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INERTIAL CONFINEMENT FUSION SYSTEMS USING HEAVY ION ACCELERATORS AS DRIVERS*

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Heavy ion accelerators are the most recent entrants in the effort to identify a practical driver for inertial confinement fusion. They are of interest because of the expected efficient coupling of ion kinetic energy to the thermal energy needed to implode the pellet and because of the good electrical efficiency of high intensity particle accelerators. The beam intensities required, while formidable, lie within the range that can be studied by extensions of the theories and the technology of modern high energy accelerators.

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Introduction

Serious interest in the application of high intensity heavy ion accelerators to inertial confinement fusion came from three different U.S. high energy physics accelerator laboratories in 1976. The first of a series of workshops was held Berkeley, California in 1976 [1]. The goal of this first workshop was to examine the claims that had been advanced by proponents, to determine if there were fatal flows in their schemes, and to identify the critical areas in which further study was needed. The conclusions were that while no fatal flaws could be found, the requirements of an inertial fusion driver were indeed formidable and several critical areas required intensive study. However, the cost of a heavy ion accelerator capable of the energy and intensity needed for ICF was already identified as a potentially serious issue at the 1976 workshop. In this paper, we will review the brief history of this program to see how the technical issues have interacted and what progress has been made towards the goal of making "heavy ion fusion," as this form of inertial confinement fusion has been called, be able to join the family of "emerging nuclear energy systems."

Heavy Ion Fusion

In this section we will examine the features of heavy ion fusion and identify the critical parameters. The interaction of the beam of energy, whether in the form of photons, charged particles, or macroparticles, with the pellet surface, is obviously the most significant question for the driver system. In contrast to the very complex physics with the wavelength dependence that has been found with laser drivers, it is believed that the interaction between heavy ions and the target pellet are completely classical; that is, the classical range-energy relationships are expected to be valid. What uncertainty there is seems to be confined to possible anomalous absorption effects in a hot dense plasma (the pellet wall) which might slightly reduce the range of the ions and would be slightly advantageous. Some uncertainty also exists in estimating the range of very slow ions, but since this applies only to a small fraction of the range, it seems to have no practical implications. Other possible problem areas that have been examined and found insignificant include fission fragments and knock-on electrons that could preheat the target (preheat is one of the serious problems with laser drivers) and plasma instabilities in the beam target interaction. It is important to note that, compared to photons and light ions, the density of the heavy ion beam is very low ... much less than the density of the target ... so that plasma instabilities cannot possibly involve collective effects with the incoming ion beam. The range of 10 GeV ions of mass > 200, is around 0.2 g/cm^2 which is less than 0.2 mm for a heavy metal target. For protons to have a similar range, their kinetic energy must be less than 10 MeV. For equal power the current of heavy ions is thus of order 1/1000 the current of protons that would be required. This advantage for the builder of a heavy ion accelerator also means that the ion must be in a low charge state since higher charge states mean more electrical current, and space charge forces, to deal with. Since the 1976 workshop, the ion energy favored by target designers has dropped from 50-100 GeV to about 10 GeV, at which it is almost certain that only singly charged ions should be considered. An example of the target parameters can be found by considering a a spherical shell: to achieve the needed compression velocity, the driver power should be ≥ 100 TW. To achieve the necessary temperature and pressure, the energy density should be ≥ 20 MJ/g. It follows that:

- Power $\geq 4\pi r^2 (10^{14})$ watts, r is pellet radius (cm).
- Energy $\geq 4\pi r^2 R\ (2 \times 10^7)$ Joules, R is range in g/cm^2.
- Range $< \rho\delta r$ where ρ is shell density.

So that, for example, for 3 MJ and 100 TW, we find:

$$r \leq 0.25 \text{ cm} \quad \text{and} \quad R \leq 0.2 \text{ g/cm}^2 \quad .$$

Thus the target spot must ~ 2.5 mm in radius and the beam energy ~ 10 GeV for mass > 200 ions. The beam pulse should be shaped, with a high intensity peak 10-20 nanoseconds long.

