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ACCELERATORS FOR HEAVY ION FUSION

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ACCELERATORS FOR HEAVY ION FUSION*

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Abstract

Large fusion devices will almost certainly produce net energy. However, a successful commercial fusion energy system must also satisfy important engineering and economic constraints. Inertial confinement fusion power plants driven by multi-stage, heavy-ion accelerators appear capable of meeting these constraints. The reasons behind this promising outlook for heavy-ion fusion are given in this report. This report is based on the transcript of a talk presented at the Symposium on Lasers and Particle Beams for Fusion and Strategic Defense at the University of Rochester on April 17-19, 1985.

MASTER

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I'm going to talk about accelerators for heavy-ion fusion, rather than accelerators for strategic defense systems. Consequently, I will first focus on generic fusion issues. I would like to begin by making an overstatement just to generate a little controversy. The overstatement is that engineering and economics are the important issues for fusion power production. Nearly everyone believes that many proposed fusion devices would produce energy if they were made large enough. In fact, stars and nuclear weapons are two demonstrated examples. Large magnetic machines will also almost certainly produce net energy. On the other hand, these very large devices might not make good environmental, engineering, or economic sense. So for commercial applications of fusion, as opposed to military applications, the important question is not whether fusion can produce energy, it is

> Can a fusion energy system be built that makes good environmental, engineering, and economic sense?

A sensible fusion system must satisfy three conditions. The three requirements are: (1) the total capital cost of the system must be acceptable; (2) the cost of electricity must also be acceptable; and finally (3) there must be a reasonable way to get from where we are today to where we want to be ultimately, i.e., there must be a sensible R&D path.

The three conditions are illustrated in Fig. 1. We do not know what the maximum allowable cost of a power plant will be in the future, but if the economic situation is similar to the current situation, it is probably a few billion dollars. To be specific, a goal of less than two billion dollars is indicated in Fig. 1. The cost of electricity, in order to be competitive, must be $\leq$ 50 mills per kilowatt hour. This goal is also shown in Fig. 1. A utopian goal of power plants that cost almost nothing and produce electricity for almost nothing is also shown. Our present position is illustrated by the region labelled "now." We need to determine if there is a sensible path that leads from "now" to our goal. There are at least two difficulties or "swamps" that must be avoided. If we make the cost of our experiments too low, we typically have difficulty with physics. If we make the cost of our experiments too large, we have difficulty with economics.

I believe that inertial confinement fusion (ICF) provides a reasonable R&D path. There are several reasons for this belief: one reason is that most drivers can grow because they are modular and they have reusable parts. A good example of this is the SHIVA/NOVETTE/NOVA sequence of lasers at Livermore. The fact that we can reuse some of the driver components helps with the economics. On the other hand, the driver is not the whole issue. We will undoubtably find that reactor engineering will be challenging and expensive. It would be greatly advantageous if we could do reactor engineering at an inexpensive low level. In principle, ICF offers that possibility. Consider typical power plant parameters, a driver energy of 3 megajoules and a target gain of about 200 giving a thermonuclear yield of roughly 600 megajoules. If the repetition rate is five Hertz, the output is about 3,000 megawatts thermal. A power plant of this size would be expensive. However, we could build a one-megajoule driver a lot more cheaply than a three-megajoule driver. Just as an example, it might be interesting to consider at test system that has a one-megajoule driver. The target gain drops somewhat compared to the gain at 3 MJ. However, relatively simple targets might produce gains of 1-10, giving thermonuclear yields of 1-10 MJ. If we were to pulse at 10 Hertz, we would get 100 megawatts of thermal power. This power level would be sufficient to do many interesting reactor engineering and testing projects. The advantage of such a system is that this small yield of a few megajoules could probably be contained in a small reactor chamber with dimensions of the order of a meter. Such a chamber would be relatively inexpensive because it is not very big. Furthermore, we might be able to make such a system tritium-self-sufficient. In order to be tritium-self-sufficient, we must capture most of the neutrons that are produced in the thermonuclear burn and that means we must surround most of the solid angle around the reactor with tritium breeding blankets. It should not be too expensive to surround a small reactor with tritium-breeding blankets. On the other hand, if we try to start with very large systems, perhaps five meters or so in size, then, in fact, we do have formidable problems for reactor R&D and tritium self-sufficiency. In summary, the example given above shows that ICF may provide a reasonable R&D path.

