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TITLE: STATUS OF CO_2-LASER FUSION

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MASTER

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STATUS OF CO_2-LASER FUSION

S. D. Rockwood

The basic concept of achieving efficient thermonuclear fusion has been proven conclusively in numerous nuclear weapons tests. The fundamental issue for inertial confinement fusion (ICF) is, how small? How small can the fuel mass be and still permit successful ignition and burn?

The ICF program has two long-term goals. The first is to provide a laboratory capability for studying weapon physics. The attainment of this goal is not represented by any one event. Rather, benefits to the weapons program are being accrued continuously with greater understanding and improved diagnostics of materials under the extreme conditions of density and temperature achieved in nuclear explosions. The commonality of ICF and weapons physics lets each program grow with advances in the other.

The second goal is to provide a controllable source of fusion energy. This goal will be much more difficult to attain, and not only requires the achievement of fusion in the laboratory but also a demonstration of engineering feasibility (VG 1).

The achievement of efficient thermonuclear burn (TNB) requires attaining a constant value for the product of fuel density, ρ, and fuel radius, R. It then follows that to keep ρR = constant as the fuel mass, M, is decreased, the density must increase as

$$\rho \sim 1/\sqrt{M} \quad . \tag{1}$$

From this simple relationship some of the problems of scaling to small fuel masses are observed. The smaller the fusion target, the better it must be fabricated and illuminated to achieve an implosion of adequate symmetry to produce the required ρ.

Preheat of the fuel prior to compression also limits the obtainable density. For the CO_2-laser driven targets this preheat comes from the hot electrons generated by the resonance absorption process. More details of this problem will be presented later. It can be shown that in the adiabatic compression of an ideal gas where PV^{γ} = constant the ratio of final to initial density scales as

$$\rho/\rho_0 \sim (E/MT_0)^{3/2} \tag{2}$$

when $\gamma = 5/3$. Thus, for a constant input energy per unit mass, E/M, the obtainable density decreases at greater than a linear rate as the initial temperature increases.

For smaller targets there is less mass to shield the fuel from preheat by the hot electrons. Thus, in scaling to small targets, just as the required density is increasing according to Eq. (1), the preheat and obtainable density is decreasing with preheat temperature according to Eq. (2) (VG 2).

The major failure in ICF to date has been the inability to achieve compressions as large as predicted in theoretical calculations. The major leverage items for correcting this situation involve target physics issues (VG 3). Improvements in understanding, and ultimately experimental performance, in these areas can decrease the energy needed for ignition by factors of 10 to 100, whereas issues of driver coupling can only decrease energy requirements by factors of 2 to 3. In the final application these factors of 2 to 3 will be very important, but for the near term there is much more leverage in attacking the target physics issues than in building larger drivers.

The target physics issues that are of greatest importance are listed in items two through five of VG 4. Since the issue for ICF is scaling to smaller driver energy and, hence, target mass, the question of the minimum ρR and fuel temperature needed to ignite a propagating burn of DT fuel is very important. Likewise, the transport of energy in the target from the region of laser absorption to the region of fuel implosion is very important. Efficient conversion of driver energy into PdV work on the fuel depends on understanding and controlling the flow of energy and its partition among various modes such as ionization, radiation, and kinetic. Finally, all of these processes must be combined with accurate equations-of-state for target materials to accurately describe the implosion of inhomogeneous targets.

An estimate of the optimum target efficiency can be made by using a rocket model where the rocket (fuel) is driven by the exhaust (material ablation) of the target. Using as a variable the ratio of initial mass to final mass, $x = M_0/M$, then the rocket reaches a velocity $V = c_S \ln (x)$ where the speed of sound in the ablating material, c_S, is the exhaust velocity. From this calculation the energy efficiency of the drive is given by

$$\eta = \ln (x)^2/(x-1) \quad (3)$$

and the momentum of the imploding material per unit drive energy is

$$p/E = 2 \ln x/(x-1)c_S \quad (4)$$

(VG 5).

These calculations are compared with experimental data in VG 6. The experimentally-measured efficiencie 'l below the predictions of this simple model. One of the principal reasons is the inefficiency inherent in trying to compress a plasma with a high velocity blowoff.

At Los Alamos these studies of hydrodynamic efficiency have been extended to measurements of the PdV work done on a fuel as a function of drive (VG 7). The results are not encouraging with maximum conversions of only a few percent of the drive energy into thermal energy of the fuel.

These experiments were performed on targets which are directly illuminated by the laser. There are several problems that are encountered in this type of target (VG 8). These problems are compounded by the preheating of the fuel by the hot electrons. Since the hot electrons have been the subject of so much concern for CO_2-laser-driven targets, the scaling of their temperature with laser intensity has received a great deal of attention both theoretically and experimentally. The results of some of this work are shown in VG 9.

Given that so much of the deposited laser energy appears as electron thermal energy, the natural question for CO_2 becomes: can targets be designed which take advantage of the energy in the electrons for driving implosions while isolating the DT fuel from preheat? The answer to this question is yes - several such target concepts have been examined theoretically during the last year, and, at least on a computer, they work. The basic thrust of the experimental program has been, and will continue to be, the verification of the key physical assumptions made in the experimental design of these targets.

One specific example has been examined by M. Alme of the Mission Research Corporation on contract to the Los Alamos program. This target uses the hot electron energy to drive the ablation. The initial target design is shown in VG 10. Initially the ablator material is on the order of a few mean free paths for the hot electrons. As the material is compressed by the implosion the hot electron temperature is allowed to rise, keeping the depth of the thickness of the compressed material to a few electron mean free paths. The hot electron temperature as a function of laser intensity just presented is used as input data for the calculations. The center of the target is void to allow improved adiabatic compression. The ablator material is LiH to avoid energy losses by radiation from a high-Z material.

The calculated pulse shape given in VG 10 yields performance of this target as shown in VG 11. While the performance of this target requires the generation of a temporally-shaped laser pulse as discussed in the early days of ICF, the reasons are quite different. Initally pulse shaping was used to provide ideal adiabatic implosions, whereas this pulse shape is used to adjust the hot electron temperature and thereby optimize electron deposition in the pusher. There are two major concerns that must be addressed experimentally before the validity of these calculations are addressed.

