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High-power neodymium glass laser systems for fusion research

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One of the key issues of scientific feasibility experiments for fusion research is to construct a laser energy driver delivering enough output power for implosion. We have constructed a series of glass laser systems: Gekko II silicate glass laser (two-beam), 0.4 TW, Gekko IV phosphate glass laser (four-beam), 4 TW, and modules of Gekko XII, which will achieve 40 TW at full size.

Laser glass is critical for delivering a large amount of power in a short duration without deterioration of the beam quality. Phosphate and fluorophosphate glasses have been investigated for an advanced laser design. Optical components have been developed which are expected to be very reliable. A system performance of lasers is also very important for experimental work.

1. INTRODUCTION

The main purpose of I.L.E. at Osaka University is to prove the scientific feasibility of inertial confinement fusion. Project 'Kongoh', aiming at fusion breakeven, has been scheduled, and is composed of two programmes. The main programme, 'Gekko', has three glass laser systems to carry out fusion research.

The Gekko II system has been in operation since 1975. It is a two-beam silicate glass laser system. The output power is 0.4 TW at 50 ps, which is mainly used for laser–plasma interaction experiments and the development of diagnostics.

The Gekko IV system has been in operation since 1978. It is the world's largest phosphate glass laser of four beams and can deliver 4 TW at 100 ps and 2 kJ in 1 ns.

Tetragonal irradiation of a pellet target is adopted for the four-beam system. The Gekko IV system, together with the irradiation facility and a target chamber, are automated by computer Okitac-50 for implosion experiments.

One beam of Gekko XII is to be constructed in 1979 fiscal year. It is designed to deliver 2 TW at 100 ps, 2 kJ in 1 ns per beam. The total system of twelve beams will be completed during 1980–2.

With Gekko II, multilayer targets have been irradiated to study energy transport, density profiles and the reflexion and absorption of laser light. X-ray shadowgraphy and image processing techniques have been developed. By using Gekko IV, glass microballoons containing D_2 gas at 15 atm (*ca.* 1.5 MPa) have been imploded. A compression ratio of 200 was measured and a neutron yield of 10^7. The X-ray spectrum of a neon-filled glass microballoon gives the parameters of the plasma core to be $\rho = 5\ \mathrm{g/cm^3}$, $\rho R = 3 \times 10^{-3}\ \mathrm{g/cm^2}$.

The subsidiary programme contains two CO_2 laser systems.

Lekko II is a two-beam, multiline spectrum system yielding 1 kJ in 3 ns. It is mainly used for experiments on laser–plasma interactions.

Lekko VIII is an eight-beam system with an output of 10 kJ in 2 ns which will be completed by the end of 1980.

Comparing the experimental results at the two wavelengths of the glass and CO_2 lasers, we can establish conclusive information on laser plasma coupling.

2. GEKKO II SILICATE GLASS LASER

Gekko II is mainly used for plasma physics studies and diagnostics development. For various types of experiment, the Gekko II laser system was upgraded to deliver laser pulses with arbitrary duration of 60–1200 ps and with controlled pre-pulse levels from 10^{-6} to 10^{-7}. Clamshell illumination optics was introduced in a target chamber for spherical irradiation experiments.

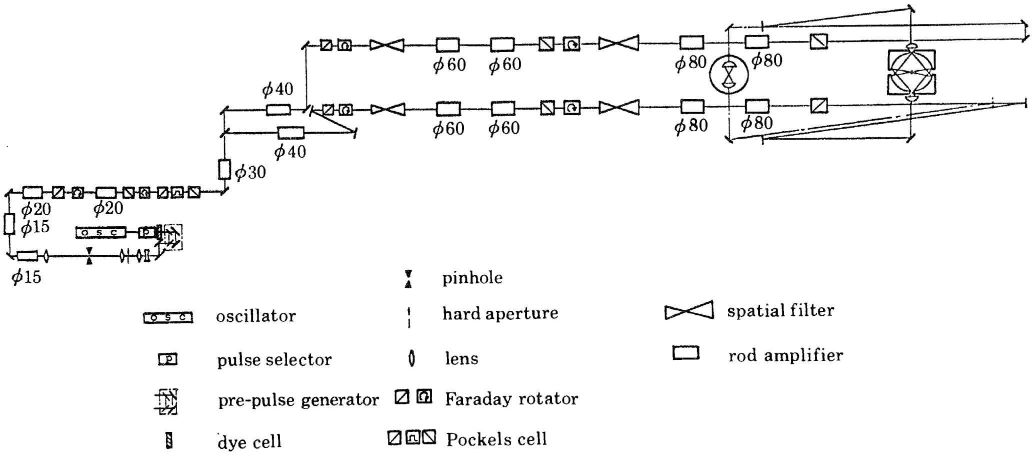


FIGURE 1. The Gekko II laser system.

Figure 1 shows a schematic diagram of Gekko II. To generate long pulses, the Nd:YAG oscillator is mode-locked with a Ni-complex saturable absorber and an acousto-optic modulator. The pulse duration is varied from 90 to 1200 ps with increasing thickness of etalons inside the resonator. For short pulse operation, the oscillator is mode-locked by a saturable dye, Kodak 9740, giving a pulse duration of 60–250 ps. A pre-pulse generator is placed after the pulse selector.