The second attractive feature of heavy ion accelerator drivers is the inherently high electrical efficiency of high-intensity accelerators. (High-energy accelerators for research in particle physics are exceptions because they frequently operate with nearly negligible current in which case the electrical efficiency is near zero.) Perhaps the best example is LAMPF, the proton linac at Los Alamos, which would be about 16% efficient if operated at its design current; but even LAMPF, with 1960's technology, was not designed with efficiency in mind. Efficiency is of no importance in designing a low repetition rate driver for pellet development experiments, but for a practical power plant driver, it is a critical factor. If f is the fraction of generated power that is recirculated to operate the plant, including the driver, then a fraction (1-f) is available as produced power. It is common practice to require the recirculating power fraction to be less than 1/3 for an economically practical conceptual design. The recirculating power $P_r = fG\varepsilon P_r\eta$, where G is the pellet gain, ε is the fusion to electric conversion efficiency and η is the electrical conversion efficiency of the driver. Using 33% for ε, we have the frequently stated requirement $\eta G \geq 10$.

The pellet gain as a function of driver energy has been studied at the Lawrence Livermore Laboratory. Their published curves [2] are reproduced in Fig. 1, where we have taken the liberty of extrapolating the LLL data beyond 10 MJ at constant slope. We also show a reduced gain curve to explore the significance if the calculated curves cannot be achieved in practice. The upper curve, labelled "KrF" may be considered an optimistic gain curve for ion drivers and also is the one used for short wavelength (0.25 micrometer) light, which has the presumed advantage of not requiring as much mass in the pellet to absorb the ion energy.

In Fig. 2, we have replotted the curves of Fig. 1 as a function of efficiency using the relation $\eta G = 10$. The anticipated electrical conversion efficiency of KrF is between 4% and 6% and for ion drivers, either light or heavy ions, the efficiency is expected to be between 15% and 25%. It is seen that, for $\eta \leq 5\%$, very high energy pulses are needed for the KrF class of driver, while any $\eta \gtrsim 15\%$ is adequate for ion drivers. On the other hand, if the lower gain curve is used, then the ion driver efficiency must be nearly 25%. The "$\eta G = 10$" points are plotted on the gain curves in Fig. 1. Also noted is the upper limit of the single pulse fusion energy yield. For KrF, the 4000 MJ point, roughly equal to the energy yield from one ton of high explosive, is virtually coincident with the lowest yield allowed for $\eta G \geq 10$ if η is only 4%. High single pulse yield obviously means a larger, more expensive reactor chamber, and with foreseeable technology, a one-ton high explosive yield seems a reasonable upper limit. One must also note that the low yield at the low-energy end of the ion beam curves carries an implied penalty. If the yield is too low, an extremely high repetition rate is implied for an adequate sized plant to be competitive. Although a few tens of pulses per second is reasonable for an accelerator, the production and delivery of pellets, and the number of reactor chambers, may become the limiting factors.

High repetition rate is, in fact, one of the features that heavy ion accelerators have inherited from the technology of high energy physics. Rf linacs typically operate at rates of 60 to 360 pps and even the linear induction accelerators will run at 20 pps or greater without penalty. Since some reactor designs are limited to about 1 pps, and 10 pps is probably nearly the upper limit for any concept (at 10 pps, if pellets are fired in at 100 m/s, they would only be 10 meters apart), it is obviously desirable for one accelerator driver to serve several reactors, much as research accelerators serve several experimental areas simultaneously.

Some other inherited characteristics include reliability and long life; several currently operating high energy physics machines are around 20 years old and most have 85% to 90% availability, which compares favorably to electrical utility plants, even though these machines are not designed with redundant systems. The physical separation of the accelerator driver from the reactor chamber has important engineering advantages as compared to magnetic confinement fusion systems. Except for the components of the final transport system, the accelerator is remote from the reactor environment and can be serviced and instrumented without shielding and radiation hardening. Even though the ions are at high energy, the energy per nucleon is low and energy that does not escape a small pellet will not escape from the accelerator structure either.

