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INVITED

REVIEW AND STATUS OF ANTARES*

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Abstract

The laser fusion effort at the Los Alamos Scientific Laboratory (LASL) has evolved from early experiments with an electron-beam-controlled large-aperture CO_2 laser to the massive engineering task of designing and building a 100-kJ laser fusion machine.

The design of Antares is based on the design of its predecessors. It builds upon technology which was developed or advanced during the design and construction of earlier machines. On one hand it is dictated by the requirements for the output, i.e., energy on target; on the other hand it is limited by existing technology or reasonable extensions thereof. Reliability and maintainability play important roles in the design considerations.

Introduction

The goal of the Laser Fusion program is to achieve inertially confined fusion for commercial and military applications. The high-power, short-pulse CO_2 laser developed at LASL lends itself very well to this task because of the high efficiency and capability to operate at high repetition rates. The 100-kJ Antares laser, the fourth step in the LASL development, is designed to provide this laser power for scientific breakeven experiments in 1984. This paper gives a brief overview of the evolution, design, and construction of Antares as a background for a number of detailed papers presented elsewhere at this conference.

Evolution

As we are gradually getting more used to the idea of very large CO_2 fusion lasers Antares becomes more tractable in its enormous size and complexity. Less than a decade ago the concept of such a large machine would have been unthinkable. However, development took place at a fast pace and what seemed to be an unlikely adventure then is now rapidly becoming a reality. The evolution began with the departure from the double-discharge laser.

The double-discharge laser is the kind of device upon which one would not hesitate to base the construction of a large reliable gas laser facility. It is simple, rugged, inexpensive, and easy to operate and maintain. Unfortunately, the laser energy output and the maximum aperture of a single cavity are relatively small. The size is limited by a gap-pressure product of about 20-cm-atmospheres compared to about 75-cm-atmospheres for an electron-beam sustained CO_2 laser.[1] By way of comparison, the Lumonics 620 can generate a short pulse of <100 J with an aperture of 10 x 10 cm. Translated into the energy requirement of 100 kJ for Antares, this would mean a system of 1000 beams and cavities. Such a large number of components and subsystems makes the facility reliability almost automatically questionable.

One way to overcome this problem and provide for a stable, large-aperture discharge is to feed an externally generated electron beam into the cavity. In this way, the generation of ionizing electrons and the control of their energy and density is separated from the parameters of the cavity. To build and operate such an electron-beam controlled CO_2 laser was successfully

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14. ABSTRACT

The laser fusion effort at the Los Alamos Scientific Laboratory (LASL) has evolved from early experiments with an electron-beam-controlled large-aperture CO 2 laser to the massive engineering task of designing and building a 100-kJ laser fusion machine. The design of Antares is based on the design of its predecessors. It builds upon technology which was developed or advanced during the design and construction of earlier machines. On one hand it is dictated by the requirements for the output, ioe., energy on target; on the other hand it is limited by existing technology or reasonable extensions thereof. Reliability and maintainability play important roles in the design considerations.

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attempted at AVCO and at LASL in 1970.[2] The success of this approach opened the door for the development of large-aperture, high-energy CO_2 lasers for commercial, military, and fusion applications. The number of cavities for a given requirement for total energy and beam size could be reduced considerably.

To initiate fusion experiments with a short-pulse CO_2 laser, a single-beam system was designed and built at LASL in 1971.[3] It employed for all its amplification stages, high-power electron-beam controlled discharge cavities (Fig. 1). Table I shows the characteristic features of that system.

The electron-gun energy was delivered by Marx generators which were allowed to RC decay. The pulse was terminated by diverter switches. The discharge chamber of the final amplification stage was powered by an LC generator with a diverter switch for pulse termination.

Based upon the experience with the low-energy single-beam system, a dual-beam module (Gemini) was designed and built in 1974.[4] The design of Gemini and, subsequently, Helios follows in principle the single-beam design. The main differences are found in the employment of one electron-beam gun for two pumping chambers, the triple passing of the gain region, and the larger aperture (14 inches vs 10 inches), Fig. 2. One of the major difficulties resulted from the use of a large-area hot cathode in the electron-beam gun. The large amount of heat deposited in the gun chamber and the thermal distortion of the cathode itself proved difficult to handle. The development and subsequent introduction of the cold cathode overcame all these problems.[5] The cold cathode employs an arrangement of thin tantalum foils which, upon ignition, generate plasma sites that, in turn, serve as electron emitters. Performance data of Gemini are listed in Table II.