Image relay optics has been introduced. The laser beam from the oscillator is expanded and irradiates a hard aperture. The image of the hard aperture is formed in front of the first spatial filter by two relay lenses. A pinhole is set at the focal plane of the first relay lens. When the radius of the pinhole is 0.65 mm, which corresponds to transmitting the zeroth-order diffraction lobe, the beam pattern is nearly Gaussian. When no pinhole is used, Fresnel diffraction rings appear. Thus an optimum pinhole size exists to give a nearly rectangular beam intensity profile. In this system it is 1.2 mm in radius, which corresponds to transmitting the Fraunhofer diffraction rings up to the third order.

To minimize amplified spontaneous emission (a.s.e.), a Pockels cell with 25 mm clear aperture was introduced. A.s.e. energy entering the target chamber is less than 10 μJ/beam.

Thermal distortion of the laser rods limits the allowable time interval between shots. This time interval was measured by observing the distortion of the interference pattern of the laser output on a Zygo interferometer for different time intervals between two laser shots. Thermal distortion becomes negligible for an interval of about 15 min. The system is usually operated at about 400, 160 and 60 GW output powers in two beams, for short (*ca.* 60 ps), medium (*ca.* 250 ps) and long (*ca.* 1 ns) pulse experiments respectively.

3. GEKKO IV PHOSPHATE GLASS LASER

(*a*) *Overview*

The Gekko IV laser fusion facility consists of a four-beam glass laser system, a target chamber and a system controller. The layout of the whole system is shown in figure 2. It took approximately 2½ years from the start of the system design to the first shot on target with four beams. Major efforts taken to develop this facility are summarized in table 1.

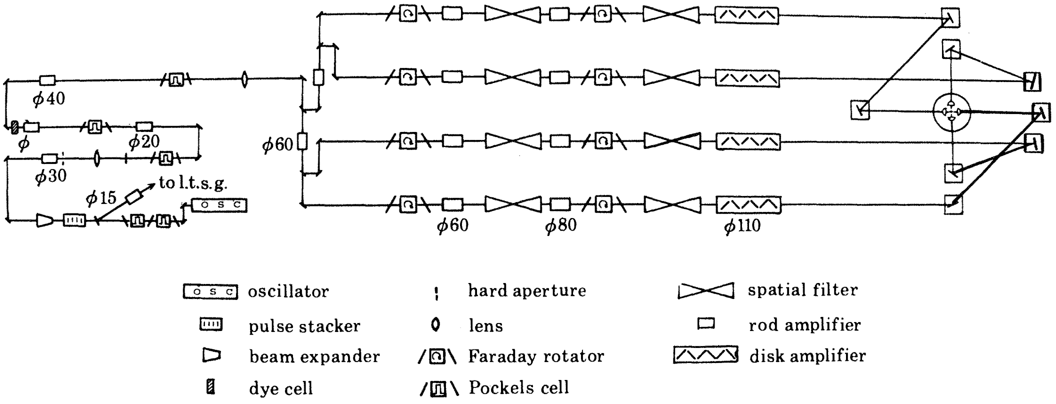


FIGURE 2. Layout of Gekko IV laser fusion facility.

TABLE 1. MAJOR WORK CARRIED OUT FOR DEVELOPMENT OF GEKKO IV

laser system

1. stable mode-locking of a phosphate type oscillator
2. reliable pulse selection from a mode-locked pulse train
3. reliability improvements of flashlamps
4. reliability improvements of dielectric coatings
5. development of high and uniform gain rod amplifiers
6. introduction and improvements of high performance disk amplifier
7. establishment of disk amplifier assembly procedures in clean environment
8. development of reliable power conditioning units
9. development and testing of vacuum spatial filter and Faraday rotator
10. reduction of pre-pulse and amplified spontaneous emission
11. simplifying alignment procedures
12. simulation of laser beam propagation

target chamber area

1. development of high precision target chamber and mirror gimbals
2. interfacing these hardwares to computer

computer control system

1. development of noise-resistant control networks
2. introduction of central control system which monitors, operates and processes all the facility and experimental procedures

The main objective was to develop a high-power, short-pulse glass laser system to obtain highest neutron yield with exploding pusher type targets. For this purpose, phosphate laser glass developed in 1977 by Hoya Glass Works was chosen as the amplifying medium. This choice, with proper system design, has resulted in a laser system delivering an output power of 4 TW, which is almost twice the original design goal.

Symmetrical target irradiation optics with four laser beams was adopted. Although irradiation uniformity is not so essential with exploding pusher-type targets, it will become important for ablative compression experiments.

A computer is used to control the system and also to store and analyse various laser–plasma data. Although it took a few months to make this system work properly, it turned out that computer control is essential for reliable operation of this complex, multi-component laser system and also for performing laser–plasma experiments with a minimum number of people.

The following sections will describe the configuration and performance of the laser system, target chamber area, and computer control. Also component development and testing will be summarized.

