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LA-UR--89-3407

DE90 002385

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SUBMITTED TO 13th IEEE Symp. on Fusion Engineering
Knoxville, TN
October 3-5, 1989

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DESIGN AND PERFORMANCE OF FUTURE KrF LASER-FUSION FACILITIES

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Abstract

The U.S. inertial confinement fusion program is investigating the feasibility of constructing a high-gain Laboratory Microfusion Facility (LMF). Considerable uncertainties and risks exist for all of the driver candidates in proceeding directly to this facility without an intermediate step. These risks fall into the categories of driver performance and cost, target physics, and target chamber performance. Los Alamos has developed a plan to resolve these issues *before* construction of the LMF. The plan calls for the construction of an LMF prototype beamline at the 100-kJ energy level and the parallel development of a large (240 kJ) KrF amplifier module. The prototype facility, called the Laser Target Test Facility (LTF), will address target physics issues at the 100-kJ level and will demonstrate the performance and cost scaling of KrF lasers. In parallel with this construction, a 240-kJ LMF amplifier module will also be developed. After successful operation of the LTF for a period of about two years and construction and operation of the LMF amplifier module, all driver issues will be satisfactorily resolved. If sufficient understanding of target physics extrapolations is realized from this facility, the LMF can then be constructed with acceptable risk. If an additional step is needed for understanding target physics and capsule ignition, the LTF can be upgraded to an energy level on target of 1-3 MJ. This upgrade would provide a direct test of LMF scale laser and optic hardware and would provide much information on the function of the LMF target chamber. The construction of a 3-MJ KrF facility could be an LMF if high target gains are achieved with shaped, broadband KrF laser pulses.

Introduction

The U.S. Department of Energy is currently conducting a scoping study of the Laboratory Microfusion Facility (LMF) [1]. A goal of the LMF is to achieve high gain from inertial confinement fusion (ICF) targets and to use both the driver and target output emissions for weapons physics experiments and weapons effects simulations. It is expected that the driver energy for the LMF will be in the range of 2-10 MJ depending on target performance for a given driver. A review of the ICF program is currently being conducted by the National Academy of Sciences. This review will examine the status and suitability of the different driver candidates for the LMF and the readiness of each driver technology to proceed based on our current knowledge of target physics.

Los Alamos National Laboratory is developing the KrF laser for ICF applications because of its attractive performance features. The natural characteristics of KrF lasers result in near-optimum target coupling for the following reasons:

- the 250-nm output wavelength of KrF laser light is very short which results in high absorption and x-ray conversion efficiencies [2],
- the achievable broad bandwidth (controllable up to $\sim 250 \text{ cm}^{-1}$) increases the threshold for the onset of laser-plasma instabilities and reduces their growth rate when above threshold [3],
- the good beam quality and suitability to beam smoothing techniques reduces inefficiencies and degradations in target performance resulting from intensity spikes [4], and
- the linear gain nature of the quasi-cw amplification allows pulse shapes generated in the front end to be propagated to target without distortion [5].

It is significant that the natural features of the KrF laser are so well suited for ICF applications because typically there is a severe penalty in driver cost and efficiency if these attributes must be generated artificially by modifying the output of an ICF driver to meet the requirements of the target.

The KrF laser is also very robust in that it is suitable for both single pulse target development applications and repetitively pulsed commercial applications. The reasons KrF lasers are suitable for commercial applications are:

- the gaseous lasing medium is non-damaging and allows heat removal during repetitive pulsing by simply flowing the gas through a heat exchanger, and
- the laser has a high intrinsic efficiency (>12%) and uses a high-efficiency pump source (projected to be >80%) to meet the efficiency requirements for electric power production.

The KrF laser is also robust in that it is suitable for the two types of target drive concepts, direct and indirect. The difference between the two approaches is that in direct drive, the fuel capsule is illuminated directly by the driver beams. In indirect drive, the driver beams are converted to x rays in a hohlraum, and the x rays are used to uniformly illuminate the fuel capsule. The short wavelength, good beam quality, and suitability to beam smoothing techniques of KrF lasers make them suitable in either target illumination geometry.

Future KrF laser-fusion systems will be similar in many respects to the existing Aurora facility at Los Alamos. This provides us with a relevant cost basis to project to future facilities. The cost and performance of these proposed KrF facilities is attractive compared to the other driver candidates.

Status of Driver Technology and Target Physics Needed for the LMF

The decision to proceed with construction of an LMF without an intermediate step depends on tradeoffs between cost, risk, need, and benefit. The users of this facility will be responsible for determining what is acceptable for these tradeoffs. From the facility point of view, three areas of physics and technology must be demonstrated or understood. They are:

- target performance must be adequately extrapolated to the useful regime,
- the driver performance and affordability must be demonstrated, and
- target chamber concept must be shown to perform as needed.

Examination of the status of these areas reveals the risk of proceeding directly to the LMF without an intermediate step.

Target physics

The Nova laser is the state-of-the-art inertial fusion driver, currently operating at ~20 kJ with a wavelength of 350 nm. Thus, extrapolations in target physics to the LMF require extrapolations of a factor of 500 in driver energy. Extrapolations of this size have considerable uncertainty and risk. One central issue is which drive approach, direct or indirect, is best for generating high gain. Both approaches have significant unresolved issues. Direct drive requires very uniform illumination over the surface of the fuel capsule. Even with uniform illumination, it is uncertain if the target can be imploded to the high densities required without significant degradation from hydrodynamic and plasma instabilities. Indirect drive targets have a different manifestation of hydrodynamic and plasma instabilities, including degrading effects due to hydrodynamic motion and the requirement for time-dependent symmetry. For both drive approaches, there is roughly a factor-of-ten uncertainty in the driver energy needed for target ignition and high gain. Additionally, high compression experiments have shown a significant degradation in expected yield [5a], possibly due to mix of the fuel and outer shell of the capsule.

Driver cost and performance

The uncertainties in target physics lead to large uncertainties in the driver requirements. Current thinking is that the driver must deliver ~10 MJ of energy in a 5-10 ns pulse with broad bandwidth and at short wavelength (or particle range for ion accelerators). The energy delivered to the target must have a peak intensity of 10^{14} - 10^{15} W/cm² and must be accurately pulse shaped with either a continuously rising pulse or several carefully controlled steps. An affordable cost for the driver of the LMF is a matter of what the customer is willing to pay for the benefits of having this national facility. Current estimates of what might be affordable are in the range of 100-200\$/J. No driver candidate has demonstrated either the cost or performance required for the LMF. All driver candidates have ongoing programs to develop the driver performance required for the LMF.

The performance and cost issues for the driver must be resolved *before* construction of the LMF is possible with acceptable risk.

Target chamber performance

The LMF target chamber has several functions. The chamber must contain the ICF microexplosion, which for the LMF is equivalent to 0.25 ton of high explosive. The chamber must protect the driver from costly damage, which might involve fast-closing shutters to protect the final optics from hypervelocity projectiles and puffing gas into the target chamber just before firing the driver to shield the final optics from x-rays. The chamber must also provide a vacuum in which the driver beams can be focussed and provide the capability for performing and diagnosing experiments. In addition, the chamber must provide shielding for the facility and yet not become so radioactive that the performance of experiments is precluded. Several target chamber concepts have been proposed [6-12], but none are assured of performing all of the required functions at an affordable cost.