To generate a 10-kJ laser pulse, four dual-beam modules were combined into an eight-beam system, Helios (Fig. 3). Helios became operational in April 1978 and delivered a subnanosecond pulse of 10.7 kJ into a calorimeter in June 1978.[6]

The electron guns for Gemini and Helios were also driven by Marx generators with diverter switches. The discharge chambers for Gemini were powered by LC generators with diverter switches; those for Helios by Marx generators employing two-mesh type-C PFN's in each stage.

Antares Design

Requirements. Whereas the single-beam facility, Gemini, and Helios were designed for absorption and compression experiments, the goal for Antares is to achieve breakeven, i.e., the energy production of the target should equal or exceed the energy input to the target. Antares is designed to produce various pulse durations and output powers, ranging from a power of 100 TW with a pulse width of 1 ns to a power of 200 TW with a pulse width of 1/4 ns.[7] To achieve this and also leave room for considerable uncertainties in the expected performance the Antares design allows for good margins in the critical areas. Table III is a summary of the performance requirements and design margins for Antares.

The design of Antares departs from that of its predecessors. The large number of beams (72) called for "electron-beam gun economy." Thus, 12 beams were combined in an annulus around a single electron gun to form a 17-kJ power amplifier module. A more efficient Helium-free gas mix was chosen (CO_2:N_2/4:1). A grid was introduced in the electron gun to provide voltage independent electron-beam density control and accommodate the requirement for a considerably lower electron-beam density for the new gas mix (50 mA/cm^2 vs 500 mA/cm^2 for Helios).[8] To reduce the likelihood of prepulse parasitic oscillations the gain region was pumped faster and the distance between power amplifier and target was increased substantially. The major differences are listed in Table IV.

TABLE I

CHARACTERISTIC FEATURES OF THE SINGLE-BEAM SYSTEM

Parameter	Stages 1 and 2	Stage 3	Stage 4
Electron Beam			
Energy	120 kV	155 kV	250 kV
Current	100 A	500 A	1500 A
Current Density	0.12 A/cm^2	0.60 A/cm^2	0.27 A/cm^2
Gas			
Pressure	600 torr	1800 torr	1400 torr
Electric Field	4.3 kV/cm-atm	3.8 kV/cm-atm	3.5 kV/cm-atm
Current	5000 A	16000 A	50000 A
Current Density	6.3 A/cm^2	20 A/cm^2	9 A/cm^2
Gain (P-20)	0.051 cm^{-1}	0.049 cm^{-1}	0.03 cm^{-1}
J/liter-atm	150	150	85
Efficiency $\frac{g_0(J)E_s}{J/\text{liter}}$			3.2%(x 1/5)

TABLE II

PERFORMANCE DATA OF A HELIOS DUAL-BEAM MODULE

Optical Design (each beam)	
Aperture	34-cm diameter
Gain Length	200 cm
Operating Pressure	1800 torr
Gas Mixture	1/4:1:3/N_2:CO_2:He
Gain	4%/cm (P-20, 10 μm)
Energy Output	1250 J
Electrical Design	
Discharge Voltage	300 kV
Discharge Current	100 kA
Pulse Length	3 μs
Energy	150 J/l-atm
Electron-Beam Voltage	250 kV
Electron-Beam Current Density	0.3 A/cm^2
Pulse Length	5.0 μs
Emitter	0.013-cm-thick Ta foil

TABLE III
ANTARES SPECIFICATIONS

100 kJ at Target 1-ns pulse
50 kJ at Target 0.25-ns pulse

Power Amplifier Parameter	Design Point	Design Margin
Mixture	CO_2:N_2/4:1	
Pressure	1800 torr	25% (2250 torr)
$(g_0 - \alpha)L$	6.0	25% (7.5)
Electrical Store	5.4 MJ	25% (7.2 MJ)
Optical Aperture	60,500 cm^2	13%