TABLE 2. MONITORING STATIONS FOR ROUTINE CHECKING OF THE LASER SYSTEM PERFORMANCE

checking item	*detector*	*location*
mode-locking	photodiode	oscillator
pulse selection	photodiode	pulse selector
pulse width	streak camera	preamplification stage
pre-pulse	photodiode	beam dividing stage
amplification	calorimeters	beam dividing stage
output energy	calorimeters	entrance to the target chamber
intensity distribution on the target	t.v. cameras	entrance to the target chamber
reflected energy	calorimeters	entrance to the target chamber

(*b*) *Laser system*

The Gekko IV laser room is designed for constant temperature, high cleanliness and vibration isolation. The whole laser system is covered with a dust shield, which also prevents wavefront distortion due to air flow.

The laser system consists of rod amplifiers up to the aperture of 8 cm diameter and a disk amplifier of 11 cm clear aperture. Two Faraday rotators and two vacuum spatial filters are used in each beam. Two Pockels cells in the preamplification stage reduce pre-pulse and amplified spontaneous emission. Another Pockels cell is placed after the 40 mm rod amplifier. Image relay optics are arranged for uniform intensity distribution at the final amplifier.

To characterize the system performance during target irradiation experiments, various parameters are monitored in each laser shot. Table 2 lists these parameters and monitoring stations to fully characterize four laser output beams.

One week in each month is used to maintain and improve the laser system. During this week, the laser system is rearranged for better operation, new components are tested in the system, disk amplifiers are cleaned, and so on. The rest of the month is used for target irradiation experiments. On these days approximately 3 hours per day are used to align and check the performance of the laser system. Target installation and alignment on target takes another 2 h. The cycle time of the laser system, which is determined by cooling time, is approximately

30 min. The shot interval for plasma experiments varies from 30 min to 2 h depending on the complexity of diagnostic equipment.

(i) *Oscillator and preamplifier*

The oscillator and preamplifier stage are shown schematically in figure 3. A single pulse is switched out of the pulse train from the mode-locked oscillator. At the pulse stacker this single pulse is shaped into a composite structure for shaped pulse experiments. This shaped pulse is amplified with four rod preamplifiers of 15–40 mm diameter. For isolation between amplifiers and elimination of prepulses, a dye cell and two Pockels cells of 6.5 and 25 mm aperatures are used. These Pockels cells are switched by avalanche photodiode and krytron units.

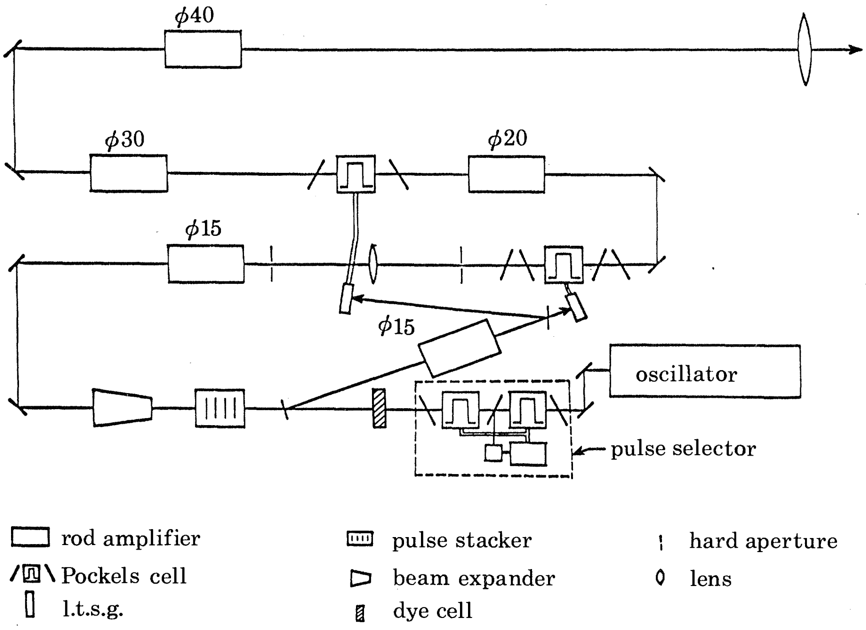


FIGURE 3. Detailed layout of the oscillator and preamplifier stage.

We use phosphate glass and a YLF oscillator mode-locked with an acousto-optic modulator and a saturable dye absorber. The generated pulse width, which is controlled by etalons in the cavity, is 10–600 ps. The output energy variation is less than 10% and the pulse width reproducibility is 20%.

The pulse selector consists of double Pockels cells and a krytron high voltage switch. By careful wiring to produce a rectangular output waveform, high reproducibility of pulse selection has been obtained.

Figure 4 is a schematic diagram of the pulse stacker that we designed. This pulse stacker has the following advantages: (1) alignment is very easy; (2) it has almost 100% efficiency; (3) because each individual pulse is reflected only once, the angular error is small.

(ii) *Rod amplifiers*

The diameters of the Gekko IV rod amplifiers vary from 15 to 80 mm.

We have tested various configurations of rod amplifiers to achieve reliable performance with high and uniform gain. In particular, we have studied the following aspects by using 60 mm rod amplifiers:

(1) laser glass: LSG-91H, LHG-5, LHG-7 and LHG-8
(2) thermal effects: birefringence
(3) parasitic oscillation and amplified spontaneous emission
(4) pumping configuration.