One concern is the growth of instabilities and a subsequent lack of symmetry in the implosion. This will limit the final ρ and degrade target performance as discussed above. The other is a geometrical decoupling of the hot electrons generated at the critical surface from the imploding pellet.

The target design just discussed uses the hot electrons in the compression drive. An alternative concept is to isolate the hot electrons from the fuel. To isolate the electrons from the fuel an effect called vacuum insulation is exploited.

When a target material is irradiated by a laser the target can be charged to a very high potential by the initial departure of a relatively small number of hot electrons. Further electron escape is then limited by the space charge. Consequently the hot electrons are confined to the expanding ion plasma and their transport is confined to the velocity of the ion expansion. This effect is called vacuum insultion and has been studied previously by both Los Alamos and Sandia.

We have continued experiments in this area and they have shown positive results (VG 12). The experiments measured the transit of fast electrons between a controlled target and a titanium foil sensor. The arrival of the hot electrons at the sensor was monitored by the emission of K_α x rays. Because hot electrons are only generated during the laser pulse, a velocity characteristic of energy transport can be determined from the known pulse length and separation of target and sensor.

The results of recent experiments are shown in VG 13. The rapid decrease in signals observed beyond a critical distance is a definite indication of the effects of vacuum insulation. The velocities are observed to be less than 1 mm/ns. This is appropriate for isothermal expansion of the ion cloud and far too slow for electrons of 80 to 100 keV. This isothermal expansion model is the basis for the analytic calculations shown. Further evidence for the control of electrons by ions is given by the change in transport velocity with materials as shown.

Vacuum insulation is a key element in some new target concepts being studied, and it will continue to be the subject of theoretical and experimetal investigation.

Another target concept in the class of designs uniquely suited for drive with a CO_2 laser is the Arcturus target. This design has proven very insensitive to details of the laser pulse shape and computationally yields energy gains of about 5 with energy inputs of 1 to 2 MJ (VG 14). Since the heating mass requires energy, the critical tests of this target concept will be performed with the Antares laser facility (VG 15).

The investigation of targets uniquely designed for CO_2 lasers is continuing at a rapid pace at Los Alamos with interaction between theory and experiments. The Antares laser will play a key role in verifying the validity of scaling relationships now being established in experiments on Helios. The next two viewgraphs show one of the Antares power amplifiers (VG 16) and the space frame being inserted into the target chamber (VG 17). The power amplifier will provide 20 kJ in 1 ns.

We have presently curtailed further development of CO_2 lasers in order to devote full attention to target physics issues (VG 18). We believe the scaling of large CO_2 lasers is well established, and if the critical physics issues of our target designs are verified with Helios and Antares experiments then we will begin the design of the next generation laser. This decision point will occur in the mid-1980's.

THE ICF PROGRAM HAS TWO LONG-TERM GOALS

(1) TO PROVIDE A LABORATORY CAPABILITY FOR STUDYING WEAPON PHYSICS

(2) TO PROVIDE CONTROLLABLE FUSION ENERGY

BOTH GOALS SHARE A COMMON, NEAR-TERM OBJECTIVE

DEMONSTRATE THE SCIENTIFIC FEASIBILITY OF THE THERMONUCLEAR BURN OF SMALL FUEL MASSES (<1 mg)

VG 1

HIGH COMPRESSION OF THE FUEL IS ESSENTIAL TO ICF TARGET PERFORMANCE

TO KEEP ρR CONSTANT REQUIRES

$$\rho \sim 1/\sqrt{M}$$

AND

$$\rho/\rho_0 \sim (E/MT_0)^{3/2}$$

EMPHASIZES THE PROBLEM OF PREHEAT

THE MAJOR LEVERAGE ITEMS IN ICF TARGET PHYSICS ARE·

(1) STABILITY OF IMPLOSIONS

(2) ENERGY TRANSPORT

(3) IGNITION CRITERIA

ISSUES OF DRIVER COUPLING ARE NOT AS IMPORTANT IN TERMS OF INCREASING TARGET GAIN PER UNIT ENERGY INPUT

THE DEMONSTRATION OF SCIENTIFIC FEASIBILITY OF THERMONUCLEAR BURN (TNB) OF SMALL FUEL MASSES REQUIRES EMPHASIZING TARGET PHYSICS STUDIES IN

(1) DRIVER/TARGET COUPLING

(2) MARGINAL IGNITION CONDITIONS

(3) ENERGY TRANSPORT

(4) STABILITY OF IMPLOSIONS

(5) MATERIAL PROPERTIES IN EXTREME CONDITIONS

AN UPPER BOUND ON TARGET EFFICIENCIES CAN BE MADE BY USING A ROCKET MODEL.