KrF Laser Program Plan

Los Alamos National Laboratory has proposed a development plan for KrF lasers that will resolve the issues and uncertainties for the LMF in as short a time as possible and for the lowest cost. The path logic leading to an LMF is illustrated in Fig. 1. The existing state of the art in KrF drivers is the Aurora facility at Los Alamos. This facility does not have the beamline design nor sufficient energy to answer questions relating to LMF issues. We propose to build a 100-kJ KrF laser-fusion system called the Laser Target Test Facility at Los Alamos. This facility will demonstrate all of the necessary system performance features of the LMF, including pulse shaping and bandwidth propagation to the target and the correct driver architecture. In addition, this system will realize significant cost reductions over the Aurora system through learning, design

improvements, and technology improvements. In parallel with the construction and operation of the LTTF, we plan to construct and operate a 240-kJ LMF amplifier module in an off-line technology development program. After this step, all of the driver technology needed for the LMF will be demonstrated. The LTTF will have two target chambers to perform both direct and indirect drive implosions. The issues of which drive approach is best will be resolved with this facility because meaningful comparisons of the different drive approaches can be done by using the same driver. After operation of this facility for a period of about two years, a decision on whether to proceed directly to an LMF can be reasonably made. In the approach to an LMF, the upgraded LTTF can be used for prototyping LMF hardware or as a stand alone target facility operating with up to 3 MJ on target.

All of the existing or proposed KrF facilities are based on similar design concepts. They all use large e-beam pumped amplifiers in the final gain stage. Pulse shaping is accomplished by generating the desired pulse shape in the front end and then propagating it through the amplifier chain to the target without distortion. The broad bandwidth desired to reduce plasma instabilities is accomplished by generating two distinct frequencies within the gain bandwidth of KrF and propagating them through the amplifier chain. Pure angular multiplexing is used in all designs to maintain pulse shape and bandwidth. What changes in the facilities in going from Aurora to the LMF is the size of the final amplifiers, the method of aperture combination, and the beam transport media, which are based on the desired output energy of the facility.

Laser Target Test Facility Design

The 100-kJ LTTF is designed to address as many driver and target technical issues as possible at the 100-kJ energy level. The answers achievable with the LTTF will be obtained for a facility cost of about 10% of what a full LMF will cost. The driver technologies that will be demonstrated on the LTTF are:

- performance of large amplifier modules (50 kJ units),

- pulse shape generation in the front end and propagation through the amplifier chain,
- broad bandwidth generation and propagation
- interstage temporal encoding, and
- aperture combination.

The layout of the LTTF is shown in Fig. 2. The facility will use two aperture-shared 50-kJ amplifiers in the final gain stage. Pure angular multiplexing to maintain the beam characteristics and provide the short pulses needed by the target. As shown in Fig. 2, there are three main areas in the facility: the amplifier area, the optical demultiplexing area, and the target area. The amplifier and optical demultiplexing areas make up a facility arm; going to higher energy is accomplished by simply adding more facility arms.

If direct-drive implosions work as predicted, the facility should have the capability to investigate target physics near ignition. Capsule stability is also a key issue that will be examined. Using indirect-drive, it is anticipated that critical issues such as symmetry, hydrodynamics, stability, and mix can be studied.

Our cost studies have shown the importance of scaling amplifier modules to large sizes. The Aurora main amplifier is currently operating at ~10 kJ. We have selected the main amplifiers of the LTTF to be approximately a factor of 5 larger in energy. We feel that this is a conservative enough step to assure successful operation of the LTTF, yet provides significant data for scaling the KrF amplifiers to the 240-kJ LMF modules.

The LTTF will demonstrate the laser system performance requirements and the laser architecture for the LMF. Specifically, the LTTF will demonstrate the pulse shaping, bandwidth propagation, and prepulse suppression required for the LMF. In addition to the specific driver technology and target physics issues being addressed, the LTTF will provide important data on the cost scaling of KrF lasers. The preliminary cost estimate for the LTTF is \$180 million for a turn-key operation.

Upgrade potential

As mentioned previously, we plan to construct a full-size LMF module in parallel with the construction of the LTTF. When the LTTF comes on line, it will demonstrate the laser system requirements of the LMF, and the LMF amplifier module will demonstrate the remaining driver scaling issue for the LMF. At this time, *if* it is felt that the target physics extrapolations and target chamber design have acceptable risks, the LMF should be built. If it is decided that a facility with energy to target on the order of 1-3 MJ is desired, the LTTF would be upgraded using the LMF amplifier technology. Each LMF facility arm provides 720 kJ to target and is configured as shown in Fig. 3. The LMF facility arm uses three 240-kJ amplifier modules that are aperture combined. Additional facility arms would be built as desired to reach the desired final energy, and the target area shown in Fig. 2 would be modified for a larger target chamber and more radiation shielding.

LMF Design

The LMF will use an architecture identical to that pictured in Fig. 3 with the number of facility arms dependent on the driver energy required. For 10 MJ, 15 arms would be required. The LMF would also operate with longer duration target irradiation pulses, so the number of individual beamlines per arm would be reduced from 144 to 60.

The target area for the LMF would differ from that of the LTTF in that significantly more shielding would be required with the high yields of the LMF. Designs for the LMF target chamber have been proposed, but all have serious issues that need to be resolved. The experience gained in the LTTF and LTTF upgrade will help provide the experience needed for a comprehensive design of the LMF target chamber.

The cost estimate for a 10-MJ LMF is in the range of one to two billion dollars. Current technology programs are developing the optics and pulsed power technology for the LMF. If technological advances occur faster or further than expected, the LMF cost can be reduced.

Summary

Los Alamos National Laboratory is developing the KrF laser for ICF applications. The natural characteristics of the KrF laser, the short wavelength, broad bandwidth, accurate pulse shaping, and good beam quality, provide it with significant advantages for inertial fusion, especially in the area of target coupling. In addition, the KrF laser is suitable for repetitively pulsed commercial applications because it is a gas laser with capability for high efficiency.

Significant uncertainties exist in the areas of target physics, driver performance and cost, and the target chamber design for the LMF. Los Alamos has proposed a path to the LMF that will demonstrate the required technology and provide greater understanding of target physics before construction of the LMF. The first step is the operation of Au.ora, where much learning on KrF technology and physics has already occurred, and target physics experiments are just beginning. The next logical step is a 100-kJ Laser Target Test Facility. The LTTF will demonstrate the driver cost scaling and performance that is required for the LMF. It will also address many target physics issues, including simultaneously investigating both direct and indirect drive. The LTTF is upgradable to the 1-3 MJ range if that option is desired.