What of the size and cost of the accelerator driver? It may be about 5 km long, but could be folded back over itself or otherwise configured to fit a site. Compared to the coal fields, rail yards and pipe lines that utilities are accustomed to, the space taken by an accelerator driver is not great. The length of the accelerator is also comparable to the length of the components of an equivalent laser which might have 100 beams each from a laser 100 meters long. Accelerators built with present technology could cost around $1 billion for a 10 MJ driver capable of running several reactors yielding perhaps 3000 MW_e. In such a system, the cost of the accelerator is a minor part of the entire plant cost. In Fig. 3 we show the results of a cost study [3] modeled after the methods used by the utility industry. It assumes a payback period of seven years for the construction funds and a capacity factor of 65%. The capital cost per GWe is $0.7E^{0.4} + 1.2$ billion dollars, in which the first term, with E in megajoules, is the cost of the driver (no savings is assumed for operating more than one gigawatt plant per driver), and 1.2 billion is the assumed cost of the rest of the plant. The points on the plot are from a study done recently by EPRI [4] using a somewhat different cost algorithm and payback schedule. If compared with other technologies of 1980, these costs are only slightly higher than fission reactor power and are less than coal power. Of course, these models are not based on real cost estimates. Nevertheless, the trends they show are significant: only a small (~ ±10%) effect due to factors of two in pellet gain, and almost no effect due to the driver energy. Below the point for which $\eta G = 10$, which is near the minimum of each curve, the power cost goes up rapidly.

Heavy Ion Accelerators

From the previous discussion about pellet characteristics, we have the following list of accelerator parameters;

• Beam Energy	4 MJ
• Ion Energy	10 GeV
• Peak Power	100 TW
• Pulse Length (shaped)	40 ns
• Ion	Hg, U, etc. ($A \geq 200$)
• Charge State	$q = 1$ to 4
• Number of Beams	~ 20
• Peak Current per Beam	500 A

At the time of the third annual workshop in 1978 [5] there were three schemes for achieving these formidable parameters. One of these, the synchrotron-storage ring system was then abandoned leaving two others:

(1) A full-energy rf linac which injects ions sequentially into a system of storage rings. When all the storage rings are full, the beams are extracted simultaneously, with further pulse compression to multiply the current. The current from the rf linac is thus multiplied by the product of the number of storage rings n_r, the number of turns each is filled n_t, and the final com-

pression C; thus $I = I_0 n_r n_t C$. The compression factor derives from the product of the compression that is imposed in the storage ring immediately before extraction, and further compression on the way to the target using induction linac modules.

(2) The second system would use induction linac modules for the entire machine in a single pass configuration. Figure 4 shows one of these modules for several parallel beam lines. Less familiar than rf linacs and synchrotrons, the induction linac is in fact, a simpler system. Essentially a linear betatron, it accelerates the beam by inducing a voltage much as if the beam is the secondary winding in a single turn transformer. In the induction linac, the current is multiplied by linearly compressing the beam, using waveform shaping in the same way that the final compression is imposed on the beam from the storage rings.

Technical Issues

Up to now we have not mentioned the requirements of the final focus system. The problem of hitting a 2.5 mm target 10-15 meters from the last focusing element translates to a requirement on the brightness of the beam. For somewhat the same reason that an out-of-focus transparency cannot be made sharper by adjusting the projector, a particle beam which has lost its brightness cannot be magically made brighter. Thus, it is essential to preserve the brightness of the beam all the way from the source to the final beam transport line. The one exception, which is useful only to a small degree, is to divide the beam into several beams and superimpose them upon final focus to the pellet.

The requirement stated above for 20 beams, is partially based on such requirements and partially on limiting the space charge forces. It does not result from a requirement for symmetrical illumination of the target; two beams, or beam clusters, provide adequate symmetry.

In the case of the rf linac system, the various beam manipulations, such as multiturn injection into the storage rings, each serve to reduce the brightness of the beam from the source and injector system. The injector for the rf linac is expected to consist of an inverted tree, or "funnel" of linacs in which each stage operates at a frequency double that of the previous stage. Because the current that can be accelerated depends strongly on particle energy, with each doubling of frequency it is possible to double the current by combining two beams into adjacent rf "buckets." Demonstration of this process, and verification of the necessary conservation of beam brightness is one of the two most critical tests of the rf scheme. The second critical test is to demonstrate the ability to store the necessary current in a storage ring without undue particle losses and loss of brightness. Beam losses can be due to background gas and charge exchange between beam particles. Such losses may be critical even for the short time (< 1 ms) that the beams must be stored. Beam loss is one of the problems that led to abandoning synchrotron systems as drivers.