$$V = C_S \, LN(X) \qquad X = M_0/M$$

$$EFFICIENCY = \frac{ROCKET\ KE}{EXHAUST\ KE} = \frac{[LN(X)]^2}{(X-1)}$$

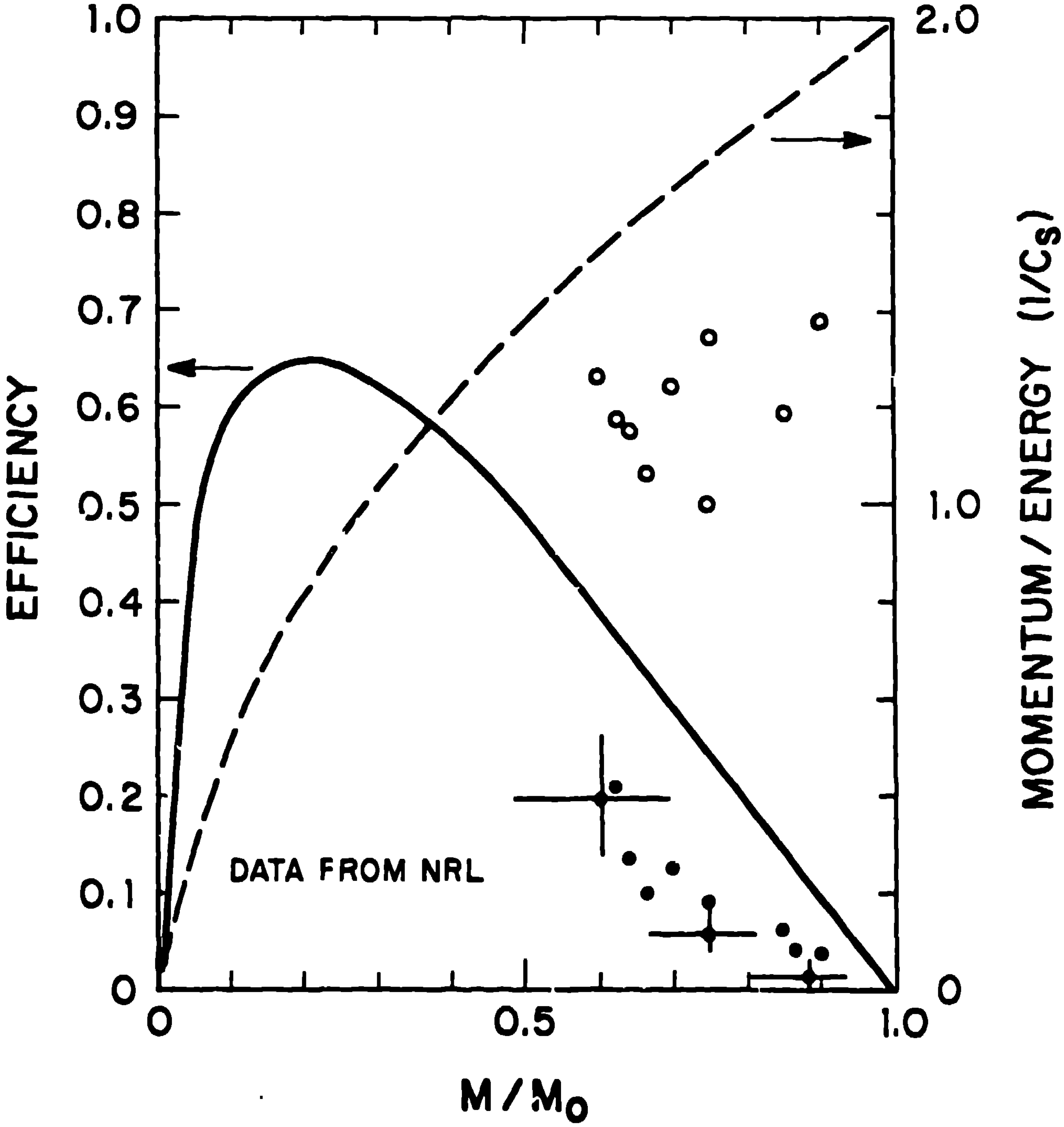
$$MOMENTUM/ENERGY = \frac{2\,LN(X)}{(X-1)\,C_S}$$

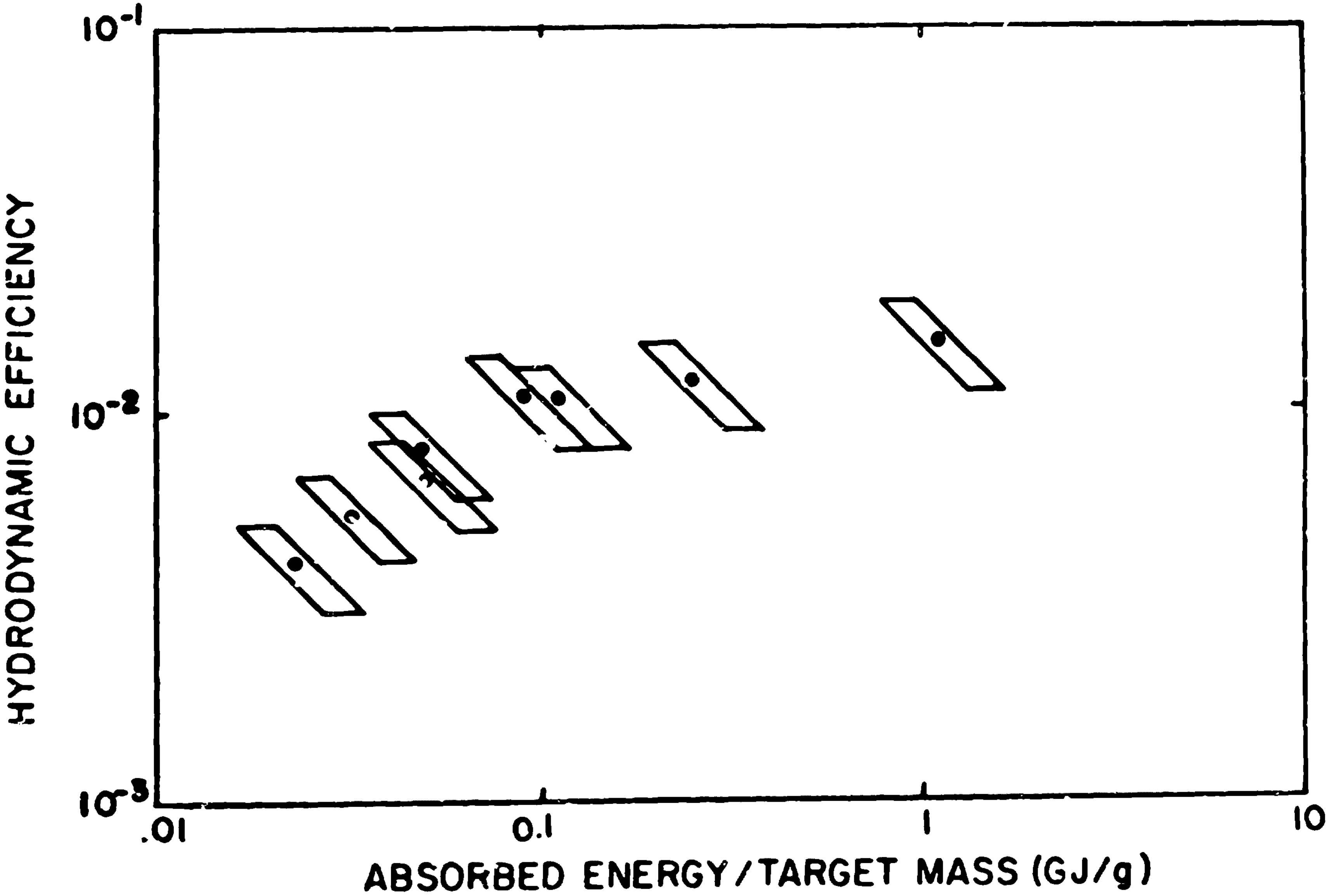
NOTE THE ADVANTAGE OF MINIMIZING THE BLOWOFF VELOCITY, C_S.