The KrF laser-driven LMF is a straightforward extrapolation of the LTTF and would be identical to the 720-kJ arm architecture characteristic of the upgrade of the LTTF. The LMF would demonstrate high gain for ICF targets and would provide an above-ground capability for performing weapons effects simulations and weapons physics experiments. Commercial applications using KrF lasers for ICF can be developed in parallel with the single-shot test facilities discussed here or delayed to after the successful operation of an LMF.

References

- [1] LMC Scoping Study Phase I Final Report
- [2] x-ray conversion efficiency as function of wavelength

[3] Bandwidth suppression of instabilities

[4] Bodner APS/DDP reference

[5] D. Hanson pulse shaping reference

[5a] YOC vs compression

[6-12] Target chamber concepts

Figure captions

1. The KrF development plan to achieve the LMF includes an intermediate step to demonstrate driver performance and to provide a further understanding of target physics.
2. The LTTF uses one amplifier arm, consisting of two 50-kJ amplifier modules. The facility also uses two target chambers for direct and indirect drive.
3. The upgrade of the LTTF uses an amplifier arm similar to that needed for the LMF. Three 240-kJ amplifiers are aperture combined for a total energy of 720 kJ.

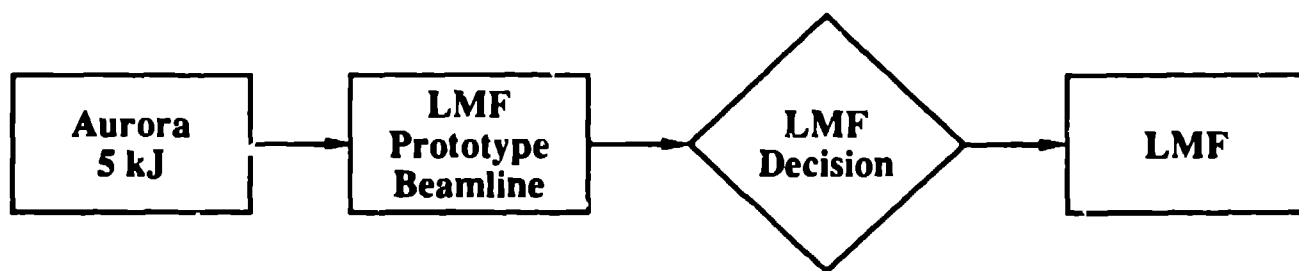


Fig. 1

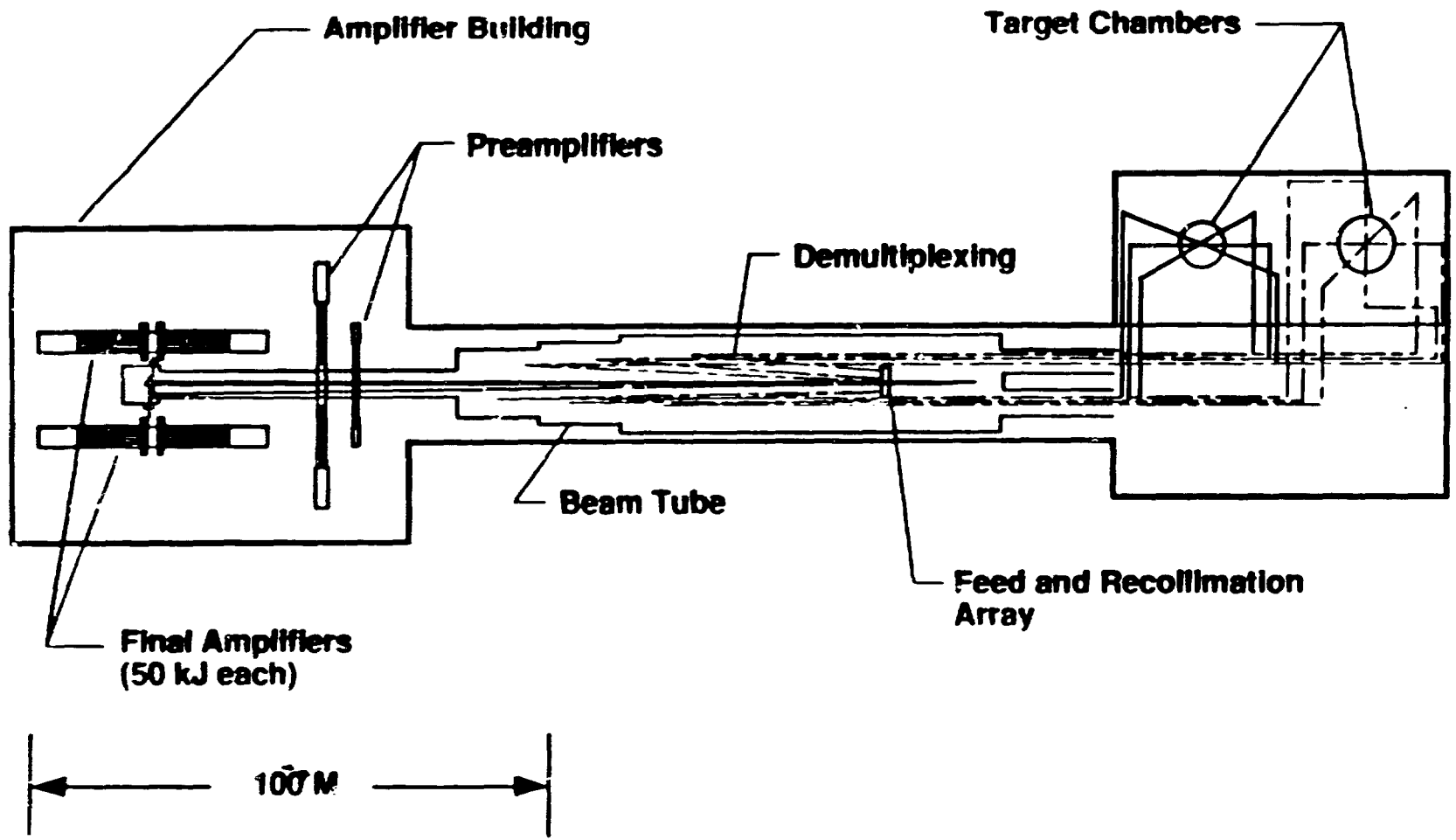


Fig. 2

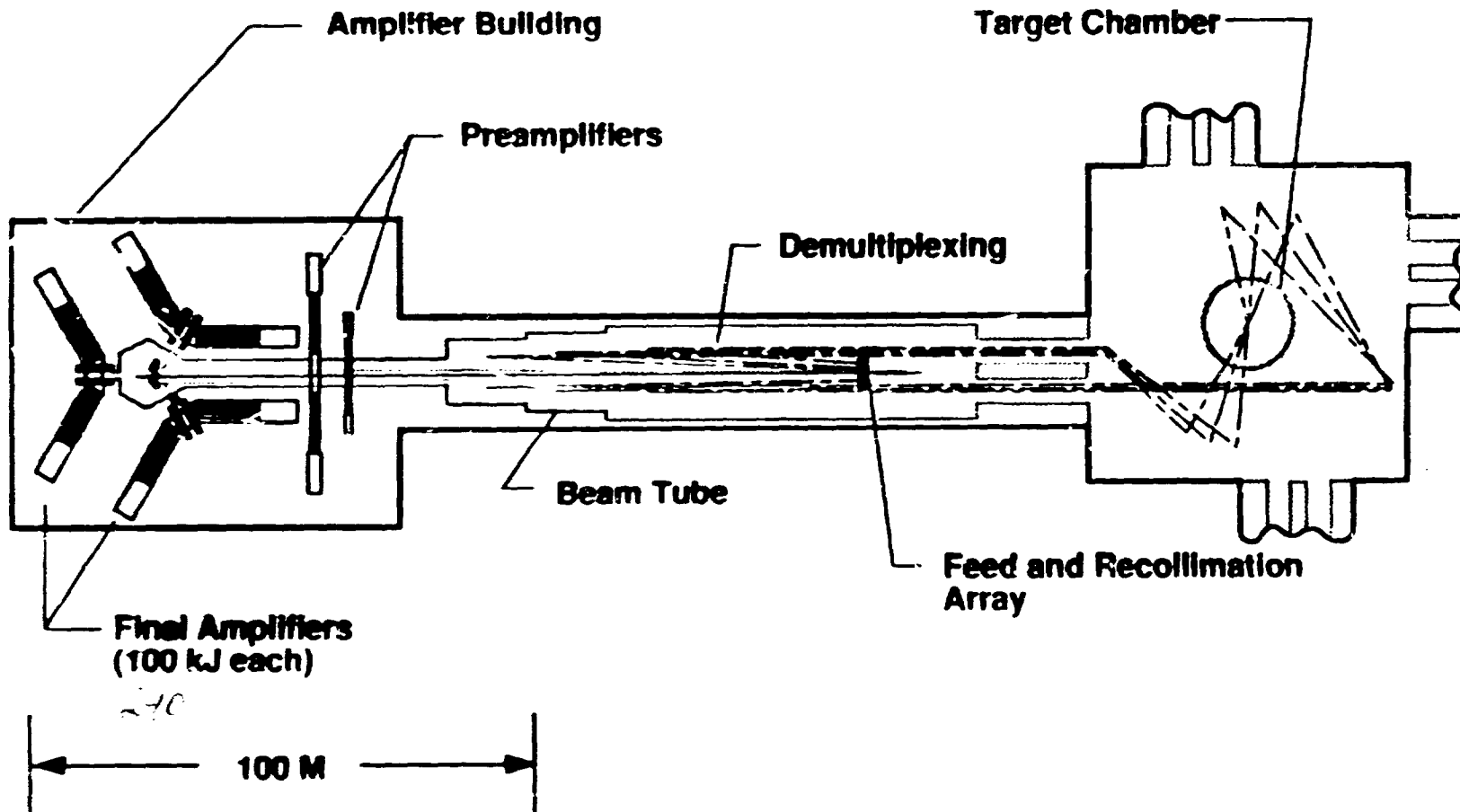


Fig 3

***Advanced
KrF Laser-Fusion
System Designs***

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KrF Laser Program**

**Los Alamos
Laboratory**

Outline

- **National Direction**
- **Need for an LMF Prototype Facility**
- **LMF Prototype Facility Design**
- **LMF Design**

National Program

- **NAS Review of all ICF Programs**
- **DOE Backed Study of 10 MJ Drivers**
- **Laboratories Developing Program Responses for Scaling to 10 MJ**