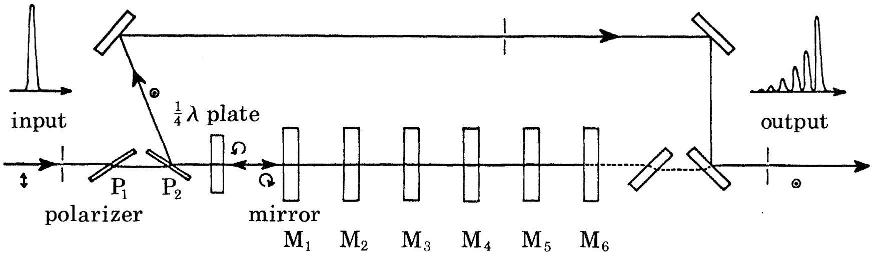


FIGURE 4. Schematic layout of the pulse stacker.

The pumping configuration is very important for high and uniform gain. We have simulated the pumping configuration by ray tracing method. The parameters varied in this simulation are: shape and reflectance of flashlamp reflectors; number, diameter and positions of flashlamps; material and Nd-doping of laser glasses and others. Comparisons between calculation and experimental results show that our simulations for pumping configurations are in good agreement with the experimental results. For example, we can expect that the optimum Nd-doping for 60 mm rods of phosphate glass is 0.7 % by mass. For this amplifier we have obtained uniform gain distributions and an αD product of 0.54.

We can extend the present results to other types of rod amplifiers.

(iii) *Disk amplifiers*

For the final stage amplifier of Gekko IV, we have developed a disk amplifier of 110 mm clear aperture.

To improve further the performance of disk amplifiers, we have evaluated the following technical items:

(1) cleanliness: assembly procedure and structure
(2) pumping configuration: efficiency
(3) edge coating glass: BSDL-6, BSDL-7, DCP-7
(4) thermal effects: wavefront distortion.

We have measured the amplification properties of LSG-91H with BSDL-6, LHG-5 with BSDL-7, and LHG-7 with ECP-7. Results for the 110 mm disk amplifier are shown in figure 5, where the gain coefficient of LHG-7, which is higher than that of LSG-91H and LHG-5, shows a gradual saturation at above 10 % cm^{-1} corresponding to an αD product of 2.3. But it did not reach complete saturation within the limits of our experiment. This improvement of performance results from the improved edge coating glass ECP-7.

Wavefront distortions of a disk amplifier have been observed after pumping at full input energy. Interferograms of an assembled 110 mm disk amplifier in double pass at 0.6328 μm were recorded. The wavefront distortion recovered to less than $\frac{1}{4}\lambda$ at 1.06 μm within 15 min. Therefore, maximum repetition rate of the disk amplifier is one shot every 30 min.

As a whole, the performance of the disk amplifier exceeds the initial design value of Gekko IV. To improve further the performances of larger disk amplifiers, improved laser glasses, edge coating glasses and pumping configurations should be tested and evaluated.

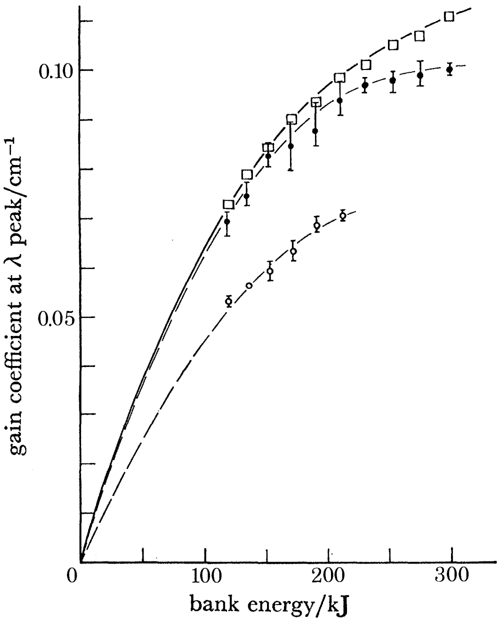


FIGURE 5. Gain coefficient of an 110 mm disk amplifier. □, LHG-7; ●, LHG-5; ○, LSG-91H.

(iv) *Amplification and beam breakup*

The performance of a glass laser system can be predicted well by computer simulation calculation of laser beam propagation. In our programme, the laser beam is propagated, starting at the preamplifier, through every optical element, down to the final amplifier. For each passage of an optical element, the spatial distribution of intensity and polarization is calculated as a function of time; the incremental and accumulated B-integral due to this element is also calculated. A two-level model is used to simulate the amplification property at various fluence levels. Birefringence of the pumped rod amplifiers due to elasto-optic effects is based on experimental data. Transmittance of a spatial filter depends on the accumulated B-integral value, which is a function of time. Fresnel diffraction effects are not taken into account in this calculation. This is justified as a first approximation, since the radial intensity distribution is fairly uniform due to adoption of the image relay configuration.

Laser system performance is evaluated by varying the peak intensity and pulse width of an initial pulse which is to be propagated. Figure 6 shows an example of radial and temporal intensity distributions during amplification stages at different pulse widths with the same initial peak intensity of 80 MW/cm^2. For a short pulse of 10 ps, radial intensity distribution becomes irregular because of the strong filtering effect of the second spatial filter in the chain near the peak of the temporal pulse shape. For a long pulse of 1 ns, spatial and temporal saturation effects are observed.

