MULTI-MEGAJOULE HEAVY ION INDUCTION LINACS

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MULTIMEGAJOULE HEAVY-ION INDUCTION LINAC*

Abstract

One of the most promising Inertial Confinement Fusion (ICF) igniter concepts is the heavy ion induction linac system. A driver providing a beam of heavy ions has the potential advantages of a short ion range in the target material, a very large power transport capability, and the ability to produce high power densities at distances of 5-10 meters from the final lens elements required in a power producing reactor.

Many driver configurations are possible, and it has been generally found that the driver would be the dominant cost item in a power plant. Some preliminary results obtained from a design and cost optimization computer program for an ion induction linac accelerator are presented. An estimate of the effect of ICF system cost on the cost of generated electricity is made.

1. Introduction

For electrons, the induction linac has been well-established as a high-current (> 1 kA), high brightness accelerator with high repetition rate, good electrical efficiency, and high operational reliability.[1,2] In such accelerators the electrons are injected at a speed close to that of light so that the beam current, I, and pulse duration, t, remain constant along the machine. The transverse focusing system is a relatively minor part of the system, and longitudinal focusing is not necessary. The design procedure thus becomes one of designing a single accelerating module appropriate to the chosen I and t; the accelerator consists of a sufficient number of such identical modules to achieve the desired final beam energy.

For heavy ions at non-relativistic ($v < .5c$) velocities, the focusing requirements dominate the low-energy end of the accelerator, and near the ion source make alternate accelerator types such as pulsed drift-tubes[3] preferable. At the high-energy end the required heavy ion currents and pulse durations are comparable to those attained with electrons, and the machines show some similarity. The character of the induction linac therefore is expected to change significantly along the machine. The ability to achieve current amplification by modest differential

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acceleration with slightly ramped voltage pulses is an important degree of freedom, but it comes at the price - to the designer - of allowing a free choice within wide limits of the beam current at any point along the machine. The upper bound on current is set by the transverse space charge limit; on the lower side, while there is no physical bound, in general one finds that a decrease in current for fixed total charge is accompanied by a decrease in electrical efficiency and an increase in cost. The particle mass and charge state may be selected from a large set of acceptable candidates, and also the integrated voltage, V_f, (kinetic energy/charge-state) is a matter of choice within limits since only the product, $(ItV_f) = Q$, is specified for a driver delivering Q joules to the target. The design procedure for a heavy ion induction linac for this application is much less transparent than for electrons even without considering the further target requirements of energy and power densities.

2. Target Design Considerations

Calculations show that a specific energy of at least 20 MJ/g is needed to drive a target capsule implosion; hence the ion beam must deposit $Q > (4\pi r^2R)(2\times10^7)$ joules in a spherical target where r is the target radius in centimeters and R is the ion range in grams per square centimeter. We find that targets with radii of several millimeters are appropriate for power production designs.

For a given total beam energy, the minimum target radius places an upper limit on ion range and therefore on the ion kinetic energy. This limit on ion kinetic energy strongly influences accelerator design.

Two types of targets are under consideration. A single shell capsule is simple but relatively sensitive to small variation in input pulse shape. A complex double-shell design achieves high gain at lower power and is less sensitive to input pulse shape. Pulse shaping would be achieved by controlled bunching in the final beam transport lines.

Fig. 1 is a plot of single-shell and double-shell capsule gain (the ratio of thermonuclear energy produced to input energy supplied) obtained from computer simulations. The single-shell capsules exhibit a flatter gain curve than the double-shell capsules. The rapid decrease in double-shell gain at lower energies results from the failure of the thermonuclear burn to propagate from the inner to the outer fuel compartment.

A single-shell capsule that needs 3 MJ of energy typically requires a peak power of about 300 TW. A corresponding double-shell capsule might require only about half as much peak power. If we assume purely hydrodynamic scaling, the peak power requirement is proportional to the 2/3 power of energy.