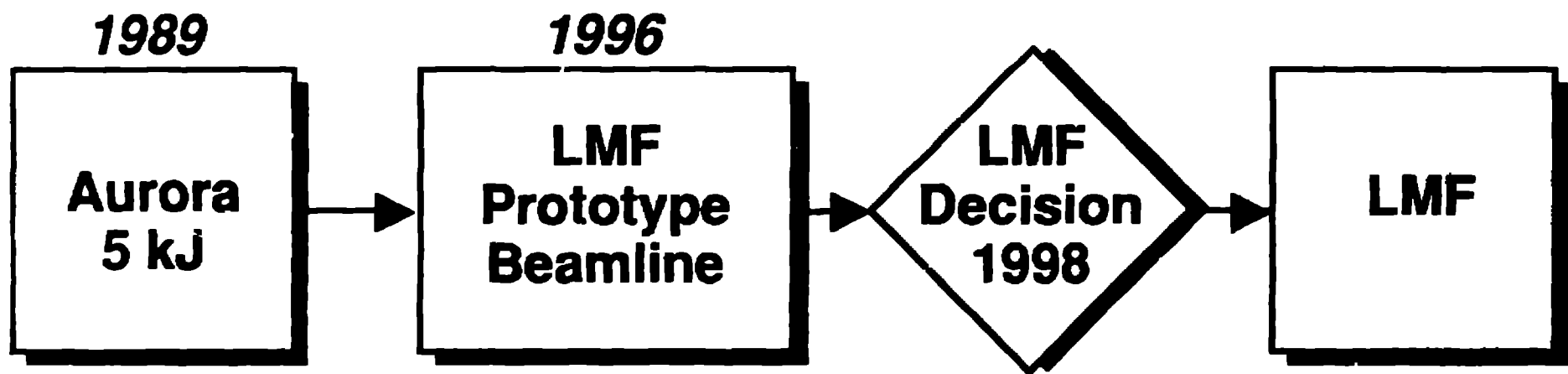
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The Laser Target Test Facility is a Crucial Element for the National ICF Program

- **Provides Comprehensive Evaluation of Direct and Indirect-drive Target Performance**
- **Demonstrate Unique KrF Laser Driver Advantages**
 - **Best combination of short wavelength and large bandwidth**
 - **Very smooth tailored spatial profiles**
 - **Flexible pulse shaping capabilities**
 - **High efficiency, gaseous medium**
- **Provides State-of-the-art Above Ground Experimental Capability for Weapons Program at Los Alamos**

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The Path to an LMF Decision Requires an LMF Prototype Beam Line



The 100 kJ Laser Target Test Facility Will Resolve Key Driver Cost and Performance Issues

- **Demonstrate Driver Cost and Technology for the LMF**
 - **Pulse Shaping, Bandwidth, Beam Quality, Smoothing, etc.**
- **Determine Optimum Target Approach and Illumination Geometry**
 - **Direct Drive and Indirect Drive (2,3, & 4 sided)**
- **Study Hohlraum Dynamics**
 - **Hydrodynamics, Symmetry, Pulse Shaping (picket vs. multistep vs. smooth continuous)**

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***An Upgrade of the LTF Would Permit
Operation up to 3.0 MJ in an
Ignition Physics Facility***

- **Verify Target Physics Projections from the 100 kJ Facility in Ignition Regime**
 - **Pulse Shaping, Bandwidth, Beam Quality, Smoothing, etc. Hohlraum Dynamics, Symmetry, etc.**
- **Study Laser-plasma Interaction in Near-LMF Regime**
- **Better Define LMF Driver and Target**
 - **Energy, Pulse Shaping, Bandwidth, Target Specifications, etc.**

***Future
KrF Facility
Designs***

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Advanced Designs Use Common Elements That Build on Previous Experience