For the linear induction accelerator system, where there is no experience with ion beams, stability of beam transport must be demonstrated. Efficient use of an induction accelerator requires that the beams be transported as near to the space charge limit as is possible. This limit increases as energy increases, so the pulse must be continuously shortened to increase the current. Because the shortening process requires that the back of the pulse be catching up with the front, it is necessary to demonstrate both transverse and longitudinal stability.

The study of the transverse stability limit is a fascinating part of the work that has been done for heavy ion fusion. The stability of periodic transport systems at low current is well established; examples such as the Interacting Storage Rings at CERN show that beams can circulate for many hours in a periodic transport system. When the current in the beam is increased, the transverse forces of space charge act as a defocusing lens, countering the focusing forces, and reducing the number of transverse oscillations each particle undergoes. The number of transverse oscillations per revolution is the "tune" of a storage ring; the space charge induces a "tune depression" of the system, which cannot be indefinitely large. In circular machines, including the storage rings for the rf linac, conventional wisdom is that the tune depression should not exceed a quarter of an integer or else the beam will be forced into a resonance and lost. For linear transport system, including the induction linac, tune is measured by the single particle phase advance per period. It has been found both analytically [6] and numerically [7] that the space charge limit occurs if the tune is depressed into a resonance. An example of high current transport occurs if the phase advance at zero current is 60° and is depressed to 24° by the space charge. These calculations are based on the use of linear forces obtained with uniform space charge distributions. In actual practice, such a distribution is unlikely to occur, so experimental verification of high current transport stability is important.

A special case of periodic transport will occur as the beam passes through the final transport system to the reactor chamber. Here the current is increasing rapidly towards a maximum value at the pellet. This problem has received very little attention up till now and it appears that both new ideas and new computer codes may be needed.

Research in Progress

The largest part of the present program in heavy ion driver development consists of work on the low velocity injector systems. Both Argonne National Laboratory which is concentrating on the rf linac approach, and the Lawrence Berkeley Laboratory which is developing the linear induction accelerator, have proposed the construction of "test bed" accelerators to demonstrate the critical issues listed above. Because of the importance of source brightness, these injection systems are critical components. The Argonne approach is to use a high voltage source and conventional low frequency accelerator structure. Parallel work is underway at Los Alamos Scientific Laboratory, where an rf quadrupole injector is under study, and at Brookhaven National Laboratory, where a miniaturized multiaperture electrostatic quadrupole system is being developed.

The injector for the linear induction accelerator must put a single long "sausage" of charge into the accelerator. A system of pulsed drift tubes is being built using grid focusing. As this system is extended to longer pulses, additional transverse focusing will be obtained from electrostatic quadrupoles. All low velocity heavy ion systems find it advantageous to turn to electrostatic focusing because the $\vec{v} \times \vec{B}$ terms of magnetic lenses are too weak to overcome the space charge forces.

Program Plans

The two test bed systems, each costing about $25 million, have been planned as test projects to find which approach to follow for a "Heavy Ion Demonstration Experiment" which would produce perhaps 100 kJ and might cost $150 million. In order to construct these test beds, annual budgets of $15 million to $25 million are needed for three to five years. The President's budget for fiscal year 1981 is $15 million which, if passed intact by Congress, would signal the start of the test bed program. The previous three years have seen funding at about the $5 million level for the total heavy ion fusion program. This can be compared with about $25 million per year being spent on accelerator research by the U.S. program in high energy physics. It is thus clear that the heavy ion fusion program is at a critical point in terms of reaching a funding level that could result in significant experimental progress.

It was pointed out earlier that even at the first workshop, the cost of the accelerator systems became an issue. The systems studies have established that the cost of electrical power generated with this technology would not depend significantly on the cost of the accelerator. However, it may well be difficult to obtain the funding for large drivers for research in the civilian application of inertial fusion. From the first workshop, the approach of the accelerator community has been to try to demonstrate that "conventional" accelerator technology could achieve the necessary power and energy for a driver. Some savings have resulted from "inventions," particularly in the area of injection accelerators, and the reduction of the ion energy from ~50 GeV to ~10 GeV has also made a small cost improvement, but it is nevertheless true that a multi-megajoule driver built with known methods would cost upwards of $500 million. Thus, while hopeful that the next budget will see a meaningful start to this program, we are nevertheless concerned about the cost and technical issues that could stand in the way of heavy ion fusion becoming an emerging nuclear energy system.