3. Accelerator Design Approach

Because of ion source and very-low-energy transport considerations, the source current is limited to about ten amperes, whereas many kiloamperes are needed at the target. The required current amplification can be accomplished by a combination of increased particle velocity and decreased physical bunch length, as allowed by focusing limits, followed by an implosive longitudinal compression in the final transport lines to the target chamber. In the final transport lines the beam is first split into 4 beams transversely, and finally it is subdivided into 16 or more beamlets for proper focusing on the target. While eventually it would be desirable to include the source, low energy accelerator, final transport lines, and final focusing lenses in a comprehensive systems study, we have concentrated on the induction linac portion from 50 MV to final energy because it is the major cost item. Cost savings arising from improvement in the appendages at either end of the linac are limited to the cost of the presently non-optimized injector and final transport, which amount to about 10 percent each. We have been studying the induction linac under the assumptions that a suitable 50 MV injector is available to supply any ion with any charge state, that the final transport is relatively insensitive to accelerator choices, and that the final buncher section of the accelerator is the same as a standard accelerator section with only slightly increased voltage ramping.

4. Methodology

To address the main part of the system, viz. the Induction Linac, a computer program (LIACEP) has been developed to sort through the possible engineering options at each voltage point, V, along the machine and to generate the desired cost and design information[4].

We start by specifying an ion species, charge state, transverse emittance, betatron tune depression and accelerator repetition rate. Next, a total beam charge sequence to be explored -- 30 μC, 60 μC, 90μC ..., etc. is specified. Then at any voltage point, V, along the accelerator the cost consequences of adding a further 1 MV are examined. The independent variable is chosen to be the current, I, with the magnet occupancy factor, k, for a symmetrical FODO lattice, as a separately varied parameter (e.g., k = .50, .33, .17, .10, .05, etc.). In this way a matrix of differential costs for each value of k and current are generated. The minimum cost option can be determined and the cost/benefit ratio of departing from the minimum can be examined. To determine the minimum cost accelerator, the unit costs are integrated over the voltage range considered.

Several design configurations and core materials are explored (See [4]).

The sensitivity of cost and efficiency to the space-charge limited current seems a general feature and it becomes important to have a good understanding of what betatron tune depression can be safely tolerated in the transport system. At present a phase-advance per period of 60 deg. with no current, depressed to 24 deg. at maximum current for a K-V distribution is used to specify current, beam diameter, and focusing magnetic field strength.[4,5]

5. Results

For driver accelerator beam energies to 10 MJ, a matrix of accelerator parameters has been considered for induction linac accelerators with the LIACEP program.

MATRIX OF DRIVER ACCELERATOR PARAMETERS

Ion Type: Cesium (133), Thallium (204), Uranium (238)
Charge State: +1, +2, and +4 (+1 only for Thallium)
Normalized Beam Emittance: 2, 3, 4, and 6 (x 10^{-5} πm-rad)
Electrical Beam Charge: 25 - 1000 μC (in ten suitable increments)
Repetition Rate: 1 hertz

A typical set of accelerator cost results is given in Figure 2. Shown is minimum accelerator cost as a function of particle energy and beam charge for uranium +1. Superimposed are 1, 3, and 10 MJ iso-beam-energy curves. Also shown is a suggested particle-energy versus beam-energy curve which represents the target physics requirements. This example shows driver accelerator cost scaling as $Q^{0.6}$. Total driver cost, which includes the injector and final beam transport, will probably scale close to the square root of beam energy for this case.

For other ions, charge states, and emittances, the results take the same form as those shown in Figure 2. Figure 3 shows a comparison of accelerator costs for the three ion types considered for a 3 MJ driver. We see here that the trend is for driver accelerator cost to decrease with decreased ion atomic mass. The normalized emittance required for the minimum cost accelerator increases with decreased ion mass. Other work shows that for a given ion and normalized beam emittance minimum accelerator cost decreases with increasing charge state, but not in simple proportion because of the constraint imposed by transverse stability on electrical current. The accelerator cost increases only slightly with increasing repetition rate.

For a 3 MJ driver total accelerator length is 10 km and efficiency is 13 percent at 1 hertz, increasing to about

25 percent for 10 hertz. The accelerator efficiency is the total beam energy divided by the sum of the energy consumed by the transport magnets during the interpulse interval and the energy consumed by the pulse modulators which drive the induction modules. The efficiency of acceleration increases along the accelerator, as the transportable beam current increases, to a value near 50 percent. The above results all pertain to cases where the accelerator capital cost is the parameter which is minimized, but the program also could be used to maximize efficiency or some other parameter. Moving off of the optimum point by a small amount with any one variable is not expected to change costs significantly.

It must be emphasized that these cost studies are useful as a design guide and as a tool for identifying the cost sensitivity to any of the input assumptions and engineering options and costs and the absolute value of the cost figures should be treated with caution.