Figure 7 shows the focusable energy per beam calculated as a function of pulse widths. Also shown are near field patterns at different pulse widths and output energies. The strong irregular intensity non-uniformity at high intensities above the curve is due to small-scale self focusing

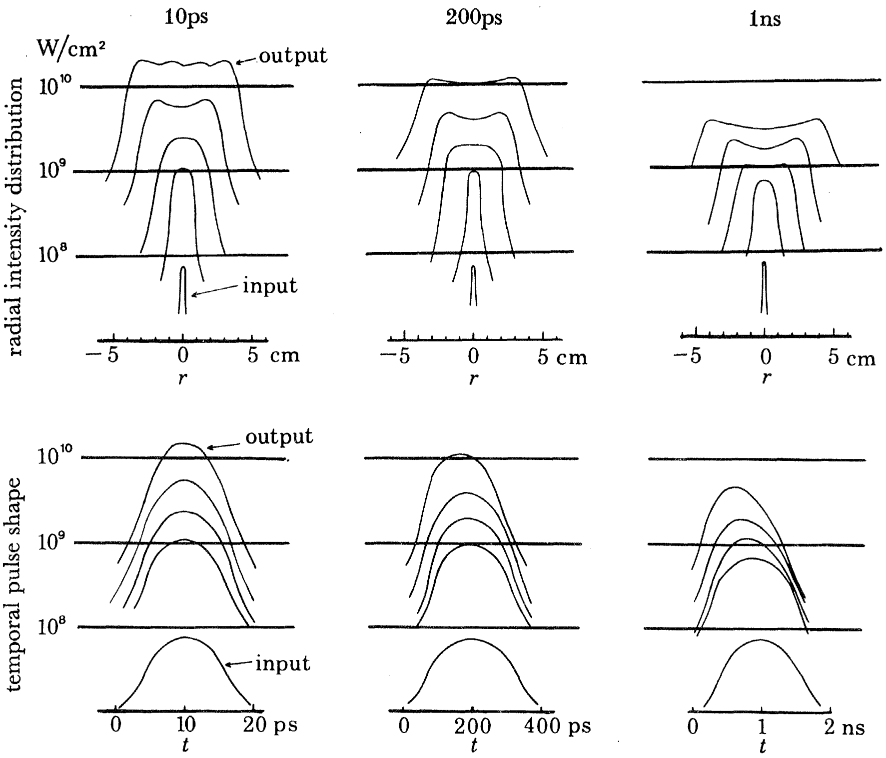


FIGURE 6. Evolution of the radial and temporal intensity distribution of a laser pulse from the input to the output of the amplifier chain at pulse widths of 10 ps, 200 ps and 1 ns.

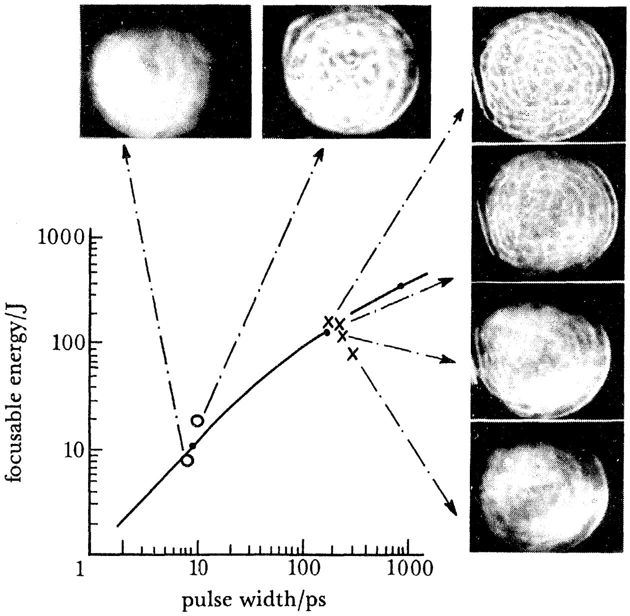


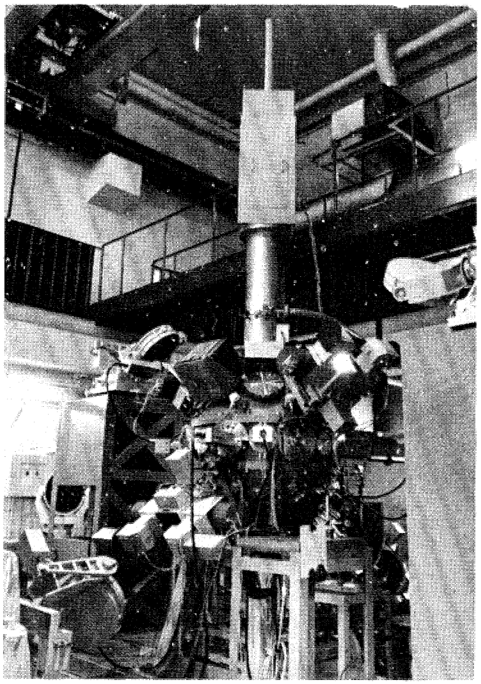
FIGURE 7. Calculated focusable output energy per beam as a function of pulse width. Also shown are near-field patterns of the laser output at different conditions.

(beam breakup). We can observe a strong correlation between observed intensity distributions and the calculated curve.