References

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Figure Captions

Fig. 1. The estimated gain curves from Ref. [2] are shown extrapolated beyond 10 MJ at constant slope. The upper curve, is essentially twice the gain of the middle curve, which has been calculated for heavy ion targets. The lower curve, half the yield of the middle curve, is plotted to show the sensitivity to anticipated practical difficulties.

Fig. 2. The gain curves of Fig. 1 are replotted with the criteria $\eta G = 10$. Practical short wavelength lasers are expected to be 4-6% efficient while ion drivers should have efficiencies of 15% or greater.

Fig. 3. Cost of electricity using the gain curves of Fig. 1 assuming 15% per year return of capital and 65% capacity factor. The capital cost is $0.7E^{0.4} + 1.2$ billions per GWe where E is driver energy in megajoules. Also shown are results from the EPRI study [4].

Fig. 4. Module of Linear Induction Accelerator showing several parallel beam lines.

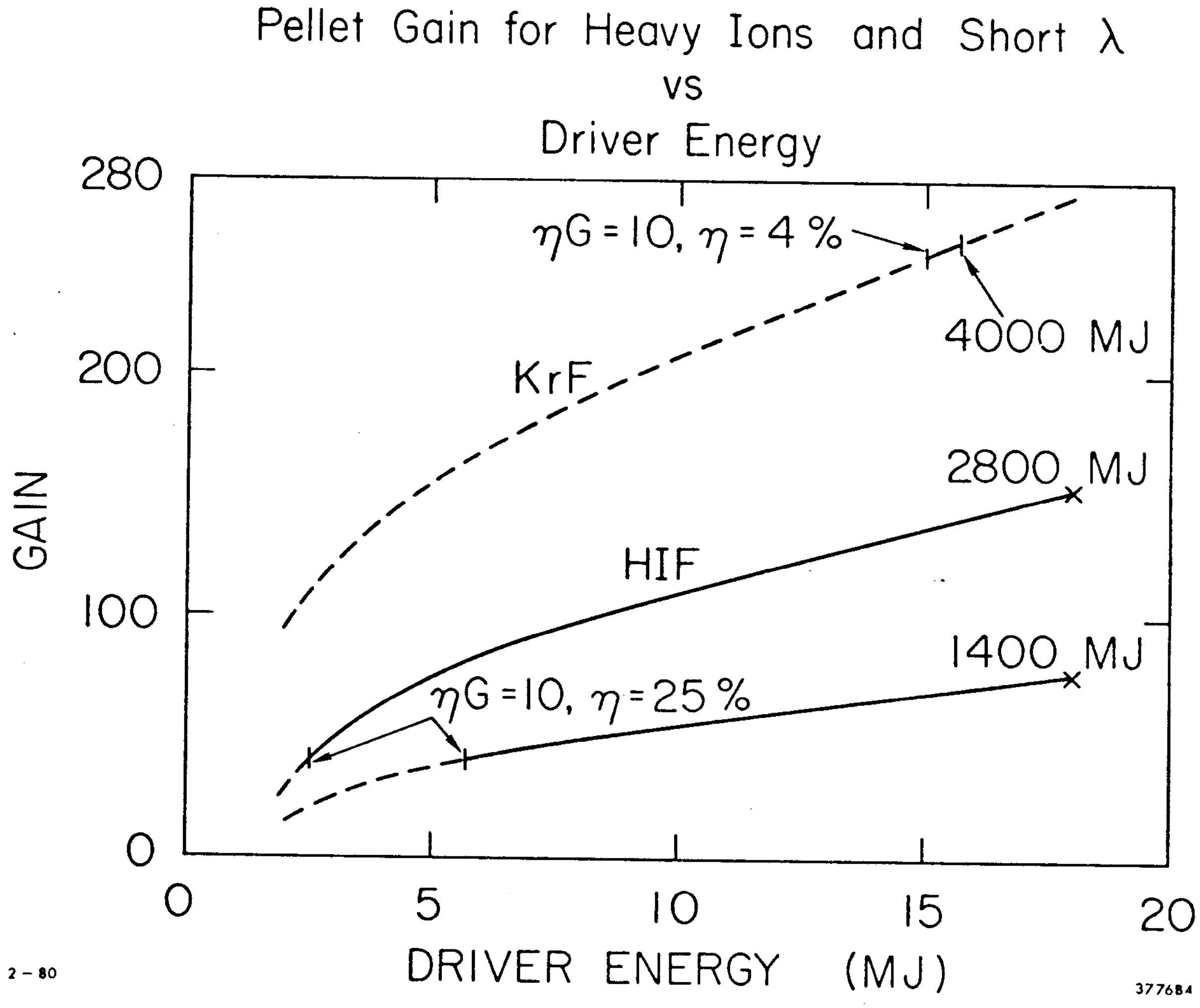
Pellet Gain for Heavy Ions and Short λ
vs
Driver Energy
280
200
100
0
GAIN
0
5
10
15
20
DRIVER ENERGY (MJ)
ηG = 10, η = 4 %
4000 MJ
KrF
2800 MJ
HIF
1400 MJ
ηG = 10, η = 25 %
2 – 80
377684