VG 5

AP-IF-VG-152

THE ROCKET MODEL GREATLY OVERESTIMATES THE HYDRODYNAMIC EFFICIENCY OF FUSION TARGETS




10⁻¹
10⁻²
10⁻³
HYDRODYNAMIC EFFICIENCY
.01
0.1
1
10
ABSORBED ENERGY/TARGET MASS (GJ/g)

VG 7

DIRECT ILLUMINATION TARGETS HAVE ADVANTAGES AND DISADVANTAGES

Los Alamos

DECOUPLING

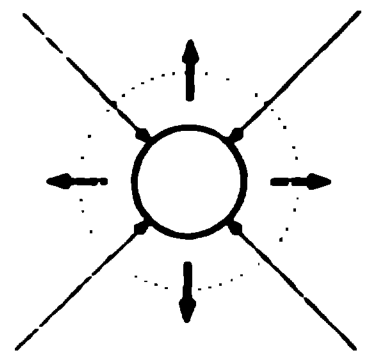
- FAST ION LOSS
- RAPID OUTWARD MOTION OF CRITICAL SURFACE
- INEFFICIENT THERMAL ENERGY TRANSPORT
  - HOT ELECTRONS IMPROVE TRANSPORT

SYMMETRY

- HOT ELECTRONS IMPROVE IT

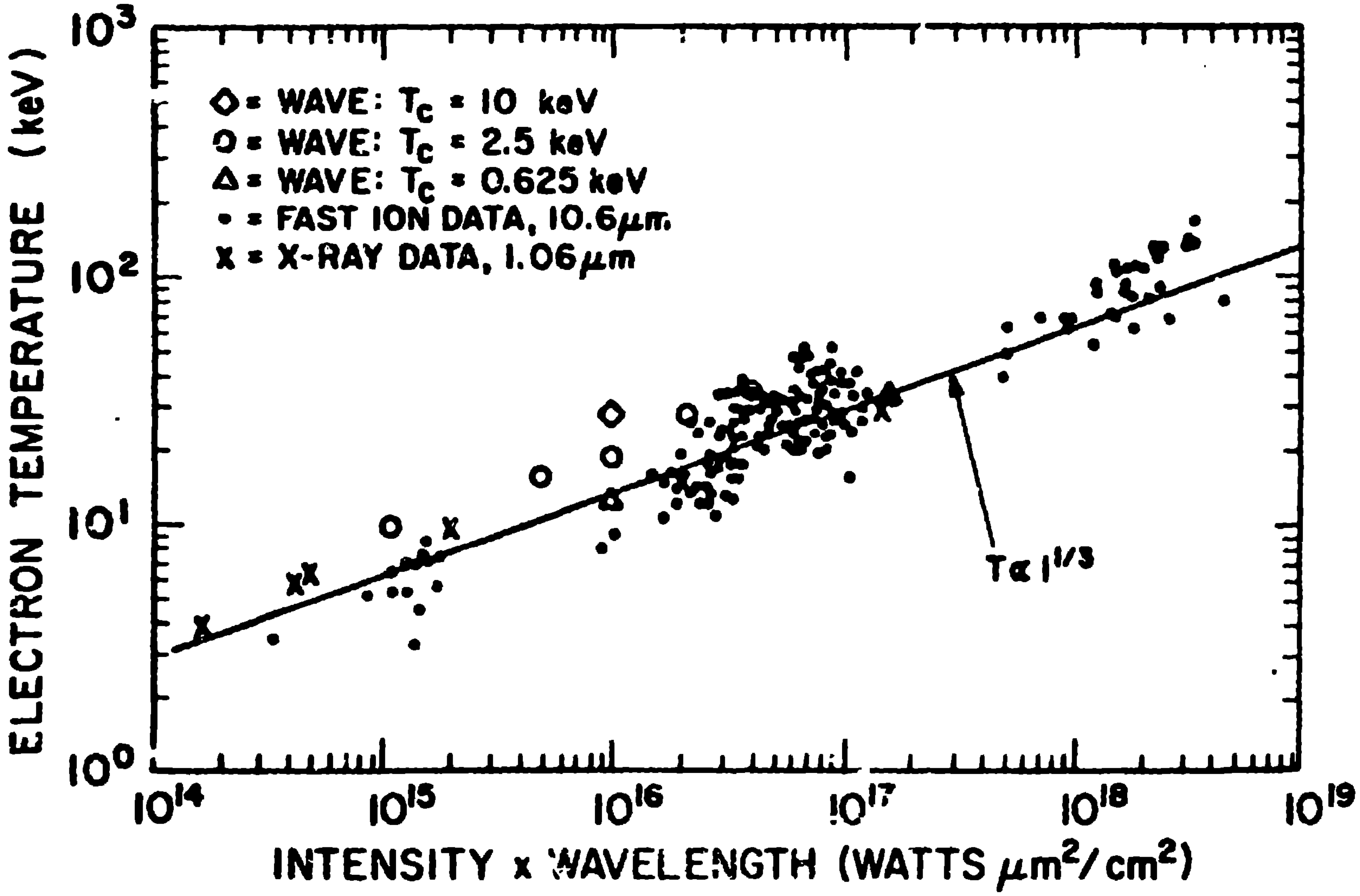
INEFFICIENT DRIVE OVERCOME WITH THIN SHELLS