- **Large Amplifier Modules (≥ 50 kJ)**
- **Time and Angle Encoding and Decoding**
- **Pulse Shapes are Generated in the Front End and Propagated Through the Amplifier Chain**
- **Amplifier Aperture Combination to Reduce Optical Complexity**

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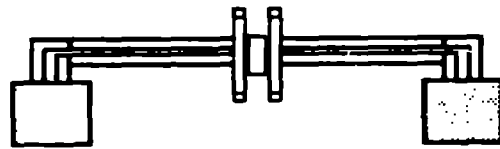
Design Choices and Constraints

- **E-Beam Pumping**
- **1.4 Meter Diameter Main Amplifier Optics**
- **Distributed Encoding**
- **Monolithic Diodes**
- **Rectangular Amplifiers**
- **Small Angle Scattering ($<10^7$ W/cm² prepulse on target)**

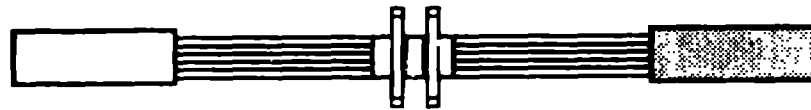
Motivation for Large Amplifier Designs

- **Designs Using Large Amplifiers are Projected to be More Cost Effective**
- **Amplifier Physics Support Scaling to Very Large (~500 kJ) Single Amplifier Units**
- **Architectures Using Large Amplifiers are Simpler**
- **Large Amplifier Designs Require Less Space**

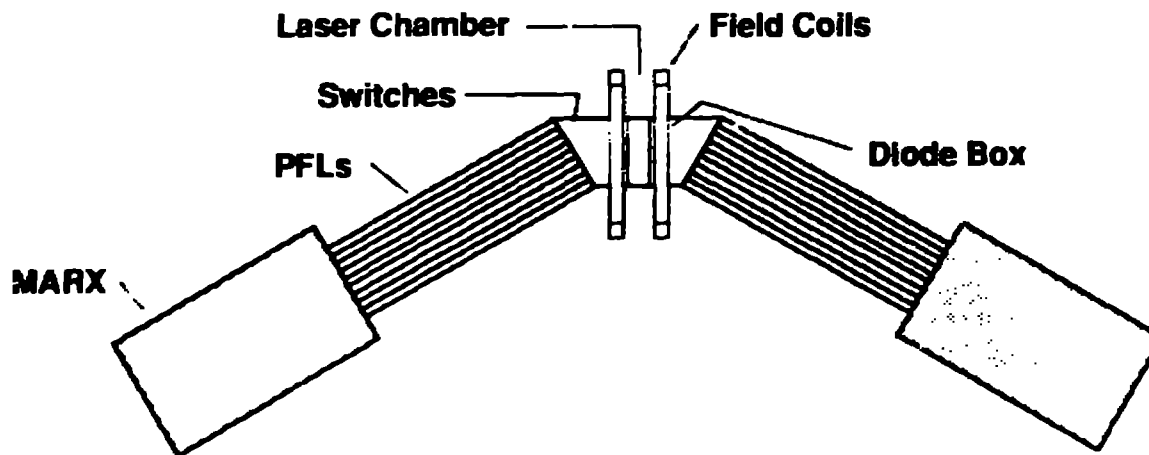
Modest Increases in Amplifier Dimensions Lead to Significant Increases in Laser Energy With Modest Floor Space Increase



20 kJ
AURORA
Class



100 kJ
Laser Target Test
Facility



240 kJ
Ignition Physics
Facility and LMF

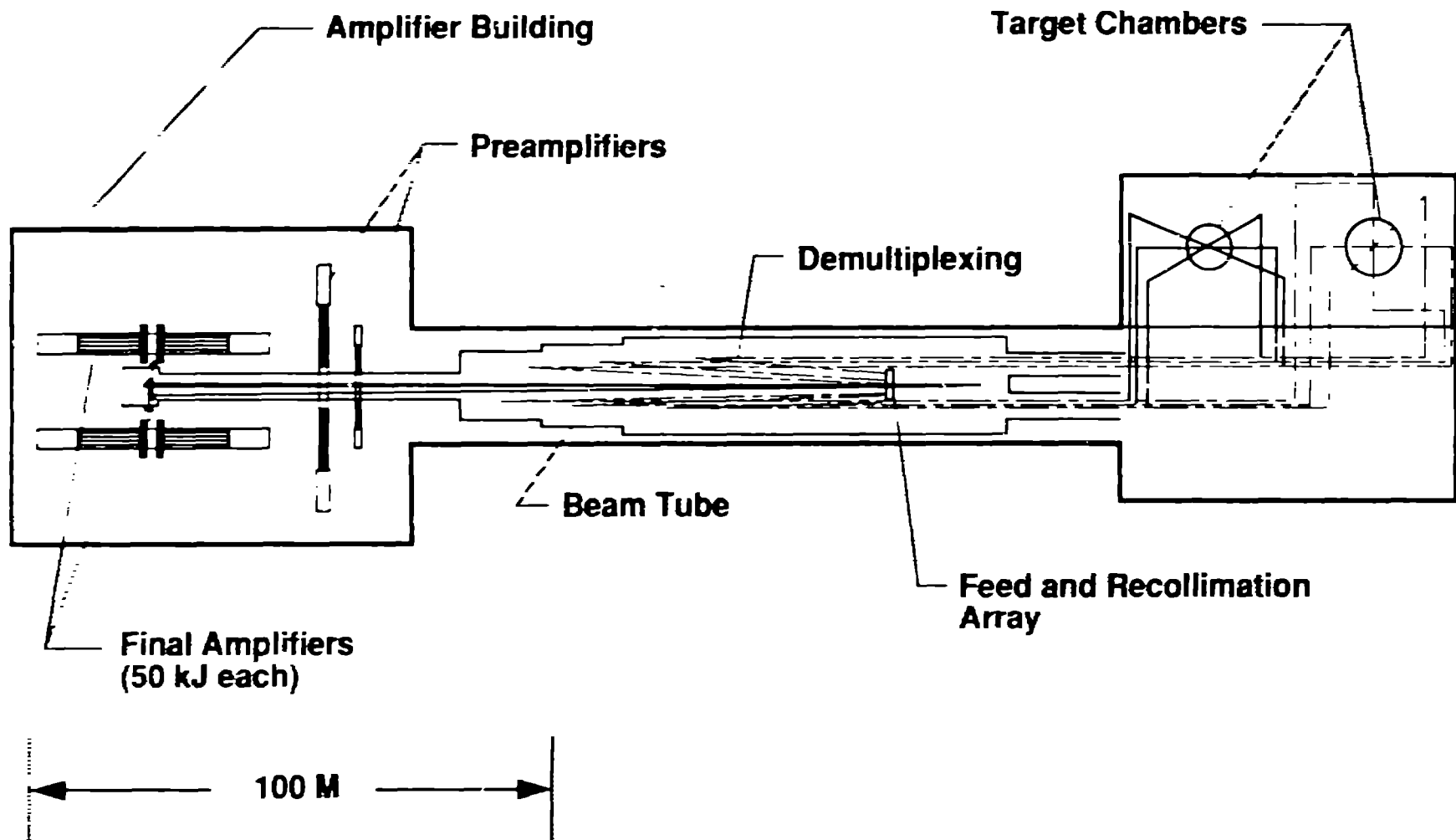
Parallel Amplifier Developments Will Demonstrate LMF Scale Technology