Fig. 1

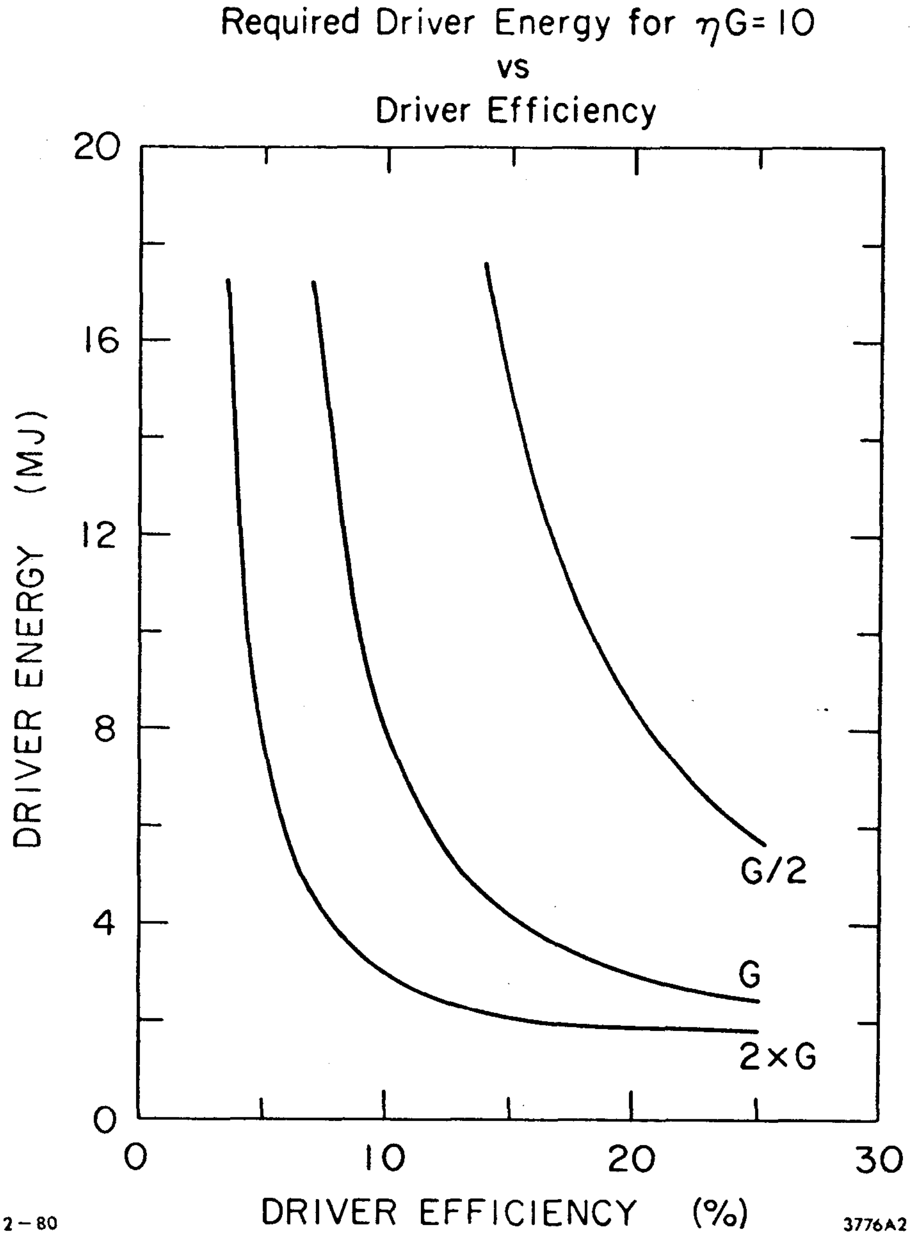

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