I would now like to turn from generic fusion issues to heavy-ion fusion. The first question is "Why are we interested in heavy-ions as opposed to other ions?" One answer to this question is based on the range-energy relations. Figure 2 shows the range, in grams per square centimeter, as a function of ion energy in GeV. For ICF targets, we would like to have an ion range that is less than a few tenths of a gram per square centimeter. Figure 2 shows that if we want to use electrons or light ions, we are constrained to energies of a few MeV. On the other hand, by going to very heavy-ions, we can consider extremely energetic ions, up to 10 GeV or perhaps somewhat higher. Thus, for heavy-ions, we would use high-voltage, low-current beams. These beams can be accelerated in a low-charge state, minimizing collective effects. Perhaps most importantly conventional accelerator technology then becomes applicable. What I mean by conventional accelerators is multi-stage accelerators. These conventional/multi-stage accelerators are well matched to the engineering requirements of fusion power production.

Accelerators are reliable; they typically operate more than 90% of scheduled time. They have a long lifetime; the large accelerators built in the '50's are still operating. They an have a high-pulse repetition rate, and of particular importance, they can be efficient (probably 15 to 35% for a heavy-ion accelerator). However, not all accelerators have demonstrated adequate lifetime for a fusion power plant. A fusion power plant, if it operates at 10 Hertz over a lifetime of 30 years, would have to pulse about 10^{10} times. That is a large number of pulses. The RF linac at SLAC, I suspect, has pulsed more than any other existing accelerator. I calculate that it has pulsed about 10^{11} times! Therefore, this type of technology certainly seems capable of meeting the requirements of a power plant. The Astron injector, as far as induction linacs are concerned, is probably the record holder for number of pulses. The Astron machine was pulsed about 10^{8} times. However, the components that go into modern induction linacs should last for more than 10^{8} pulses. New types of capacitors are advertised to have lifetimes in excess of 10^{9} pulses. Thyratrons, for switching at 10 pulses per second, should last about 10,000 hours, or about a year. Therefore with a maintenance program for replacing some components, we should be able to build an induction linac that would also meet the requirement of 10^{10} pulses.

Despite my original emphasis of engineering and economics, the accelerator must, of course, also meet the scientific requirements for fusion. The ability of accelerators and focusing systems to meet target requirements depends strongly on particle mass. Target performance depends on four parameters: (1) the focal radius of the beam; (2) the ion range, which depends on ion kinetic energy and mass; (3) the power; and (4) the beam energy. How easy is it to meet the target requirements? First consider beam brightness, or phase-space density. The target requirements and the properties of the focusing systems place a lower limit on six-dimensional (6-D) phase-space density. Liouville's theorem as it is conventionally applied to accelerators, states that the 6-D phase-space density at the target, has to be less than or equal to the 6-D phase-space density at the ion source. There are some schemes that violate Liouville's theorem but most of them do not seem to be applicable to fusion.

It can be shown that the 6-D phase-space density needed at the target divided by the 6-D phase-space density available at the ion source goes as M^{ε}/θ^2 where M is ion mass and θ^2 is a measure of the solid angle occupied by the beam (or beams) converging onto the target. If the target gain is held constant by fixing beam radius, ion range, beam power, and beam energy, then $\varepsilon \lesssim -3$. The exact value of ε depends on the assumptions that are made, but in any case heavy-ions can meet the requirement of Liouville's theorem more easily than light ions.

Another important consideration is the strength of space charge forces relative to beam stiffness. Quantitatively, the important parameter is generalized perveance, $K \propto I_0 Z^2 (1-f)/(Mv^3)$, where I_0 is particle current, Z is ion charge state, f is fractional neutralization by electrons, and v is velocity. Again fixing target performance, it can be shown that K goes as $(1-f)M^{\varepsilon}$ where $-2.5 \lesssim \theta \lesssim -0.5$. The exact value of ε depends on the charge state of the ions.

Another important parameter is the beam plasma frequency

$$\omega_{pb} = \left(\frac{4\pi n e^2 Z^2}{M}\right)^{1/2}$$

where e is the electron charge.