TABLE IV
MAJOR DIFFERENCES BETWEEN ANTARES AND HELIOS

Change	Antares vs Helios		Reason
Longer distance between power amplifier and target	200 ft	20 ft	Longer buildup time of prepulse parasitics
Faster pumping to peak gain	1.5 μs	3 μs	Shorter time available for build-up of parasitic oscillation, higher efficiency
Different gas mix in power amplifier	CO_2:N_2 4:1	CO_2:N_2:He 4:1:12	Higher efficiency, no helium handling
Annular arrangement of cavities around e-gun	Number of cavities per gun 12	2	Fewer guns, large annular optics, fewer beams
Employment of current control grid in e-gun	E-beam current density 50 mA/cm^2	0.5 A/cm^2	Different gas mix requires lower e-beam density, better density control
Larger exit window diameter	18"	16"	Availability of larger salt windows
Higher discharge voltage	550 kV	330 kV	Gas mix with higher impedance
Higher e-gun voltage	500 kV	300 kV	Gas mix with higher density

Major Limitations.[9] The most important limitation in the design of Antares is optical in nature. A window, transparent to 10.6-μm light, is necessary between the high-pressure (1800 torr) discharge cavity and the low-pressure (10^{-6} torr) target chamber. The best window material available is NaCl and the largest size windows made to date have a diameter of 18 inches. This, coupled with a safe limit for the energy flux of a 1-ns pulse of about 2 J/cm^2, dictates the number and aperture of the laser beams.

The mirrors are made of copper-plated aluminum by a micro-machining process. They have no influence on the selection of the beam number but limit the smallest size of the turning, folding, and focusing mirrors, and thereby the size of the space frame, target chamber, and turning towers. The inability to fabricate very large mirrors had one other effect on the final Antares design. The original plan to use annular optics was abandoned. This would have had the advantage that only 6 instead of 72 independent laser beams would have had to be managed.

Having chosen an annular arrangement of the discharge cavity, one additional limitation is imposed by the maximum permissible azimuthal magnetic field in the electron gun as well as in the cavities. Axial feed currents to the gun and cavities increase with axial length. The accompanying azimuthal magnetic field deflects electrons away from the feed end and causes non-uniform gain in the cavities. Requiring a certain degree of gain uniformity limits the length of the gun and an individual cavity. As a result, the Antares gun is fed from both ends and each cavity is subdivided into four sections.

The worst enemies of the high-energy gas laser are parasitic oscillations which can develop from spontaneous photon emission in the optical system prior to the actual shot. They can damage optical elements, cause a loss of energy and deposit prepulse energy on the target and thus destroy it.

To prevent these oscillations the gain-length-time product of each amplifier cavity has to be kept below a safe value. Computational analysis and experimental evidence limit the single-pass gain-length in a double-pass optical design for the power amplifier cavity to $gL \leq 6$ for a 1.5-μs pumping pulse. As a consequence a high input energy of 90 J per power amplifier is required which makes a powerful electron-beam controlled amplifier necessary for the output stage of the front end.

The Antares Facility. Most of the Antares design is now completed and the major portion of the hardware is under procurement. The buildings are all under construction. A model of the entire facility is shown in Fig. 4. One recognizes clockwise from the upper left corner, the warehouse, the facilities support building, the laser and energy storage hall, the target building, the mechanical equipment building, and the office building. The front-end room is located underneath the laser hall. Figure 5 is a view of the laser hall with the 6 power amplifiers and 24 energy storage units. Figure 6 gives a clearer picture of the target chamber and the six beam turning towers.

The generation, amplification, and transport of the laser beams is schematically shown in Fig. 7.

The Antares front end (Fig. 8) generates six beams with an aperture of 15 x 15 cm and energy of 225 J each (of this, only 90 J are utilized in an annular beam with 9-cm i.d. and 15-cm o.d.). Six oscillators are used to generate six tunable beams which are combined into one single beam. In addition to six switchout Pockels cells there are four Pockels cells in series to provide a contrast ratio (energy) of approximately 2.4×10^{12}. Amplification is achieved with two double-discharge amplifiers and three dual-beam modules. The dual-beam amplifiers are very similar to the Gemini and Helios amplifiers but smaller in size.