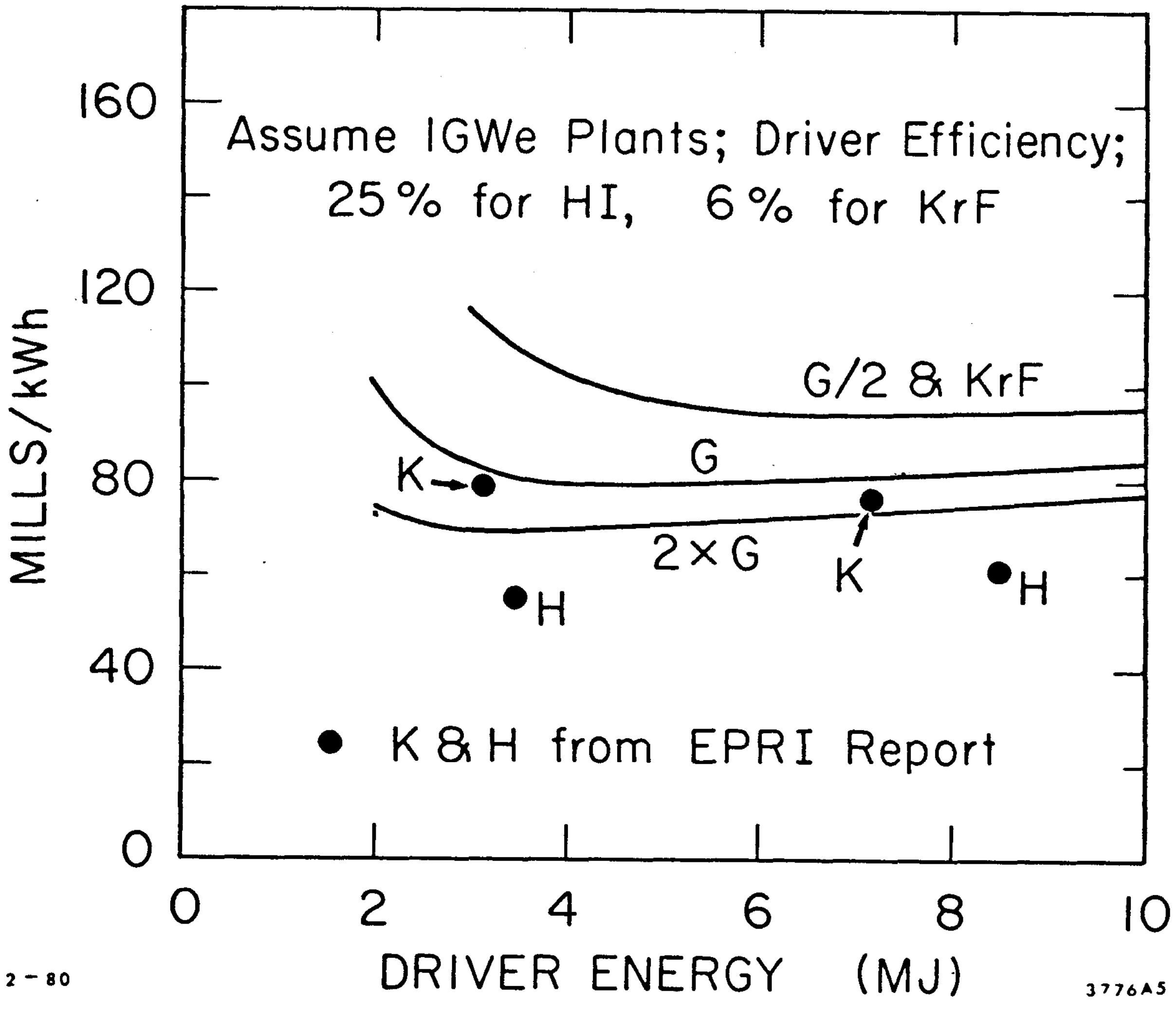
Fig. 2