The divergence angle is 1.1×10^{-4} rad. Beam divergence increases slowly as the output power increases, and it becomes 0.19 mrad at the output power of 1 TW per beam. This divergence is still small enough for the laser beam to be focusable on a 50 μm diameter target. At this condition the peak intensity at the focal point of a 15 cm aspheric lens becomes 0.3 EW/cm² (3×10^{17} W/cm²).

(v) *Target chamber*

The target chamber area consists of eight turning mirrors and a target chamber with monitoring instruments. Each of the four laser output beams is reflected twice by totally reflective turning mirrors and enters a target chamber from one of the four vacuum ports which form a tetrahedron so that a target is symmetrically irradiated by four laser beams. A picture of the target chamber area with some plasma diagnostic equipment is shown in figure 8.



(vi) *Computer control*

To operate efficiently the Gekko IV system, a control system with a computer is essential. It has four functions: laser control and monitoring, target position control, experimental data acquisition, and data analysis.

Figure 9 shows a block diagram of the laser control and monitoring system. The functions of laser control are power conditioning, laser firing, and monitoring of the pre-shot and post-shot status of the laser system. The pre-shot monitoring checks the flow of water and nitrogen gas used for cooling the amplifiers, the charging status of laser power supply, and the vacuum of the spatial filters. If these monitors find any anomaly, the laser shot is stopped and capacitors discharged. The post-shot monitoring checks laser calorimeters for measuring laser energies at

15 different positions and pick-up coils for monitoring currents of all the flashlamp circuits. Results of these monitors are displayed on a graphic display console. All operations from charging to firing are commanded by the operator console.

A block diagram of the target control system is shown in figure 10. The target position is monitored by two orthogonally positioned vidicon telemicroscope viewing systems, having

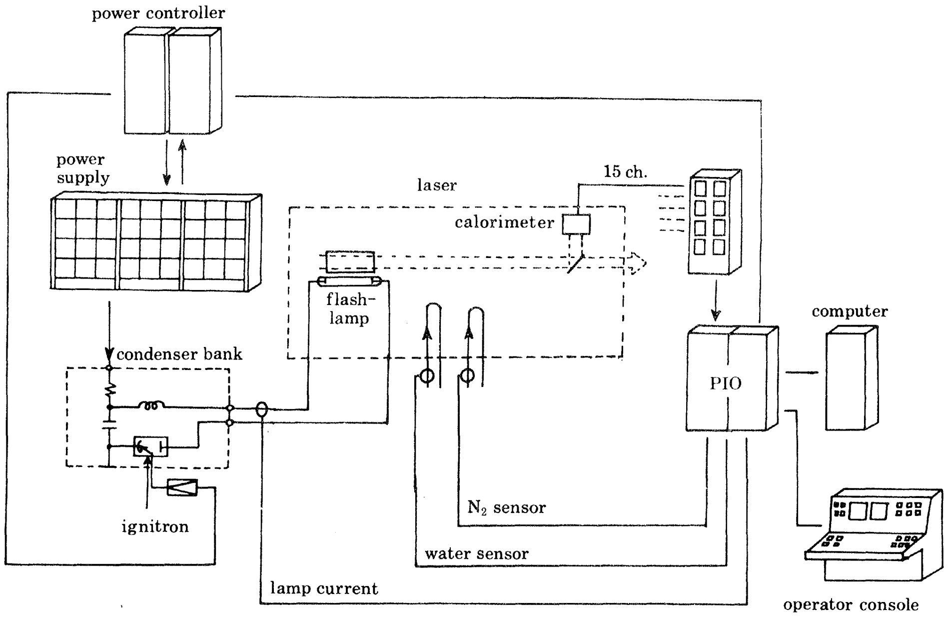


FIGURE 9. Block diagram for control and monitoring of the laser system.

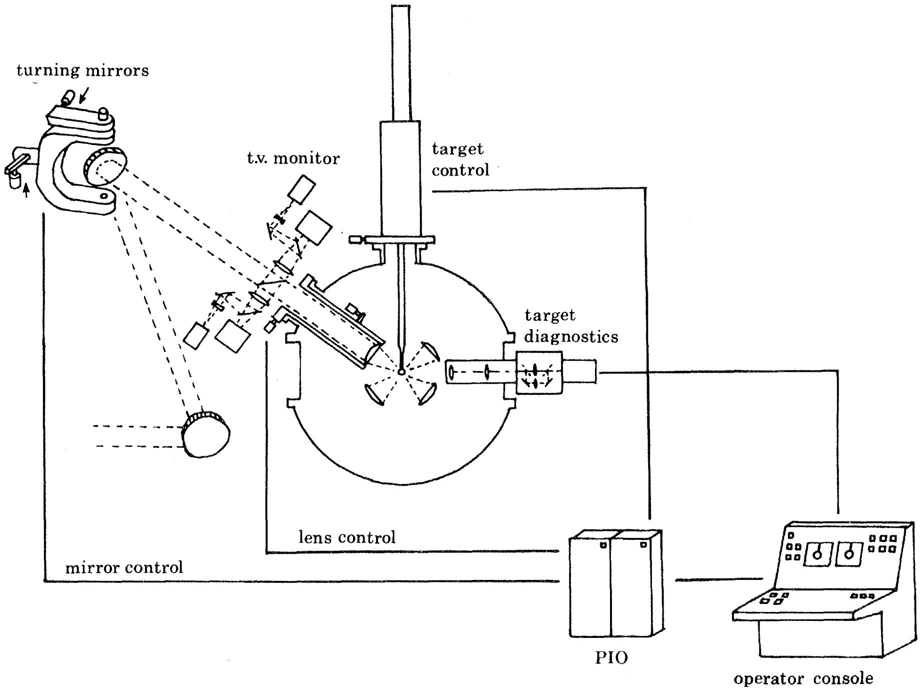


FIGURE 10. Block diagram of the target control system.

dual magnifications of 3 and 20. The image of the target is set automatically to a reference position with an accuracy of better than 2 μm.