The 6 beams are directed upward into the power amplifiers which split each beam in 12 ways and provide the final two-pass amplification (Fig. 9). As indicated above, each power amplifier consists of one central electron-beam gun surrounded by 12 discharge chambers. Because of magnetic field limitations the gun is fed triaxially from both ends and the discharge chambers are sectioned with a resulting total of 48 chambers. Two azimuthally adjacent chambers are fed electrically through one coaxial cable with a voltage of 550 kV and a current of 40 kA. The gun is directly connected to the gun pulser which provides a gun voltage of up to 600 kV, a grid voltage of about 400-500 kV, and a cathode current of 40 kA. The output laser beams pass through 12 salt windows into the low pressure optical section where they are combined into one annular beam with the help of a periscope mirror pair.

The annular beam is then transported through an evacuated beam tube into the target building. It is turned by a set of turning mirrors into the target chamber. This is done to prevent back streaming of neutrons into the laser hall. Inside the cryogenically pumped target vacuum chamber a space frame supports a second set of flat turning mirrors and a set of focusing mirrors. A typical beam pass in the target chamber is shown in Fig. 10. The distance between the focusing mirrors and the target is approximately 1.61 m.

Pulsed electrical energy has to be delivered in different shapes and at many different places throughout Antares (Fig. 11).

The switchout cells require a very small amount of energy (approx. 10 mJ) and a relatively low voltage (12 to 25 kV). However, the risetime of the voltage pulse into 10 parallel 50-ohm loads (Pockels cell plus cable) has to be $t_r < 1$ ns and the jitter between cells has to be <50 ps. This requirement will be met by using one fast multi-channel spark gap to energize all cells. Delays between cells will be achieved through different lengths of very low loss cables.

The preamplifiers require the following energy, voltage, current, and pulse duration:

Lumonics K-9225:	160 J,	40 kV,	2 kA,	3 µs
Lumonics 602:	1640 J,	150 kV,	7.5 kA,	3 µs

The Lumonics K-9225 is also operated at a repetition rate of 3 pps for alignment purposes.

The three electron guns of the driver amplifiers are fed from a common Marx generator with an energy of 25 kJ and open-circuit voltage of 630 kV. The single-mesh LC Marx is matched to the gun impedance and produces a slightly oscillatory current with a half period of 17 µs and a peak value of 10 kA.

Each of the six driver amplifier pumping chambers is driven by a similar single-mesh Marx as above (25 kJ, 630 kV) with a peak current of 48 kA and a half period of 3.5 µs.

Each electron gun of the power amplifier is energized by a 10-stage Marx generator (70 kJ, 600 kV, 40 kA) which is allowed to RC decay. In view of the varying requirements for electron-gun voltage and impedance, this is considered the best solution. In an earlier design stage the gun pulser was an impedance matched A-type network with a peaking circuit to provide fast rising voltage for uniform gun ignition. The Marx generator feeds both ends of the electron gun where one side is connected through a tunable inductor to achieve current symmetry in the gun (Fig. 12).

Each power amplifier section (12 annular cavities) is energized by a 10-stage Marx generator with an open-circuit voltage of 1.2 MV, an energy of 300 kJ, and an LC impedance which is approximately matched to the load.[10] The short-pulse duration calls for a low generator inductance of about 3 µH, which is accomplished through multiple zig-zag folding of the Marx (Fig. 13). Each Marx is connected via 6 coaxial cables to 12 anodes. The cables are dry-cured standard (145 kV) utility cables which have been tested for a pulse voltage of 1 MV.

Because of the complexity of the Antares system there exists also a very large and complex optical alignment system which is not discussed in this presentation. The electronic control system is based on a computer hierarchy (Fig. 14). A network of computers permits control of individual systems or beam lines in a stand-alone mode or the coordinated control of the entire facility. Low-level control is achieved with microcomputers (LSI-11) and intermediate-level or high-level control with minicomputers (PDP-11/34, 60 and 70). To avoid the typical problems of transient interference in a high pulsed electro-magnetic environment all computers and computer interfaces are heavily shielded and all signal transmission takes place via fiber optic cables. A typical fiber-optic link is shown in Fig. 15. It consists of a signal generator (Pearson current transformer), an electro-optic converter, the fiber-optic cable, and an opto-electric converter.