Parameter:	Aurora Class Amplifier	50 kJ Amplifier	240 kJ Amplifier
Ultimate Amplifier			
Energy (kJ)	20	50	240
Width (m)	1.0	1.1	1.3
Diode area (m ²)	2.0	5.2	14.6
Extraction duration (ns)	480	576	750
Voltage (kV)	675	800	1000
Optical fluence on recollimator optics (J/cm ²)	1.0	2.0	5
Recollimator optic diagonal (cm)	15	29	69

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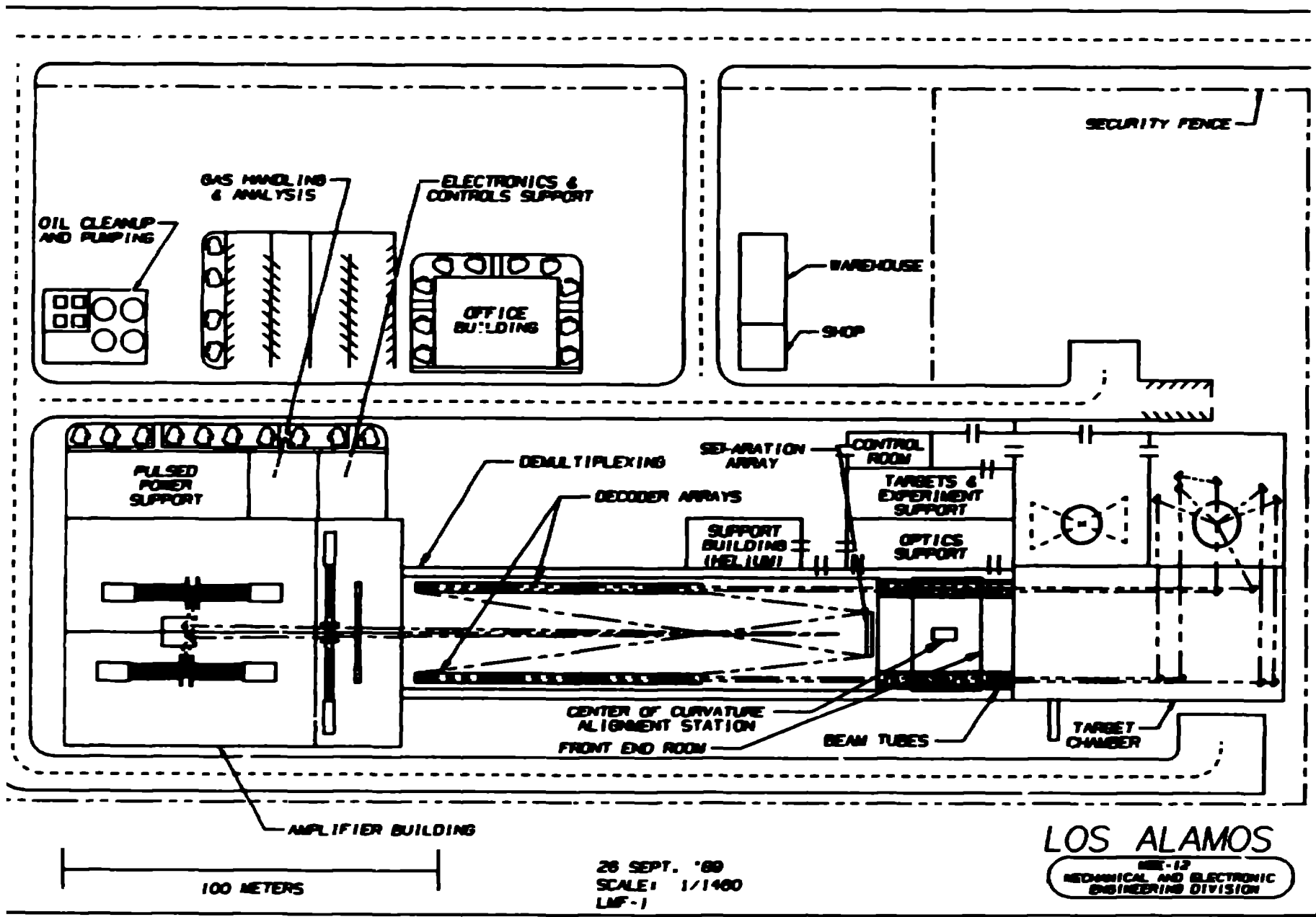
The 100-kJ LTF Facility Layout Showing the Final Three Gain Stages