Experimental data are collected on memory disks and magnetic tapes after each laser firing. Two-dimensional image information and time-resolved data are digitized and transferred to the computer in on-line mode. Some of the time-resolved data are transferred in off-line mode. Oscilloscope traces recorded on Polaroid film are read by a curve reader in off-line mode and transferred to the computer.

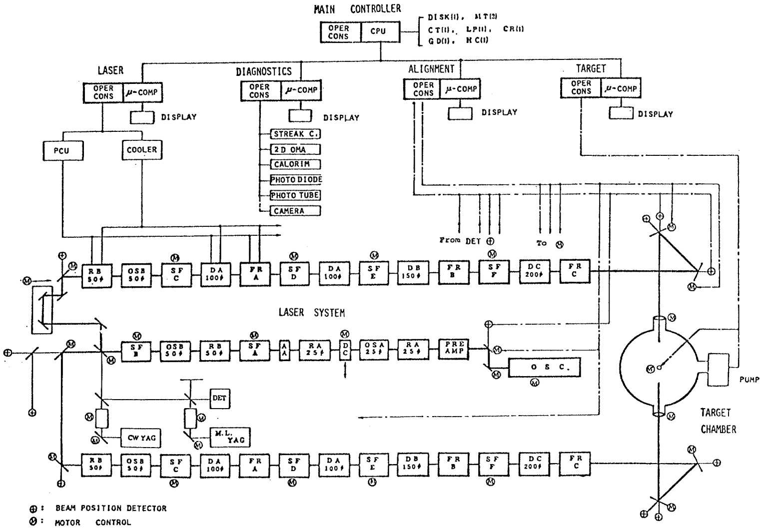


Figure 11. Gekko XII modules under development.

4. Gekko XII new glass laser

Gekko XII is a glass laser system to be used for isentropic compression experiments yielding pellet gains of over 1%. Projected performances of this laser system are maximum output energy of 20 kJ in 1 ns and peak focusable output power of 40 TW in 0.1 ns. Construction of this high output energy laser system with existing laser glasses will require the development of a very complicated multi-beam laser system. This complication will be reduced by using new laser glasses of lower nonlinear refractive index, which are being developed by laser glass manufacturers.

To establish basic techniques and knowledge required to construct Gekko XII on an engineering basis, preliminary studies were undertaken during 1977–9. This project is called Gekko XII Module (GXII-M) Development. To develop a reliable laser system, the following aspects are stressed in this programme.

1. A laser system is designed based on computer calculations that simulate system performance.
2. The performance of each laser component and the total system should be evaluated by constructing and testing a complete laser line.
3. To establish techniques for a multi-beam laser system, an automatic alignment system including synchronization of pulses on target should be constructed and tested with the two-beam laser system.

4. Computer command of the whole system should be established. Control modules for laser system, laser alignment, laser beam diagnostics, and target positioning should be developed and tested. Hardware and software for these modules should be easily expandable to Gekko XII.

The total system being developed and tested is shown schematically in figure 11. G XII-M consists of a laser system, automatic alignment system, laser beam diagnostic units, and a target chamber including target positioner. These are controlled by four independent controllers that are subject to the central main controller. Specifications of this system are given in table 3. The laser system, which uses phosphate laser glass, employs mostly disk amplifiers up to the final aperture of 20 cm diameter.

In 1977, sample modules of major components have been manufactured and tested. In 1978, the laser system was installed and tested at ILE Osaka University. The whole system was installed and tested in 1979.

TABLE 3. SPECIFICATIONS OF THE GEKKO XII MODULE

laser system	
1. Output power	2 TW/beam (0.1 ns)
2. Output energy	1 kJ/beam (1 ns)
3. Pulse width	100 ps to 2 ns
4. Pulse shaping	pulse stacker
5. Stability of output energy	$< \pm 10\,\%$
6. Background light	$< 100\ \mu\mathrm{J}/10^{-6}$ sr per beam
7. Wavefront distortion	linear $\frac{1}{2}\lambda$, nonlinear λ
8. Protection from reflexion	protected for 50 % reflexion
9. Repetition rate	< 30 min
alignment system	
1. Laser alignment	
centring	$< \pm 1$ mm
pointing	$< \pm 5$ s
2. Focusing optics	
centring	$< \pm 1$ mm; $< \pm 5\ \mu$m (on target)
pointing	$< \pm 1$ s
focusing	$< \pm 10\ \mu$m
3. Beam timing	$< \pm 10$ ps
laser beam diagnostics system	
1. Oscillator diagnostics	mode locking, pulse selection
2. Amplification property	energy measurements at 11 points
3. Output beam diagnostics package	8 items are measured
target irradiation system	
1. Target chamber	1200 mm i.d., 10^{-6} Torr
2. Target positioning	$\pm 5\ \mu$m, 16 targets selectable
3. Focusing lens	
x, y, movement precision	$< \pm 5\ \mu$m
z movement precision	$< \pm 10\ \mu$m
4. Turning mirrors	angular movement precision $< \pm 0.5$ s
system control	
1. Laser controller	automatic control or remote manual control selectable
2. Alignment controller	
3. Target controller	
4. Laser beam diagnostics controller	
5. Main controller	

5. SUMMARY

The present status of our glass laser programme may be summarized as follows.