Busbar Cost of Electricity for Heavy Ions and KrF
vs
Driver Energy

2-80

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Fig. 3

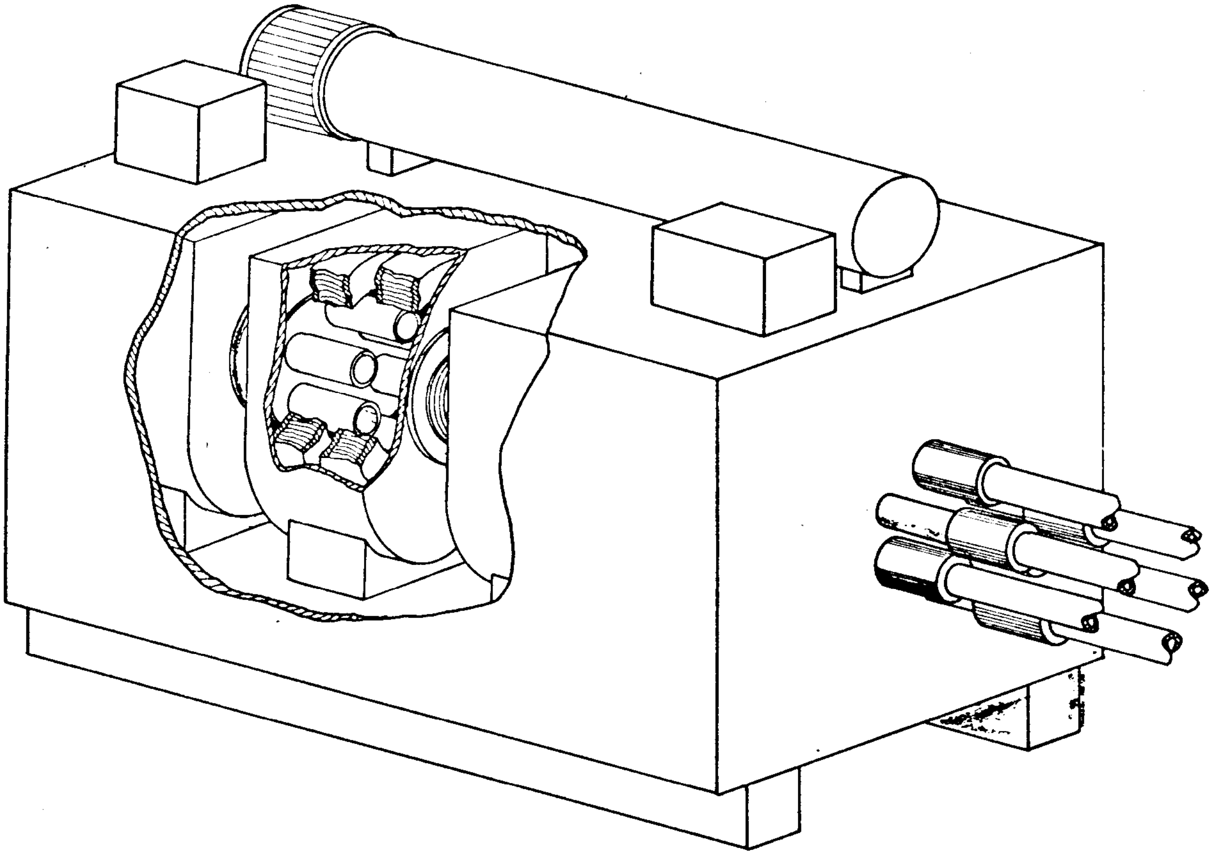

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Fig. 4