Beams with higher ω_{pb} are more susceptible to various instabilities than beams with lower ω_{pb}. For fixed target parameters $\omega_{pb} \propto M^{\varepsilon}$ where $-1.2 \lesssim \varepsilon \lesssim -0.2$.

The design constraints associated with Liouville's theorem, generalized perveance, and beam plasma frequency are not easily satisfied. In order to use conventional accelerator technology, and in order to satisfy these constraints, we are pushed in the direction of heavier ions.

Based on the considerations described above, it appears that heavy-ion accelerators are reasonable in terms of getting us to our final goal of power production. However, it has been a little bit difficult to come up with a reasonable accelerator R&D path. I would like to outline briefly the R&D path in the United States. In the U.S. we have chosen to develop multiple-beam induction linacs. Figure 3 shows schematic diagrams of two types of fusion accelerators, a multiple-beam induction linac and an r.f. linac and storage ring system. An induction linac is a simple high-current device. The r.f. system is more complicated. In the r.f. system, ions from a number of ion sources (only four are shown) are funneled together to provide the beam for the main accelerator. However, the current in the main accelerator is not adequate to drive the target and therefore it is necessary to stack the beam into a series of storage rings in order to get adequate power for the target. The simplicity of the induction linac is important, because the beam manipulations such as funneling and stacking almost inevitably increase the 6-D phase-space volume occupied by the beam and, as stated earlier, a small 6-D phase-space volume is needed to meet the target requirements.

There are other reasons for the choice of induction linacs in this country. Induction linacs can have high pulse repetition rates. The ATA induction machine at Livermore[1] is designed for operation at 1 kHz. Furthermore, ATA and other similar accelerators have given us considerable experience with kiloampere electron induction linacs. A target requires ~10^{14} watts. Therefore, for 10 GeV heavy-ions, the 10 kA beam current demonstrated at ATA gives the required 10^{14} watts.

The experience with induction linacs is important. Because of this experience we have already developed the circuitry, the pulsers and the induction cores necessary to handle the currents required for ion beam fusion, but unfortunately the beams that we are now putting through these machines are electrons. The basic acceleration circuitry does not know the difference between electrons and ions. It only knows about current. On the other hand, electrons are relativistic and ions are non-relativistic, and there are enormous differences in beam dynamics. Therefore, the really important question for heavy-ion fusion is:

> Can we confine, accelerate, transport and focus the high beam current without destroying the beam quality?

The beam quality is good enough at the beginning of the accelerator; a typical ion source temperature might be ~1 eV. At a final energy of 10 GeV, the transverse energy is 10 orders of magnitude below the directed energy, which means that the intrinsic beam divergence is $\sim 10^{-5}$ radians however 10^{-3} radians is nearly adequate for fusion. Unfortunately there are a number of possible sources of trouble. There are non-linear space-charged forces or magnetic forces associated with the beams; there are also potential instabilities, multiple beam interaction effects, and imperfections in the machine. Incidentally, efficiency is not a separate issue. The efficiency of an induction linac can be good if the current is high. The circuitry designed for accelerating electrons appears capable of providing efficiencies as high as 50%. Usually, the currents associated with ion accelerators are lower than the currents associated with electron machines, and that is the reason why the efficiency is not 50%, but perhaps 15 to 35%.

In general a particle in an accelerator does not move directly along the axis of the accelerator in either position or angle. As a consequence it is necessary to provide focusing forces to keep the particles in the machine. These focusing forces then cause the particles in the machine to undergo oscillations called betatron oscillations around the central orbit. As one adds space charge, the space charge forces of the beam tend to counteract the applied focusing forces. As a consequence, both the amplitude and the wavelength of the betatron oscillations increase. If the space charge is increased to the point that the beam plasma frequency is close to the single-particle betatron frequency, it is possible to accelerate very high currents, and improve both the cost and the efficiency of an induction linac. Unfortunately, analytic theory shows instabilities as the beam plasma frequency approaches the single-particle betatron frequency. The analytic theory is based on idealized particle distribution functions. Numerical simulations which use more realistic particle distribution functions do not necessarily show these instabilities. At any rate, it is necessary to perform experiments, and a number of experiments have been performed, the largest at Lawrence Berkeley Laboratory.[2]

The results of the experiments are in agreement with the numerical simulations and show that the analytically predicted instabilities are not observed. In fact, it has been possible to transport beams at very high space-charged densities without observable degradation of beam quality. We now believe that we can transport currents that are three or more times larger than thought possible several years ago.