6. Economic Feasibility

The economic feasibility, simply translated, means that the capital costs of the facility are not too much more than the costs of other energy systems. For a fusion energy system, since the fuel costs are generally assumed to be negligible, the critical parameter is the amount of recirculating power. The net power P_{NET} is given in terms of the total power P_{TOT} by

$$P_{NET} = (1 - f)P_{TOT}$$

where f, the fraction of power recirculated, is given by

$$f = (\eta g \varepsilon)^{-1}$$

in which η is the electrical conversion efficiency of the driver, g is the pellet gain, and E is the overall thermal-electric conversion efficiency of the power plant. The value of P_{TOT}/P_{NET} is plotted in Fig. 4 as a function of driver efficiency η for the case of a 3 MJ/pulse driver. The pellet gains assumed are $g = 100$ for the optimistic case and $g = 50$ for the pessimistic case. The thermal-electric efficiency is assumed to be one third.

The lowest cost source of electrical power available today for new, large-scale construction, is the light water nuclear reactor. In 1977 dollars, Rossin and Rieck[6] found that the busbar cost of nuclear power was $0.035/kWh including 20 percent for fuel. If, for the sake of simplicity, one assumes that the capital cost of the ICF power plant is the same as for a light water reactor power plant, expressed in dollars per total kilowatts, then the ratios shown in Fig. 4 show by how much the cost of ICF generated power will exceed the cost of light water reactor power.

The above assumptions ignore the cost of fissile fuel and the cost of the driver system. If the cost of fissile fuel directly offset the cost of the fusion driver system, then the above calculation would accurately predict the cost of ICF power. With current technology, the best estimates for the cost of a 3 MJ driver is around $1 billion, so that even if the driver can operate two reactor systems rated at about 1 GWe each, the driver costs increase the cost of the power plant by about 50 percent, not the 20 percent assumed. However, since this form of energy will not be available until 20–30 years from now, the relevant fuel cost is the cost at that future time, discounted for general inflation. Historically fuel costs increase by 3 percent above general inflation so that in 30 years the cost of the fissile fuel would amount to half the cost of power, or just about what the capital cost of the fusion driver would add.

Thus we conclude that there exists a scenario, obviously lacking rigorous proof and therefore open to argument, that an ICF plant could generate fusion power at cost as low as 12 percent above the cost of light water reactor power thirty years from now. This assumes that the pellet gain is 100 or more and that the driver efficiency is about 25 percent. If the driver is a heavy ion accelerator, best current estimates are that the efficiency would be 10-25 percent, depending on rep rates. Finally, the cost of the pellets has been assumed to be included in the operating cost, and the capital cost of the pellet factory, including tritium separation equipment if the D–T reaction is used, must be included in the cost of the power plant.

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TARGET GAIN VERSUS DRIVING ENERGY