Status of the Antares Construction. The Antares schedule (Fig. 16) as part of the overall inertial confinement fusion plan foresees that the Antares facility will become operational and ready for target experiments in the spring of 1984.

As a first step towards this goal the first beam line (of six) will be completed and checked out in the fall of 1981. The major milestones in this effort are:

• Power amplifier and energy storage system installed	April	'80
• Electrical and small-signal tests complete	August	'80
• Single-beam front-end ready	November	'80
• Single-sector energy extraction	February	'81
• 12 sector energy extraction	April	'81
• 17 kJ/1 ns pulse centered and focused	October	'81

All Antares buildings are now fully enclosed and internal work is progressing. Figure 17 shows the target hall with its 6-ft-thick walls and 5-ft-thick ceiling. The laser hall and the front-end room will be available for joint occupancy in August 1979. It is presently anticipated that all buildings will be complete and ready for occupancy by LASL in December 1979.

Most of the components and systems development and 75% of the design are complete. All major hardware for the first beamline has been procured and will begin to arrive at LASL in June. A pumping chamber section is shown in Fig. 18. The output amplifier for the front end will be tested at LASL starting in July. The performance test of the first energy storage unit will begin in July. Half of the control components network is on hand and is being used for software development. The electron-beam gun (Fig. 19) will be assembled and readied for test in August. Installation of the gigantic target vacuum system (beam tubes and chamber) will begin in August.

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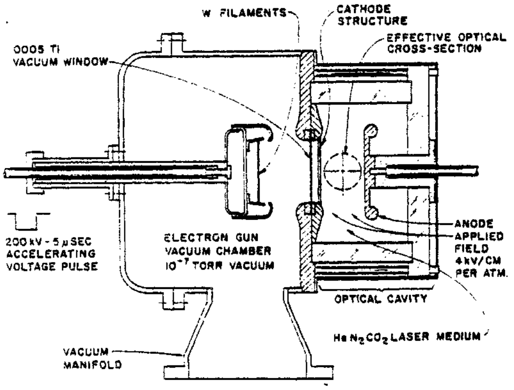

Fig. 1. Electron-beam-controlled CO_2 laser amplifier.

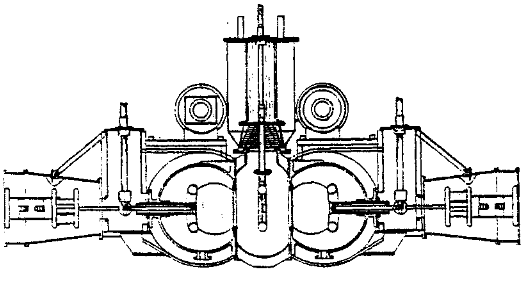

Fig. 2. Cross-sectional view of dual-beam module (Helios).

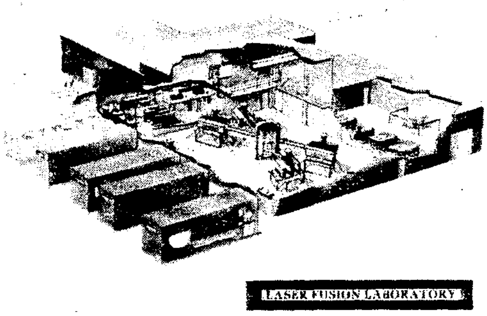

Fig. 3. The LASL Helios facility.

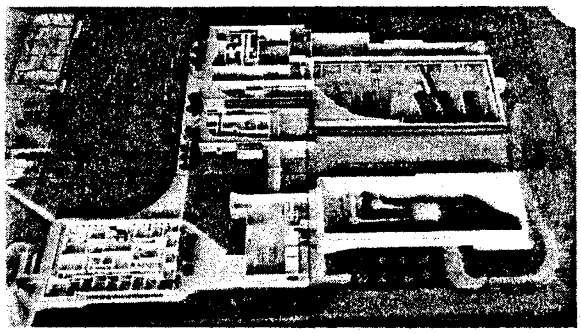

Fig. 4. Model of the Antares facility.