The experiments that have been performed have tested only transverse beam dynamics. Lawrence Berkeley Laboratory is now building a so called MBE-4 accelerator which is a multiple beam experiment with four beams. The MBE-4 will enable us to study longitudinal beam dynamics and multiple beam interactions.

Incidently, one place where there could be some overlap between the heavy-ion fusion program and SDI is in this area of multiple beams. SDI would like very bright beams and also high currents. These same characteristics have led us to consider multiple beams for fusion.

Cost has traditionally been an issue for heavy-ion fusion accelerators. We believe this issue can be resolved. Less expensive materials are being developed for induction cores, insulators, and magnetic focusing magnets. Much of this progress is being driven by programs other than heavy-ion fusion. Fabrication techniques can also be improved. Beam neutralization and control by electrons is being studied theoretically and experimentally and could give cost benefits. Progress in fast repetitive switching technology at Livermore could open the possibility of new types of inexpensive induction accelerators. Finally, we believe that improved target designs are possible.

In conclusion, heavy-ion fusion is a promising fusion option. ICF provides a sensible, economical reactor development path; and multi-stage accelerators are capable of satisfying the engineering requirements of fusion power production. Multi-stage, heavy-ion accelerators also appear capable of satisfying the ICF target requirements. High efficiency is very important because it gives some margin of safety if the targets don't work as well as we hope. We have developed a logical accelerator R&D path; and the experiments that we have performed so far have been encouraging. Finally, cost reductions seem likely.

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Figure Captions

Figure 1: A reasonable goal for fusion energy production in terms of cost of plant and cost of electricity is indicated above. Our current position is also indicated. A sensible fusion energy program should take us from where we are now to our goal on a path that avoids the alligators lurking in the swamps on the left and on the right.

Figure 2: Range as a function of ion kinetic energy for a variety of charged particles. For inertial fusion, the range should be less than a few tenths of a gram per square centimeter. For heavy-ions, the kinetic energy can be $\lesssim$10 GeV. The curves in this figure are based on aluminum target material at a density and temperature typical of inertial fusion.

Figure 3: Schematic diagram of an induction linac and an r.f. linac plus storage rings. These systems are the two principal approaches to heavy-ion fusion.