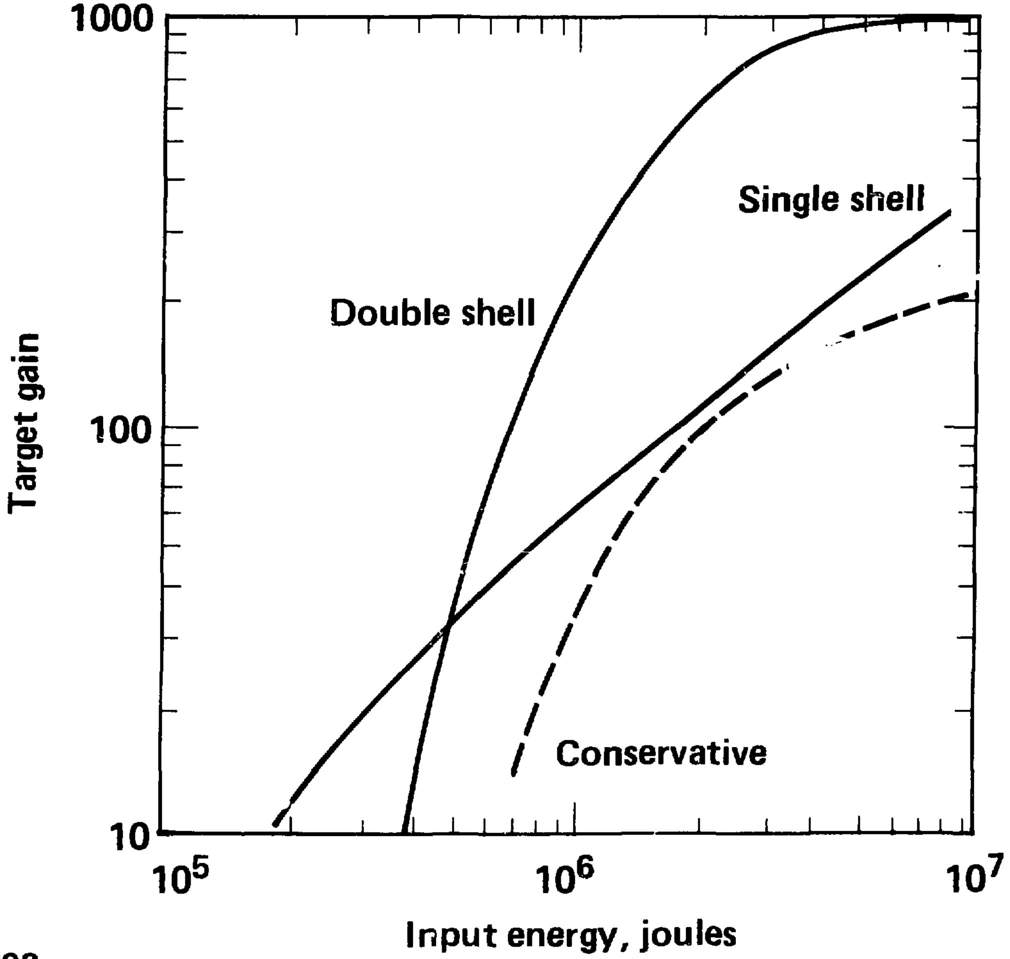

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Fig. 1 - Calculated target gains for single and double-shell capsules.