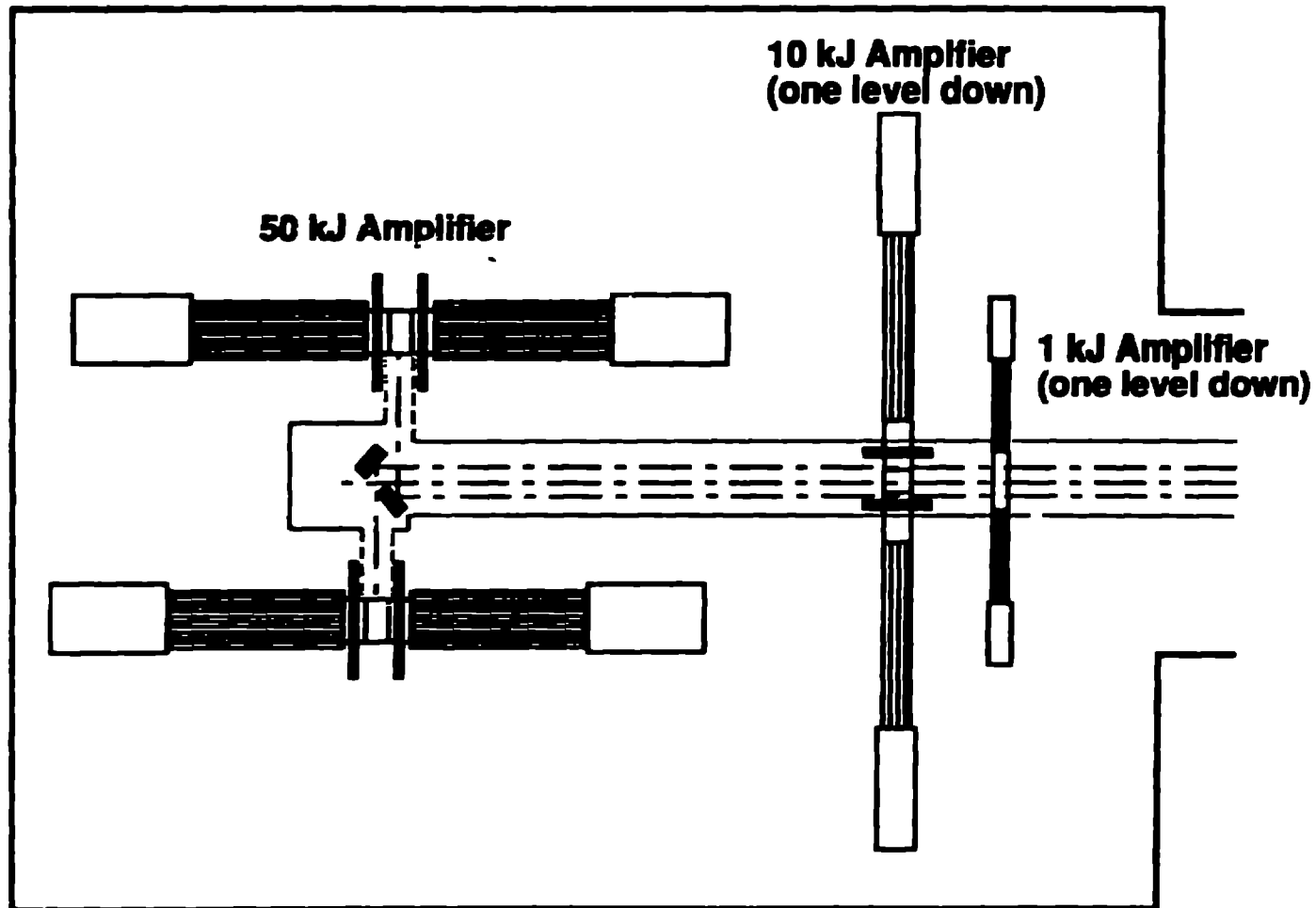
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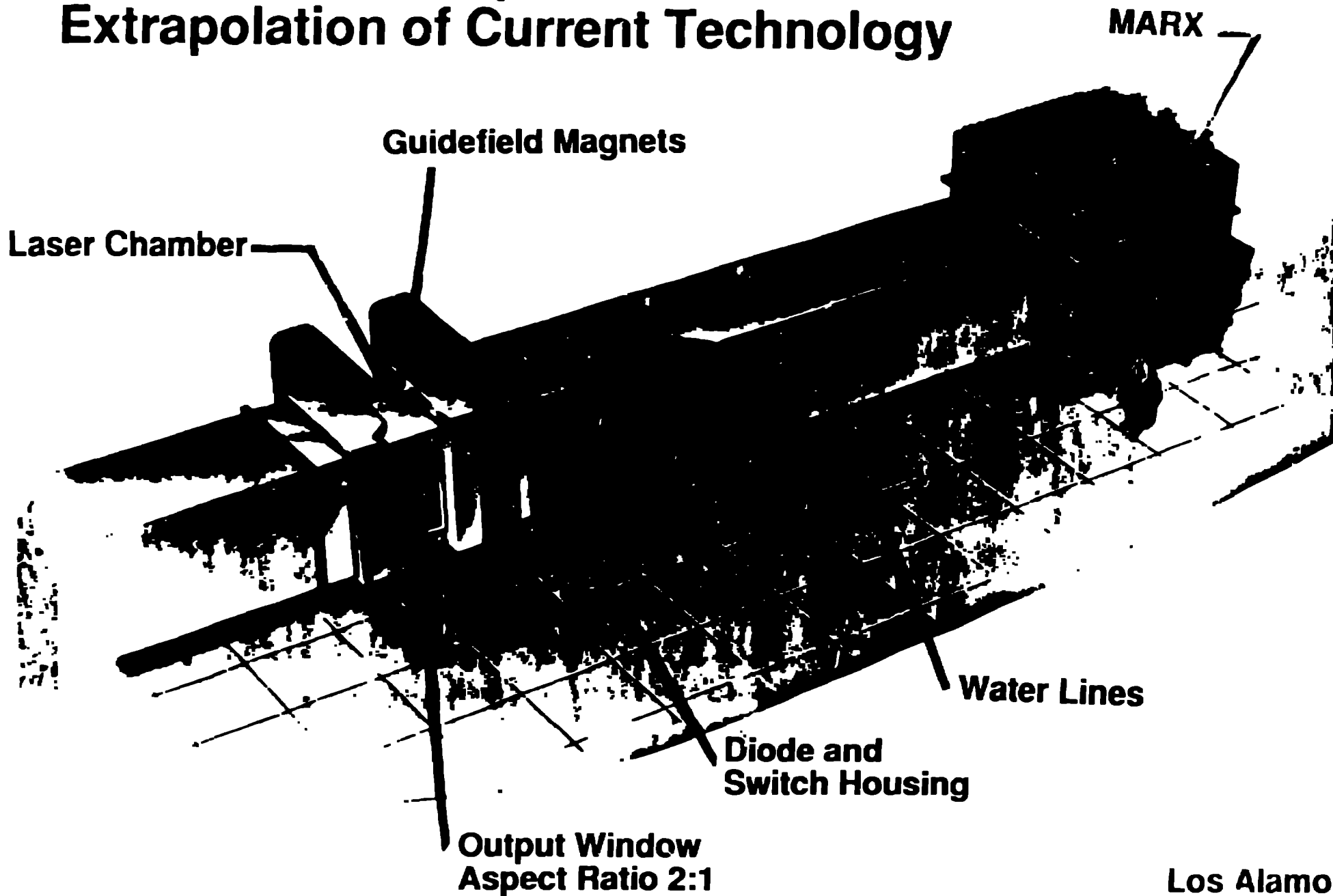
100 KJ LASER TARGET TEST FACILITY LAYOUT