- IMPLIES LONG SHAPED LASER PULSE
- STABILITY AND SYMMETRY BIG ISSUES
- DECOUPLING STILL SERIOUS



MRC HAS DEVELOPED A POSSIBLE TARGET

THEORETICAL AND EXPERIMENTAL SCALING OF HOT ELECTRON TEMPERATURE WITH INTENSITY

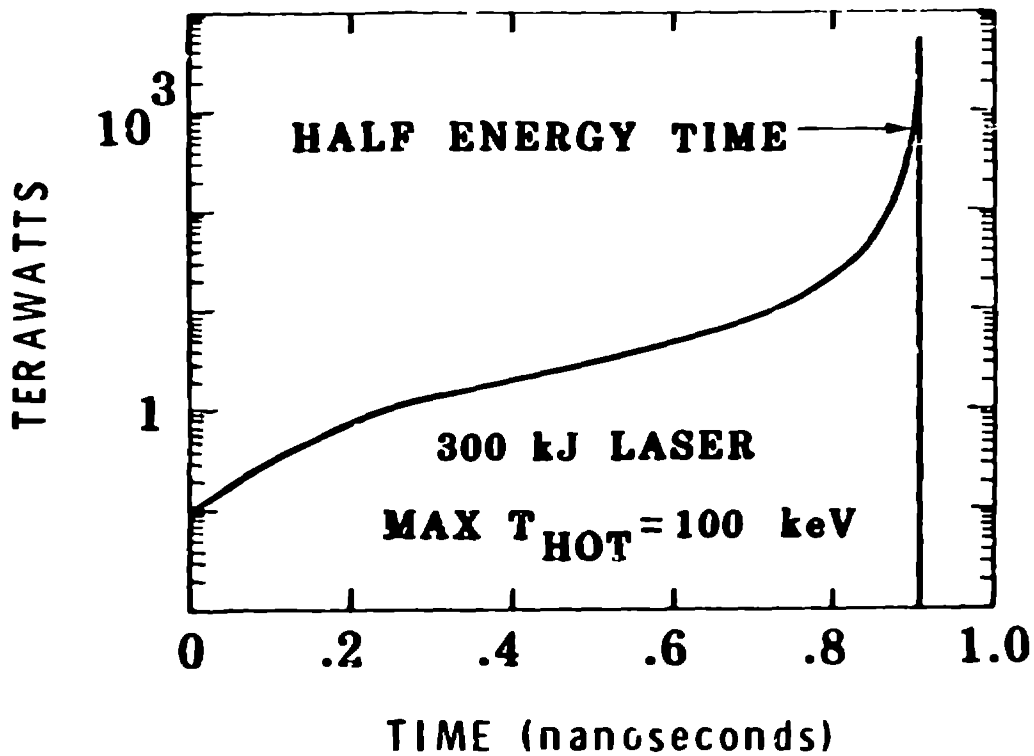


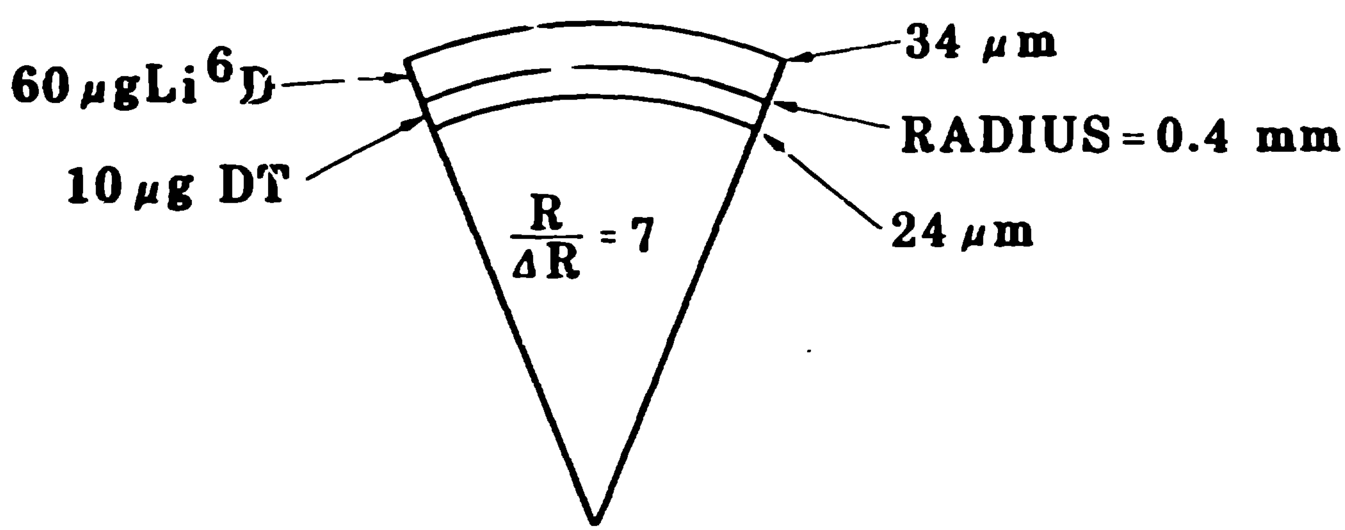
VG 9

AP-IF-VG-122

10 μg HOT ELECTRON DRIVEN TARGET

LASER POWER



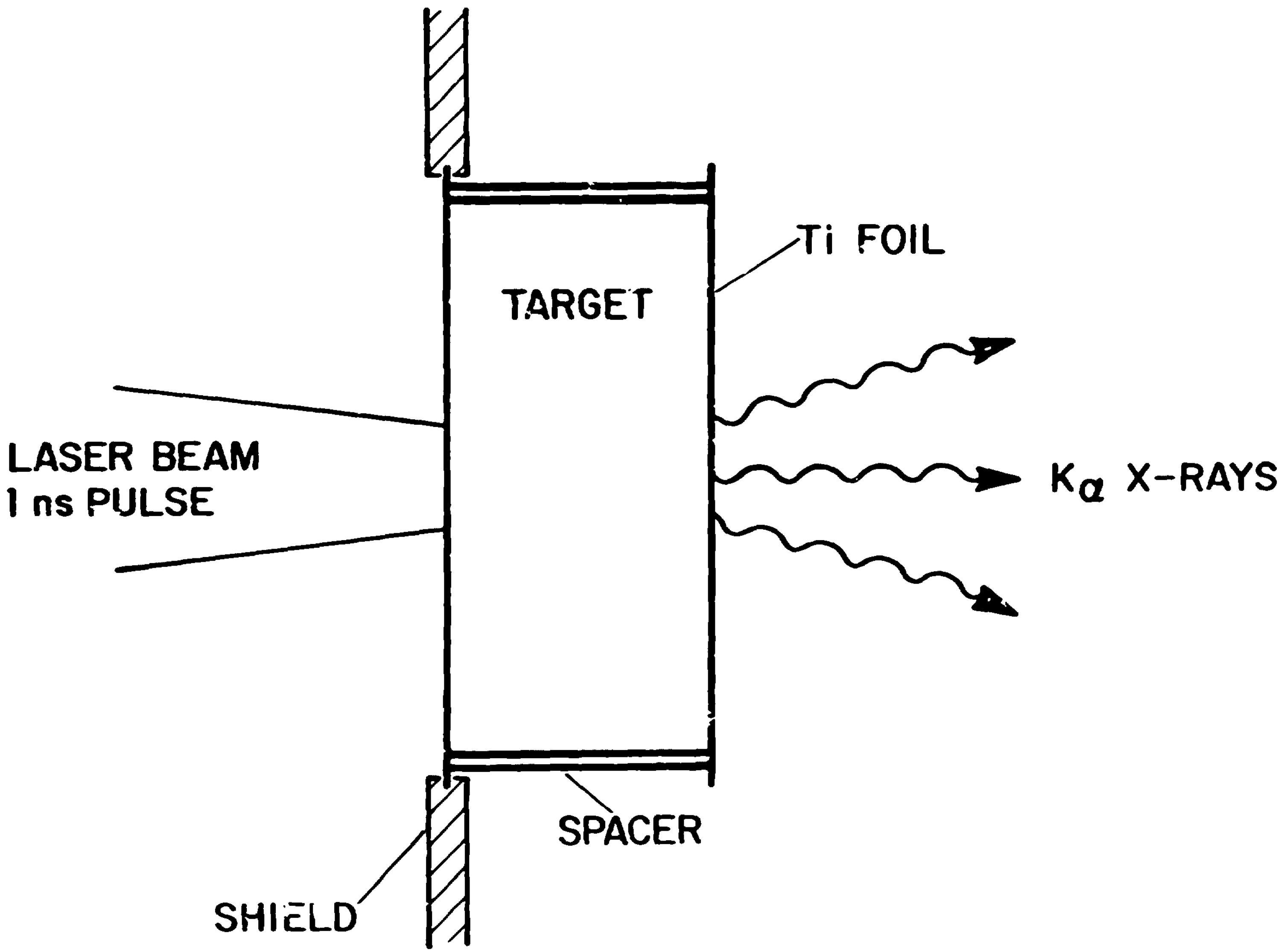


VG 10

DIRECT HOT ELECTRON DRIVE (MRC)