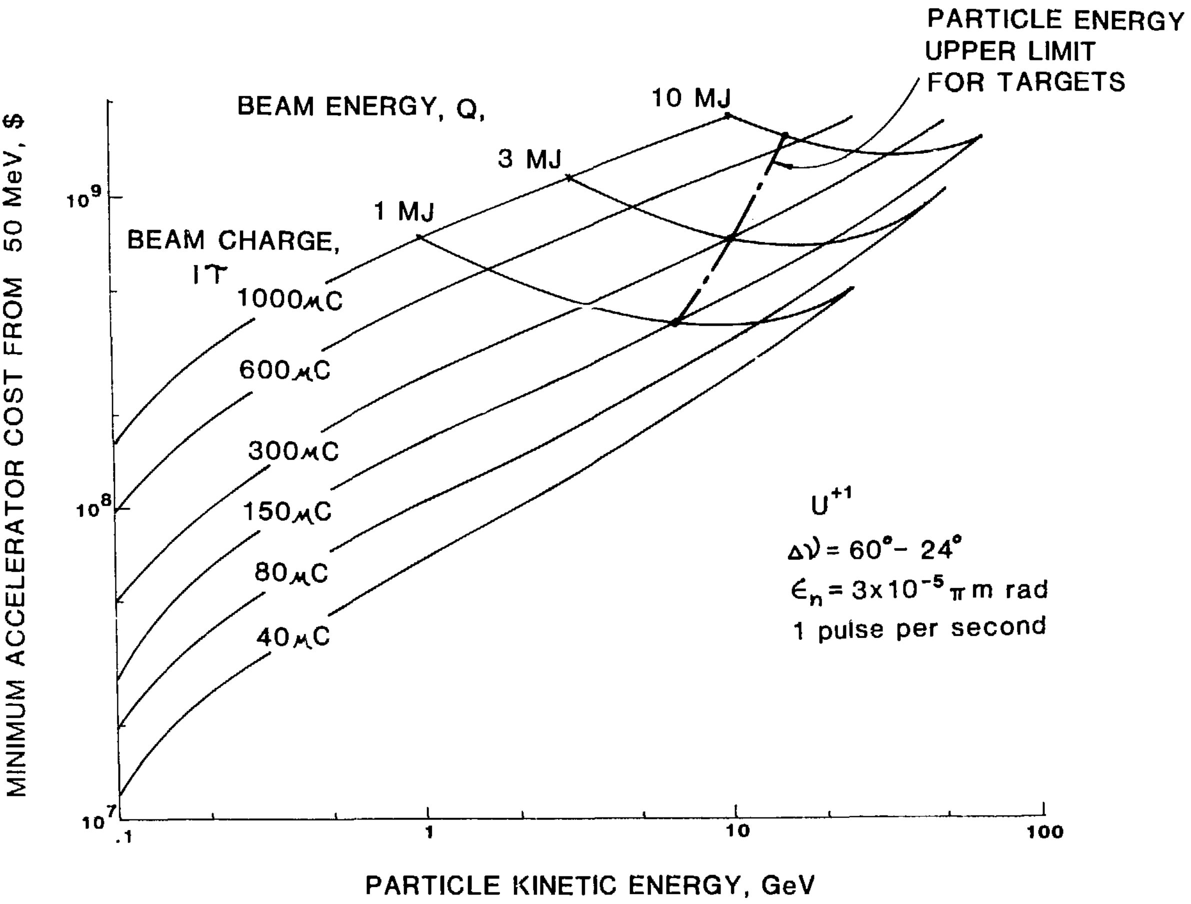

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Fig. 2 - Representative accelerator cost results from the LIACEP program.

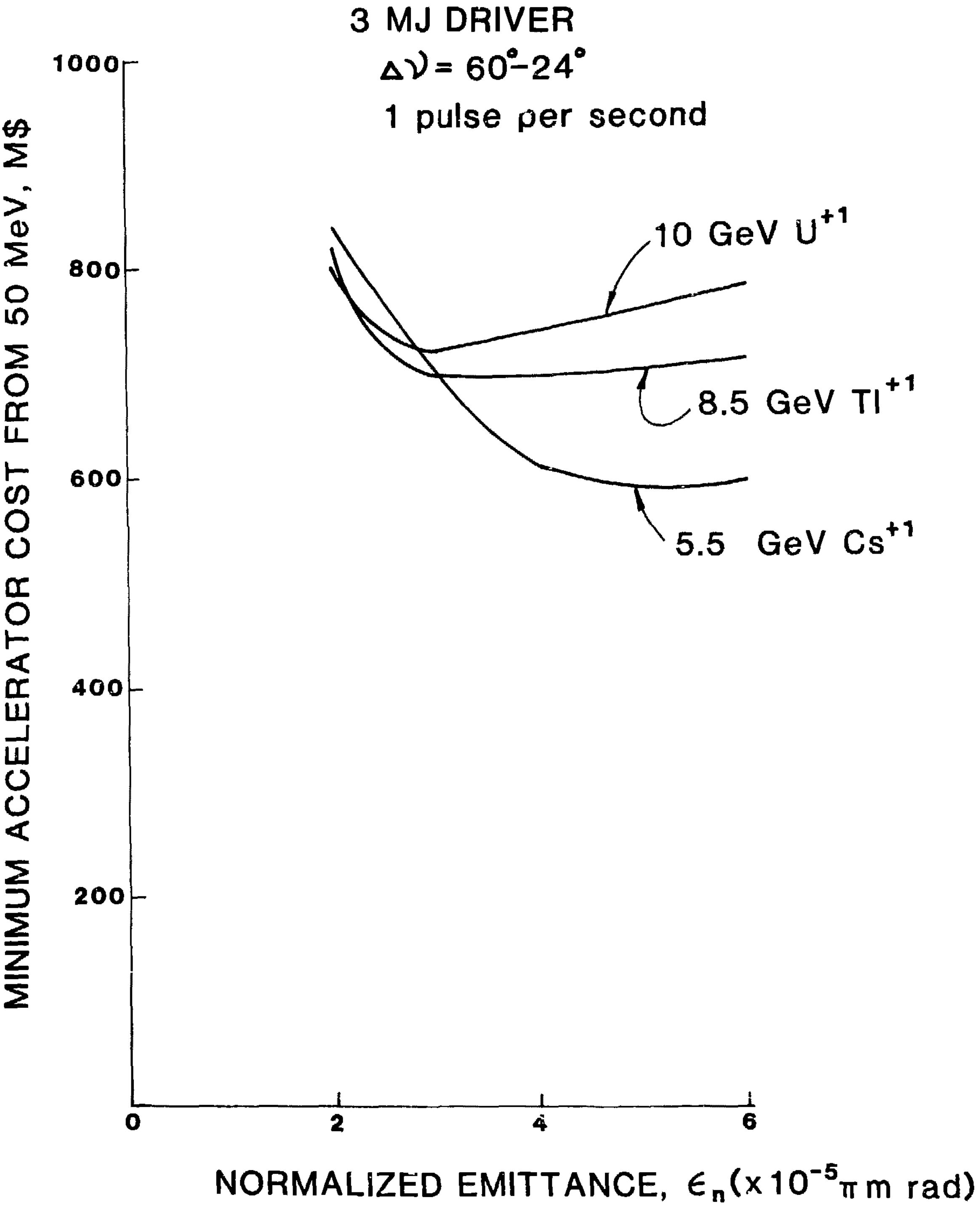

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Fig. 3 - Accelerator costs for Uranium, Thallium, and Cesium Ions.

