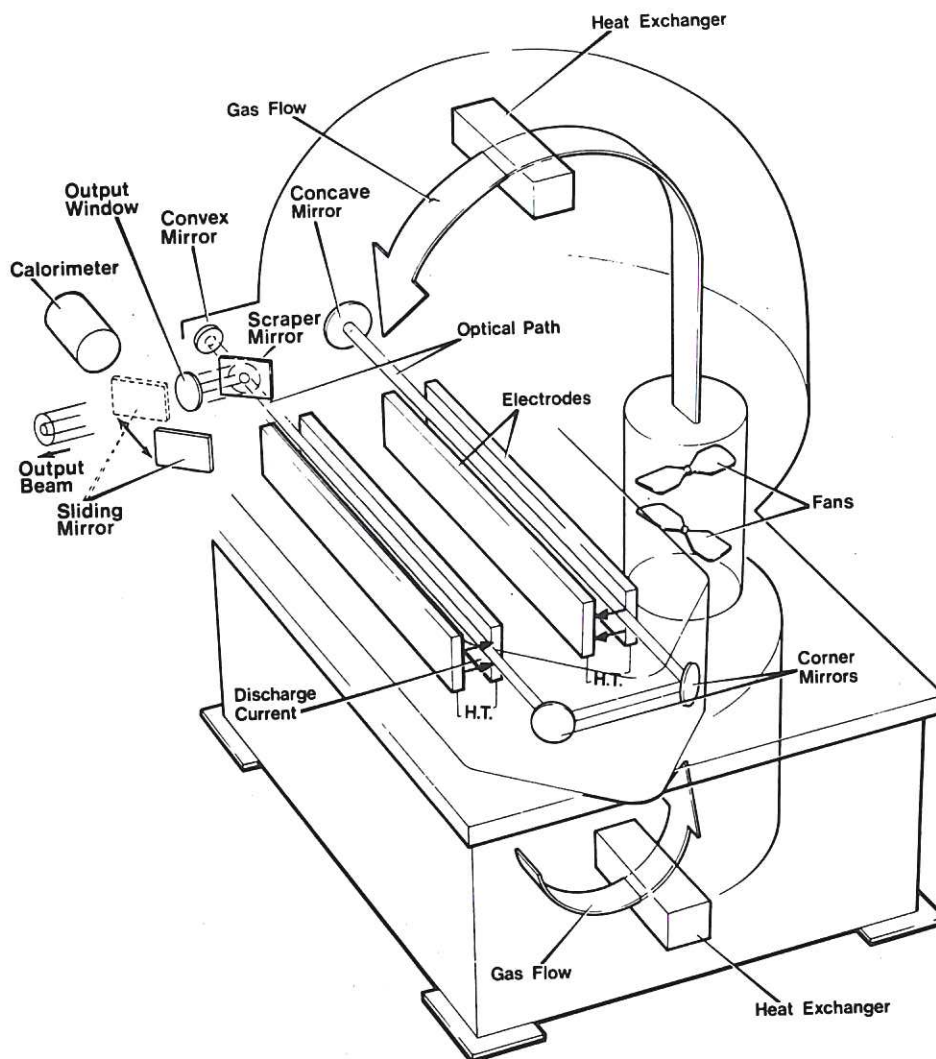materials-processing (after Ref.7)

Figure 2 Diagram of Culham's Fast Transverse Flow CO_2 Laser, CL5

Output power: 5 kW	Power Supply: 75 kVA at 415 volts AC
Head Dimensions: 1.6m x 1.4 x 2.0m high	Gas Consumption: 150 l/hour
Head Weight: Approximately 2.0 Tonnes	Cooling Water: 3,000 l/hour – 15°C
	(70 kW Power Dissipation)