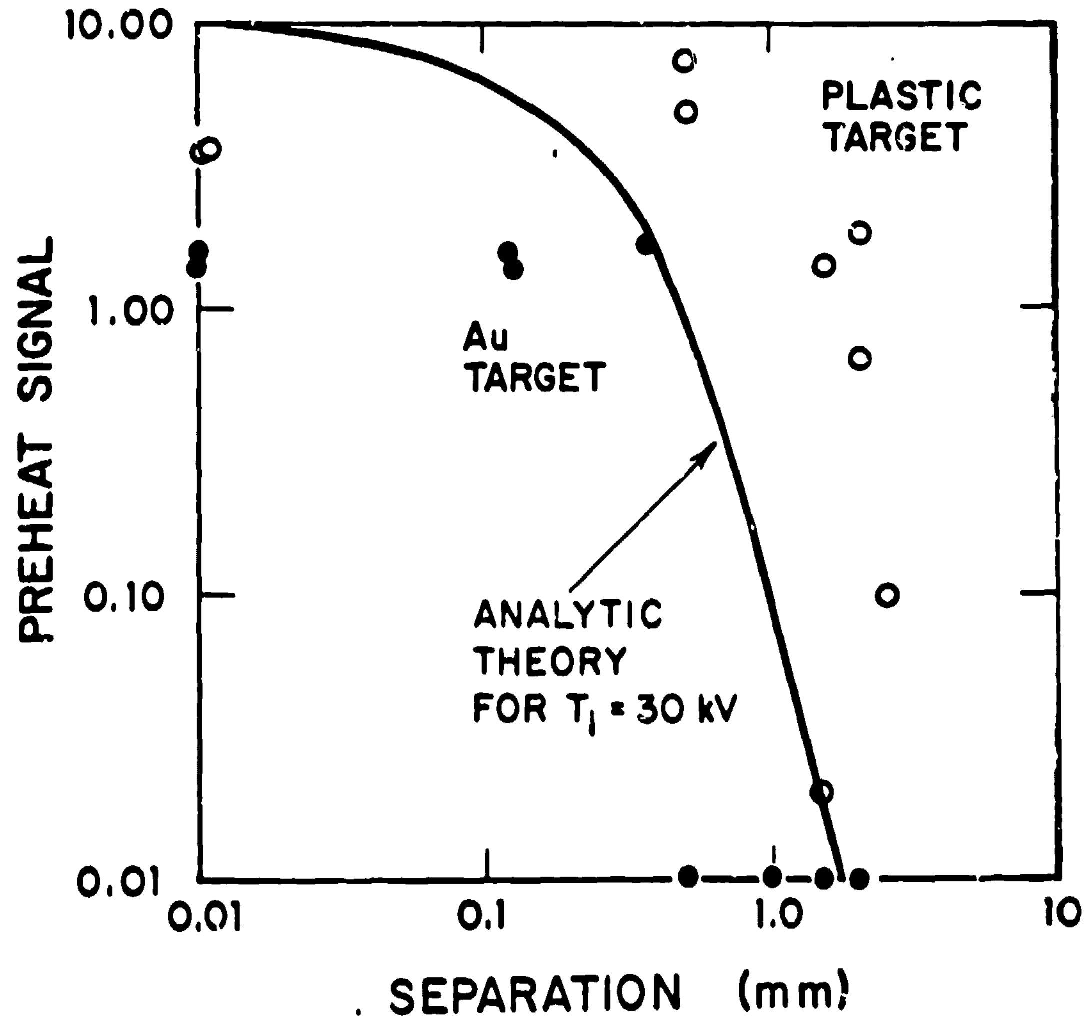
- CONTROL PREHEAT BY INCREASING T_{HOT} AS ρR RISES
- CALCULATIONS WITH MACH I (FAST)
  - NO BURN
  - SPECIFIED HOT ELECTRON DEPOSITION
- 10 μg CAPSULE DRIVEN WITH 300 KJ
- 100 μg CAPSULE DRIVEN WITH 1.0 MJ

EXPERIMENTAL SET-UP FOR MEASUREMENTS OF VACUUM INSULATION



VG 12

EXPERIMENTAL RESULTS SHOW THAT ELECTROSTATIC INSULATION WILL SHIELD THE FUEL FROM PREHEAT BY HOT ELECTRONS.