Avoid alligators

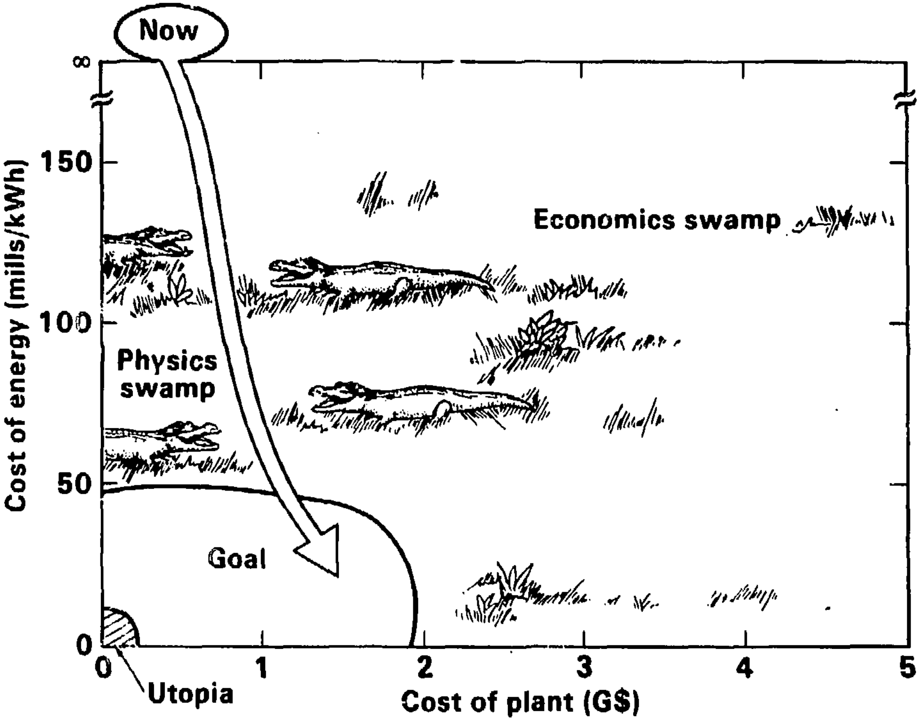

Figure 1

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Heavy ions allow the use of high voltage, low current beams

- Acceleration can occur in a low charge state
- Collective effects are minimized
- Conventional acceleration technology is applicable

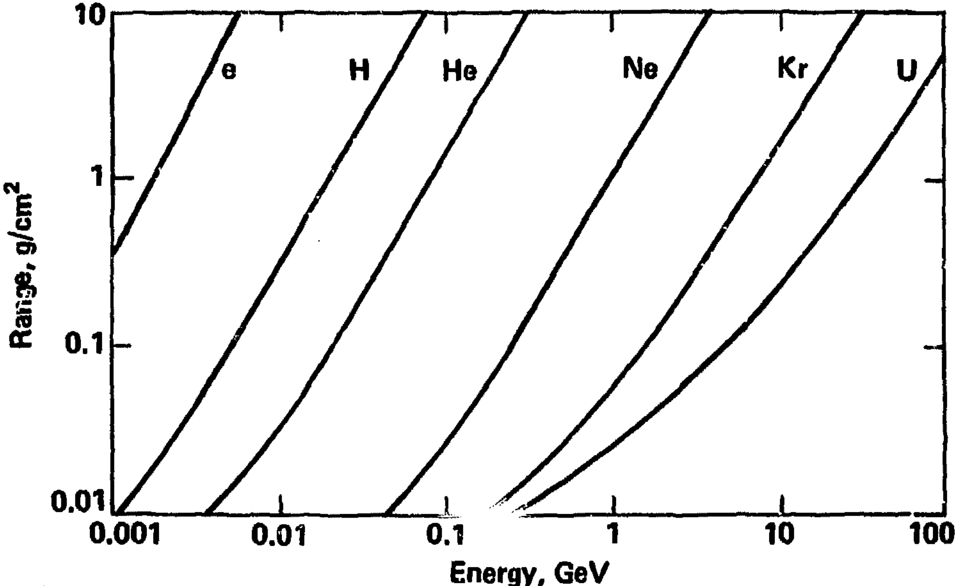

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Figure 2

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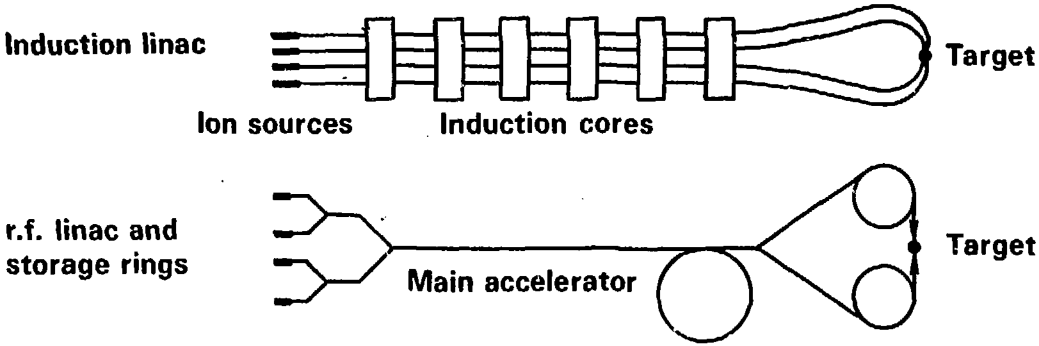
The U.S. Program has chosen to develop multiple-beam induction linacs

- Induction linacs are conceptually simple



- Simplicity is important. Beam manipulations almost inevitably increase the 6-D phase-space volume occupied by the beam. A small focus requires a small 6-D phase-space volume.

Figure 3

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