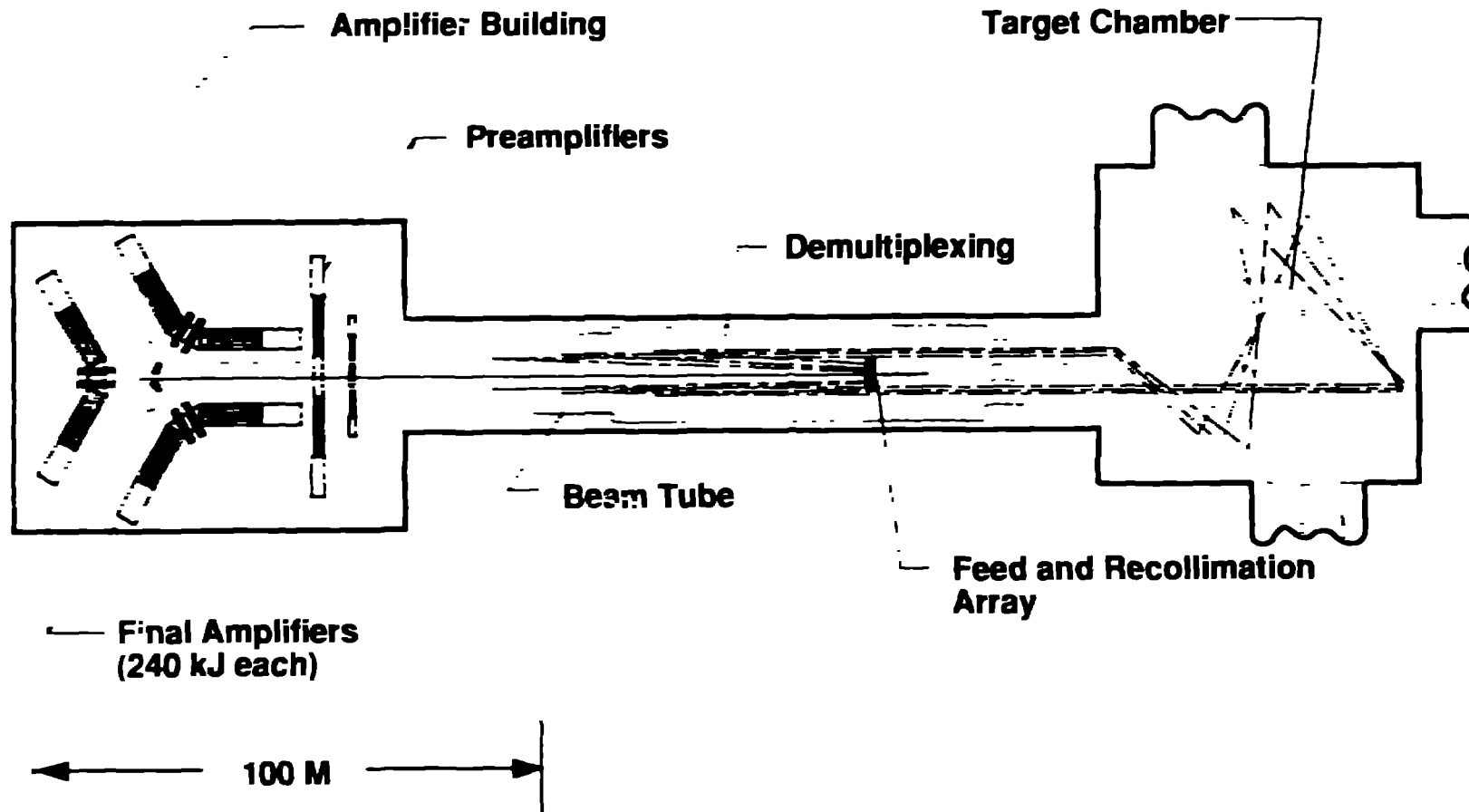
Schematic of the Last Three Stages of Amplification for the LTF



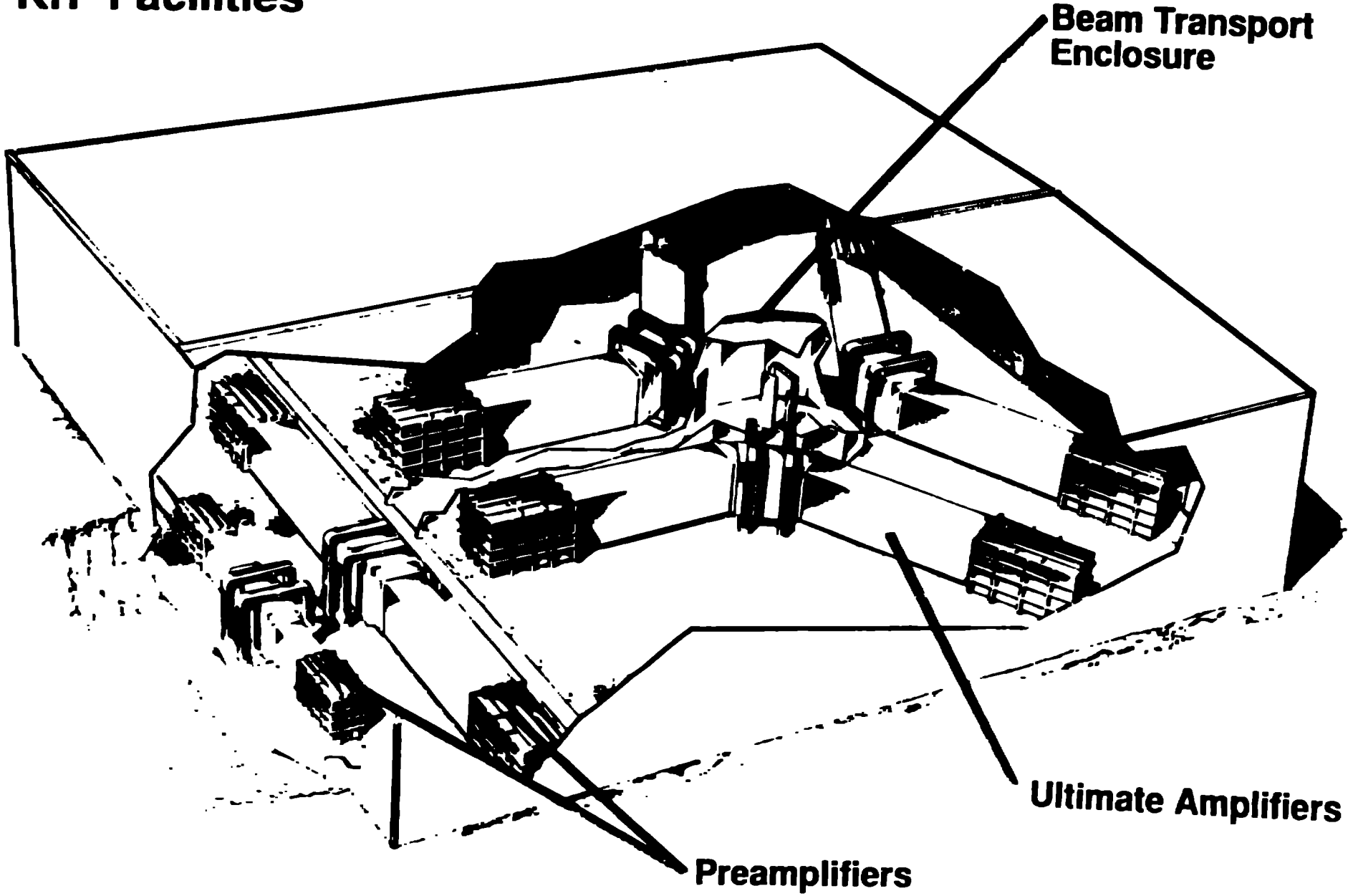
The 50 kJ KrF Amplifier is a Modest Extrapolation of Current Technology



Laboratory Microfusion Facility Beam Line (Upgradeable to 3 MJ)



Multiple Amplifier Clustering is Used to Simplify the Optics Design for Large KrF Facilities



Summary

- **An Intermediate Cost and Performance Risk Reduction Step is Required Before Proceeding to a 10 MJ LMF**
- **Los Alamos Proposes a KrF Laser-driven LTTF to:**
 - **Resolve Target Physics Issues**
 - **Determine LMF Driver Requirements**
 - **Demonstrate Driver Cost and Performance**
- **Los Alamos Has Conceptual Designs for:**
 - **A 50 kJ Amplifier Module (PSI and SRL)**
 - **An LTTF Prototype Facility (100 kJ Upgradable to 3 MJ)**
 - **A 10 MJ LMF**