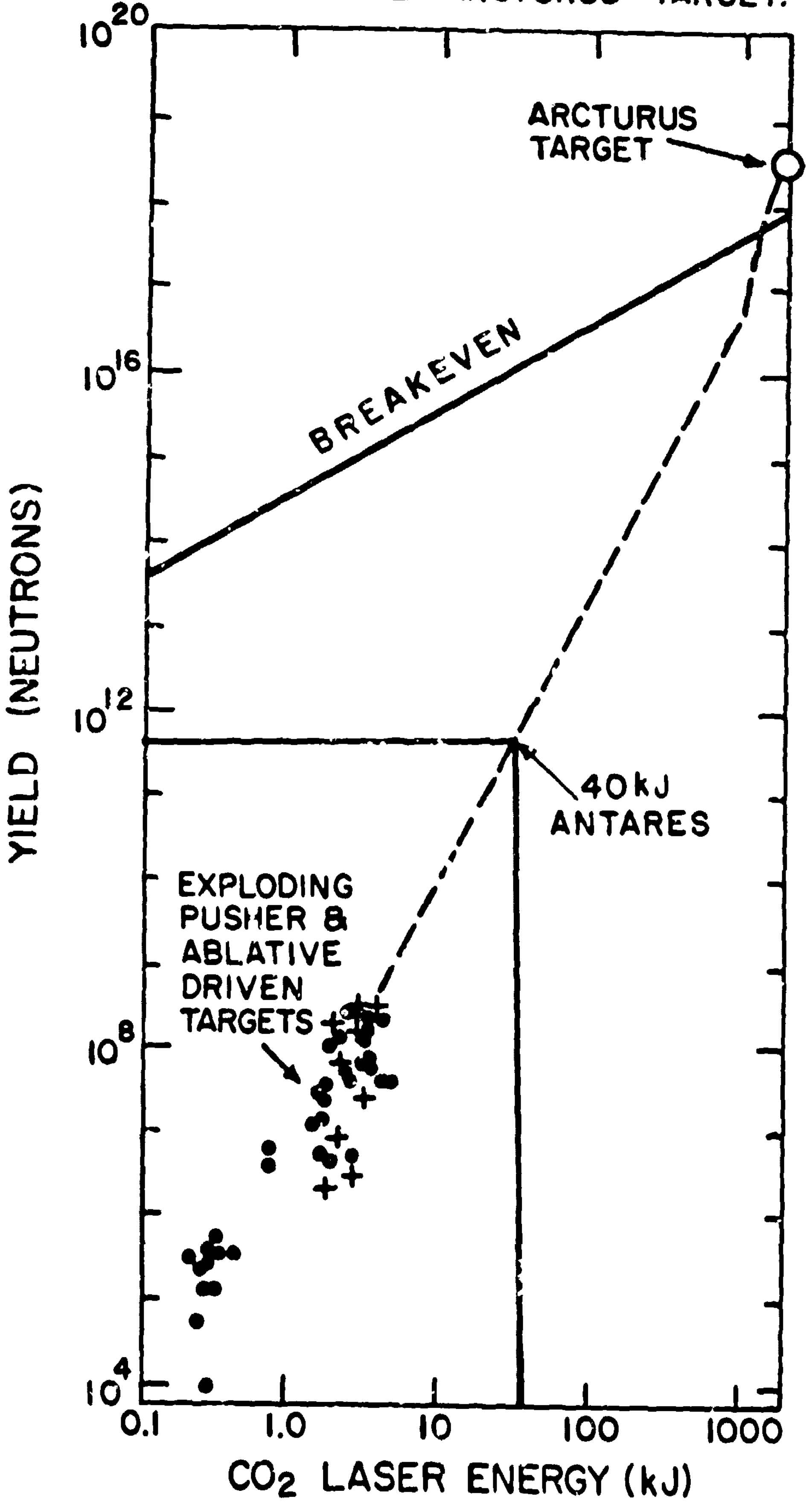


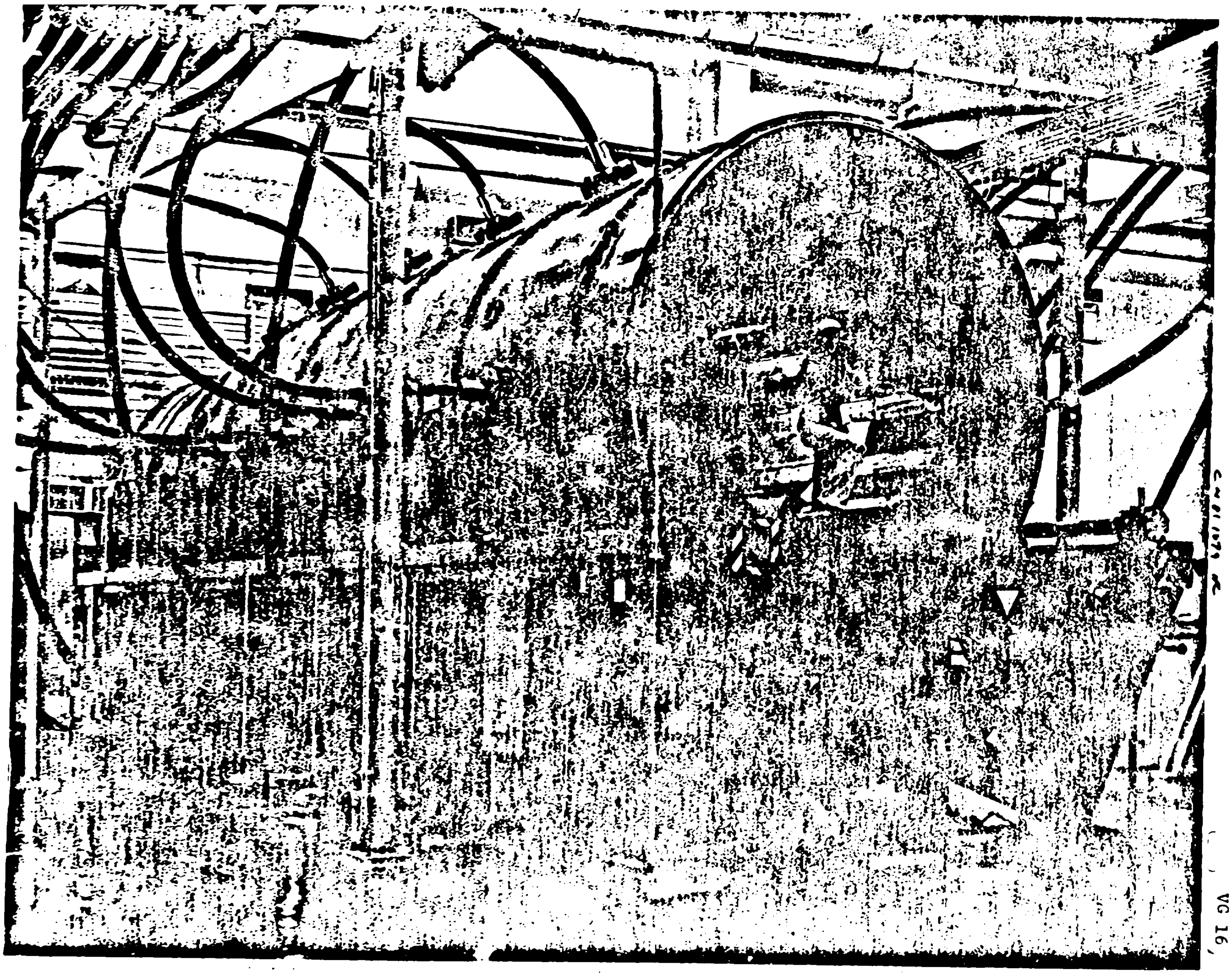
THIS IS A VERY IMPORTANT RESULT FOR NEW CO_2 LASER TARGET DESIGNS.