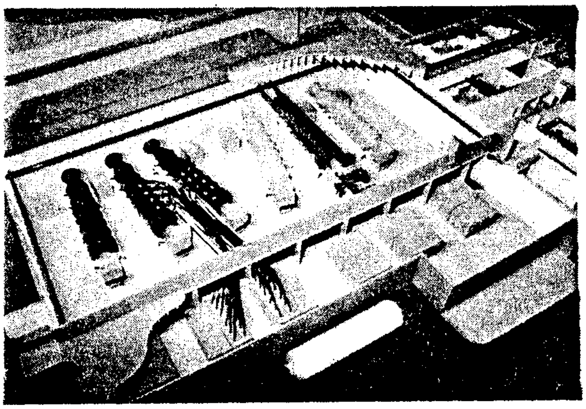

Fig. 5. Laser hall with 6 power amplifiers and 24 energy-storage units.

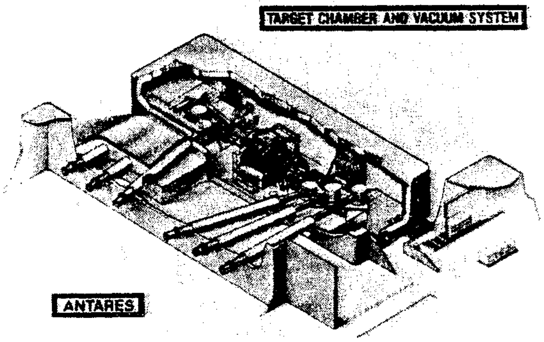

Fig. 6. Target chamber and vacuum system.

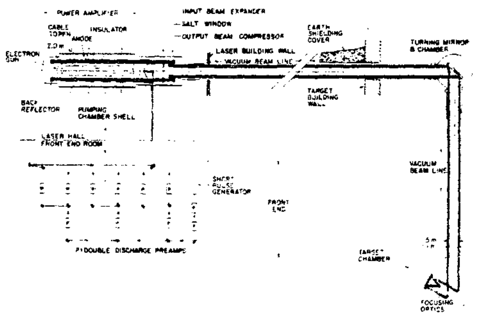

Fig. 7. Optical schematic of Antares.

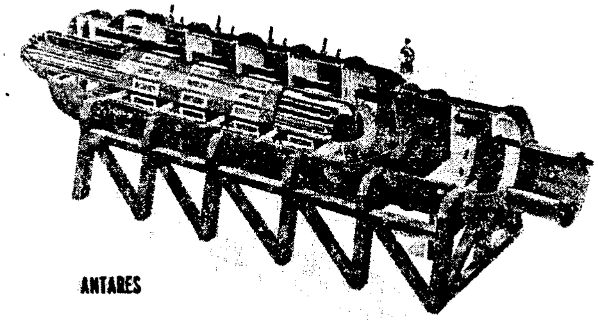

Fig. 9. Artist's conception of the power amplifier.

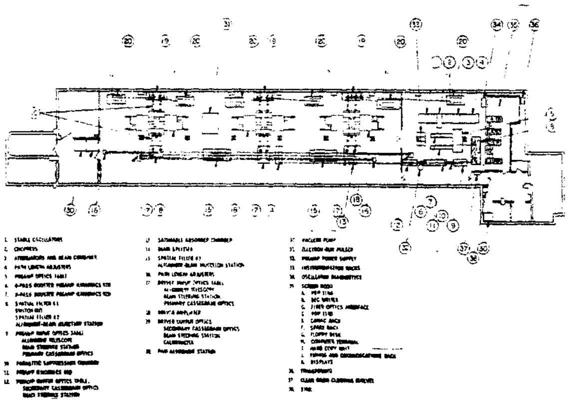

Fig. 8. Antares front end.

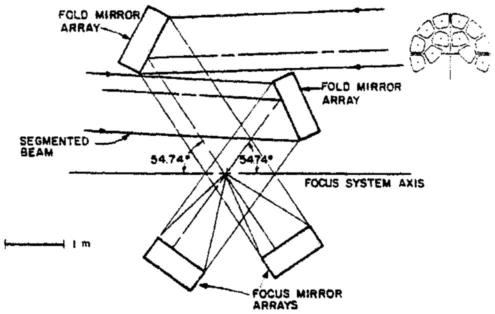

Fig. 10. Antares focus system.