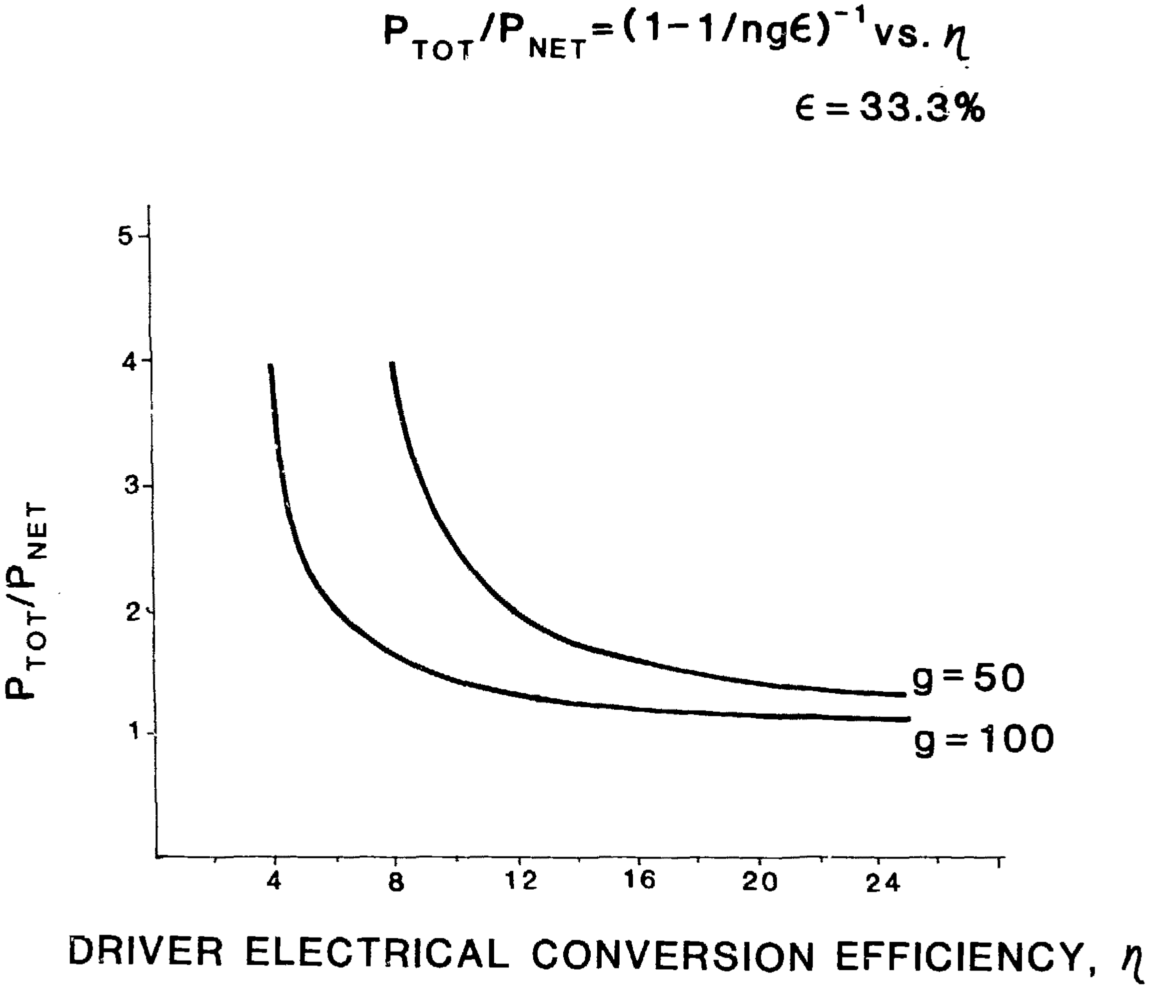

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Fig. 4 - Effect of driver efficiency and target gain on the ratio of total power/ net power.