THE ARCTURUS TARGET

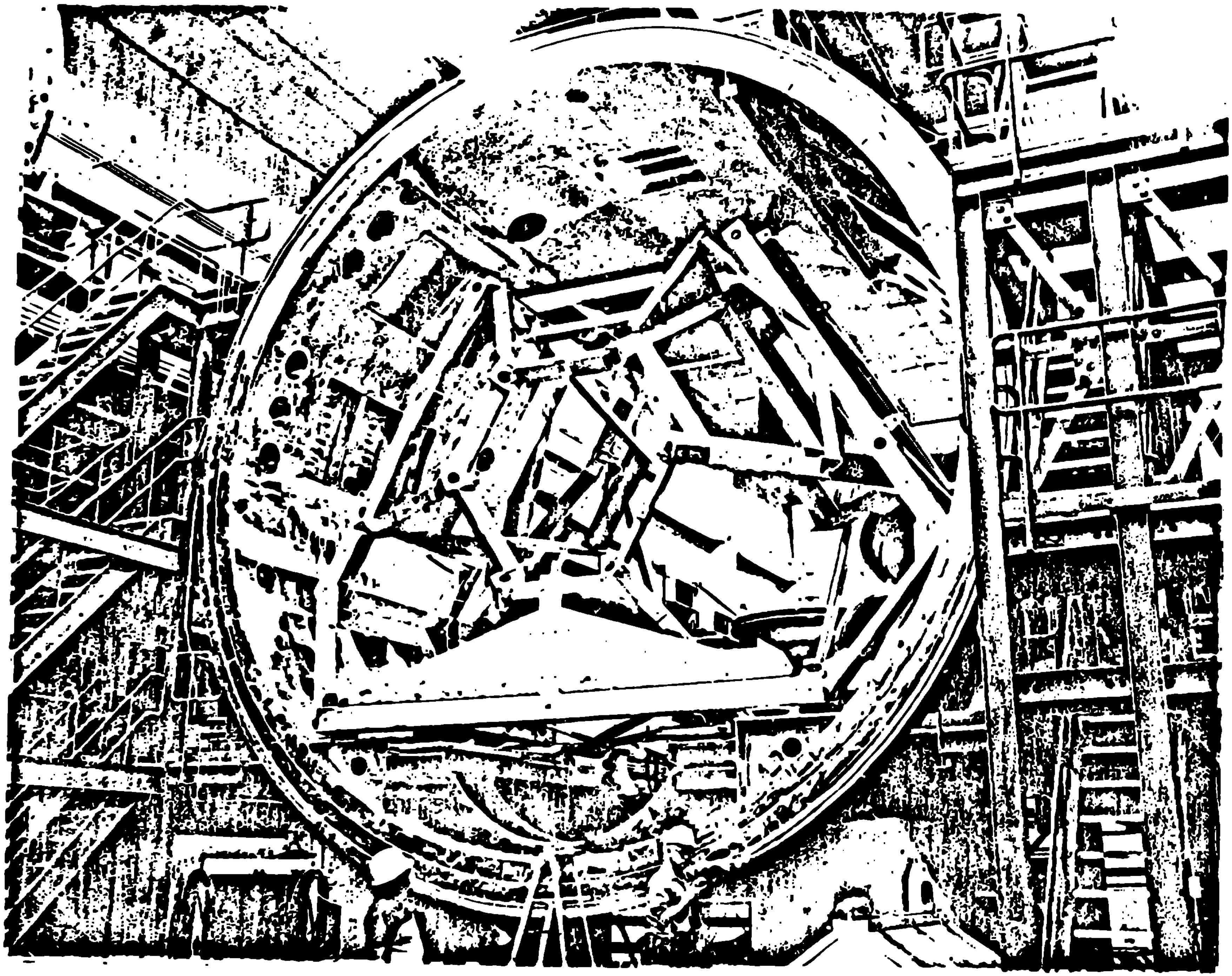
- IS INSENSITIVE TO LASER PULSE SHAPE
- PROVIDES ENERGY GAINS OF 5 TO 10 WITH INPUTS OF 1 TO 2 MJ

ANTARES WILL BE USED FOR CRITICAL TESTS OF THE ARCTURUS TARGET.





VG 16



VG 17

THE ADVANCED CO_2 DRIVER DECISION CAN OCCUR IN FY84-FY85