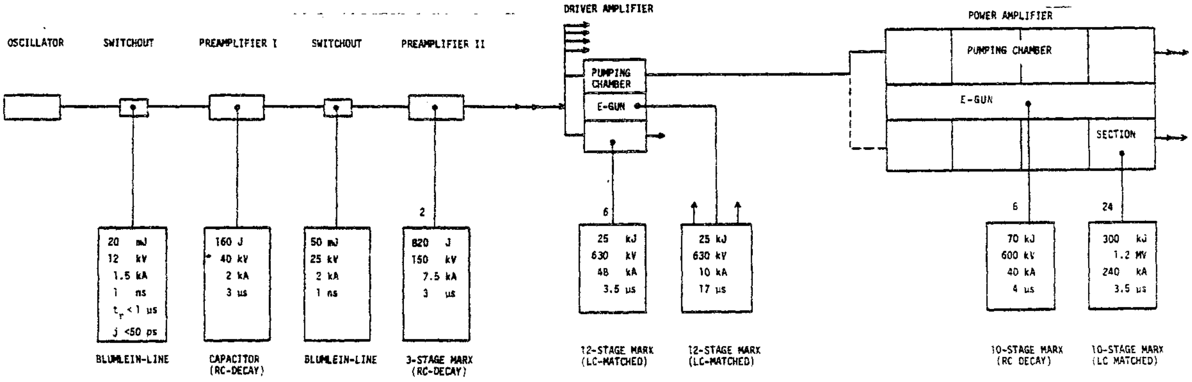

Fig. 11. Pulsed power for Antares.

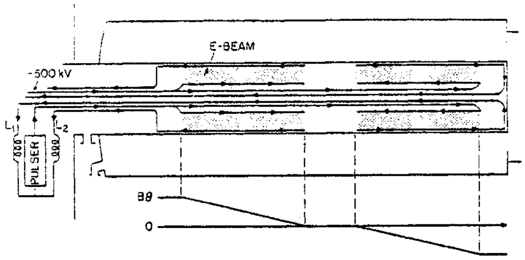

Fig. 12. Symmetric feeding of the electron-beam gun to reduce the azimuthal magnetic field.

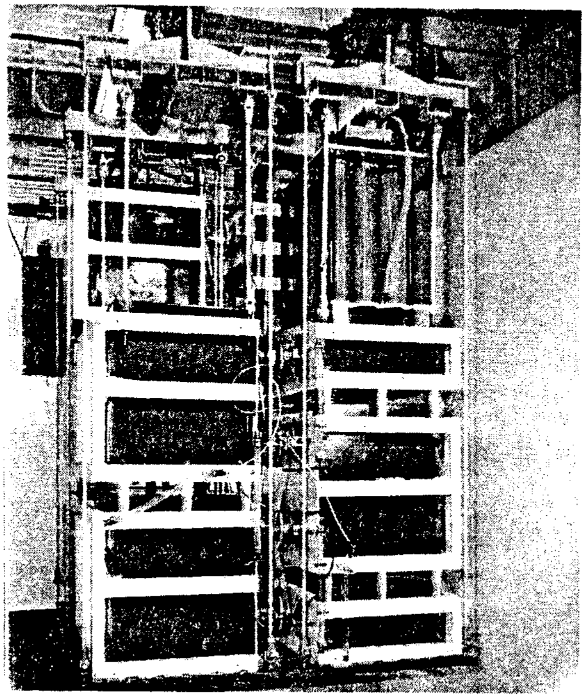

Fig. 13. Low-inductance Marx configuration.

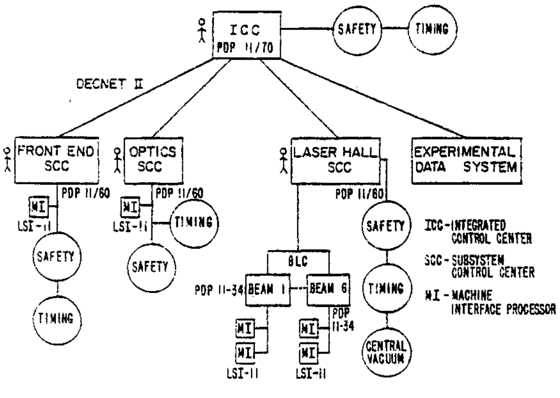

Fig. 14. Antares control system implementation.