1. We have developed a two-beam laser system, Gekko II, and a four-beam laser system, Gekko IV.

2. Various optical, electrical and mechanical problems related to these laser systems have been experienced and solved.

3. Basic techniques and knowledge required to construct a 20 kJ laser system, Gekko XII, are being developed on an engineering basis.

4. The performance of Gekko XII will depend greatly on component improvements, especially on laser glass and dielectric coatings as well as automatic control.

BIBLIOGRAPHY (Yamanaka)

Annual Progress Report on Laser Fusion Program nos ILEAPR-77 and ILEAPR-78. Institute of Laser Engineering, Osaka University.

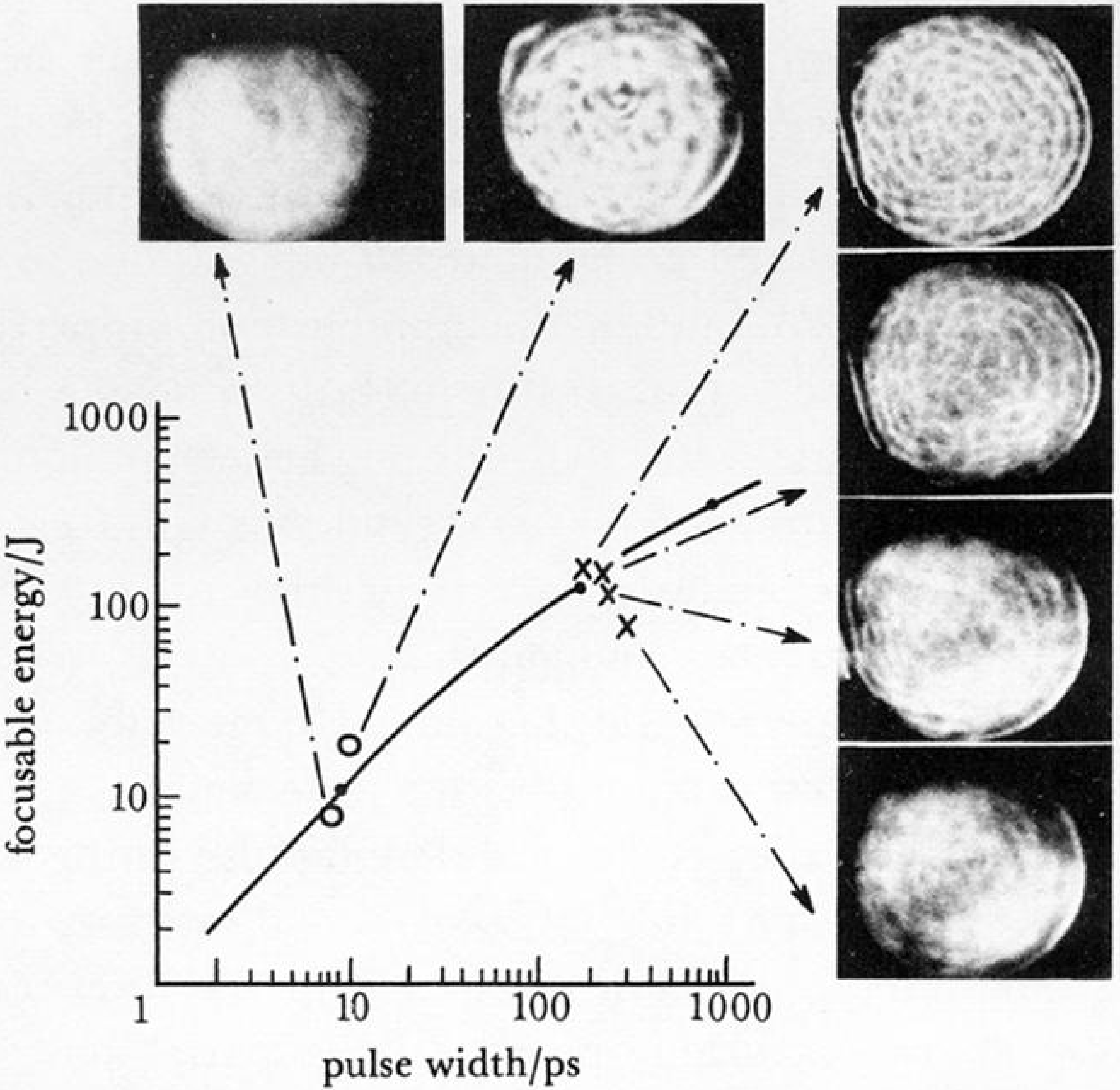


Figure 7. Calculated focusable output energy per beam as a function of pulse width. Also shown are near-field patterns of the laser output at different conditions.