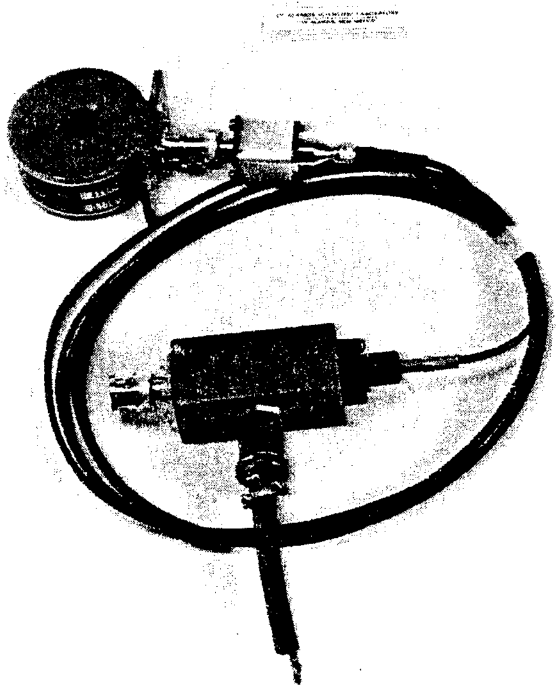

Fig. 15. Fiber-optic signal transmission link.

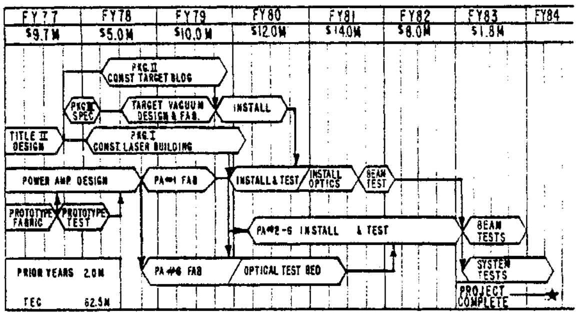

Fig. 16. Antares summary schedule.

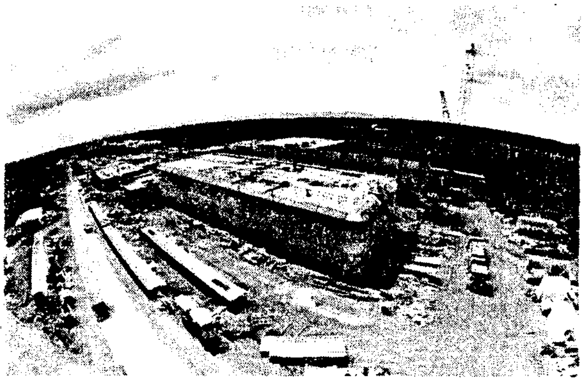

Fig. 17. Facility construction, target building in foreground.

Fig. 18. Pumping chamber sections in production.

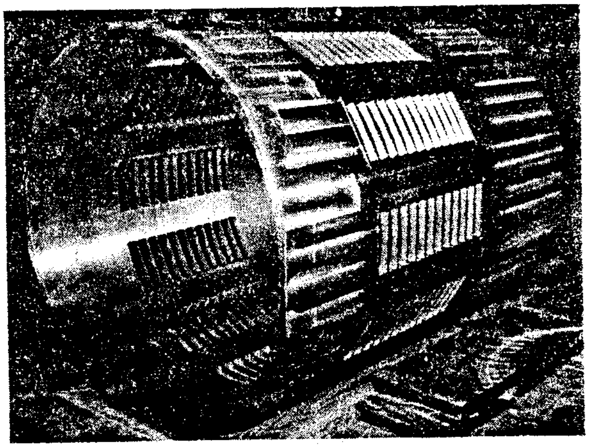

Fig. 19. One of four sections of the electron-beam-gun vacuum shell.