Title
HIGH-ENERGY HEAVY-ION BEAMS AS IGNITERS FOR COMMERCIAL-SCALE INTERTIAL-FUSION POWER PLANTS

Author
Judd, D.L.

Publication Date
1977-12-01

Presented at the International Scientific
Forum on an Acceptable Nuclear Energy Future of
the World, Fort Lauderdale, FL,
November 7 - 11, 1977

LBL-7267 c. 2

HIGH-ENERGY HEAVY-ION BEAMS AS IGNITERS FOR COMMERCIAL-SCALE INTERTIAL-FUSION POWER PLANTS

David L. Judd

December 16, 1977

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

HIGH-ENERGY HEAVY-ION BEAMS AS IGNITERS FOR COMMERCIAL-SCALE INTERTIAL-FUSION POWER PLANTS*

David L. Judd

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

December 16, 1977

ABSTRACT

Commercial-scale inertial-fusion power can be generated by producing a steady succession of thermonuclear microexplosions of small pellet targets whose ignition requires supplying a few magajoules in a few nanoseconds, a goal well beyond the present single-shot capabilities of high-power pulsed laser and electron-beam systems which also lack the needed repetition-rate capability of order one per second. However, existing high-energy accelerator technology with straightforward engineering extrapolations, applied to pulsed beams of heavy ions in low charge states, can meet all requirements. The relevant accelerator capabilities are discussed; three widely differing types of accelerators show promise. Needed developmental work is mostly on lower-energy components and can be conducted at relatively low cost. Some of the work started at several accelerator laboratories on this new approach within the past year are described, and possible goals of an early demonstration construction project are indicated.

*Work supported by the United States Department of Energy

1. INTRODUCTION

The goal of producing large quantities of useful power by magnetically confined controlled thermonuclear fusion has been vigorously pursued at an increasing scale in this country and abroad for a quarter of a century. During this period the scale of the required system, and in particular the complexity and cost of the reactor vessel and its associated equipment, appear to have been increasing as our knowledge has increased, while the goal has seemed to be retreating as time goes on and may still be a quarter of a century away. Although there is currently substantial well-founded optimism as to its attainment, a proof of convergence is lacking. In addition, the routine operation and maintenance of such a complicated reactor over a lifetime consistent with its initial cost depends on the evolution and development of future technologies and is not assured.

A good many years ago some thought was given to breaking this possible deadlock by a technique often used by mathematicians; reduce the problem to one already solved. The idea came out of a program called Plowshare named from the biblical injunction to "beat your swords into plowshares", and the previously solved problem was the detonation of thermonuclear bombs. It was proposed to contain such explosions in cavities within the earth and to transport their heat to the surface. To produce 1000 megawatts of electric power would require exploding a few tens of megatons (high explosive equivalent) per year. Although it might be hard definitively to disprove the technical feasibility of this plan, its environmental impact report would be difficult to write today.

A more acceptable version of this concept, very much in the modern spirit, was then put forward. We hear from time to time that "small is beautiful", so miniaturize it! For example, one ton per second, or a tenth of a ton ten times a second, will drive the same 1000 MWe power plant and the explosions can be contained within a man-made reactor vessel of practical size and strength. From this idea the present inertial-fusion program has evolved. This approach has the practical advantage relative to magnetic-confinement fusion that the reactor vessel is vastly simpler. There is also a conceptual advantage; the "convergence proof" that the technology of larger explosions is well understood gives confidence in calculations of the ignition requirements for small pellet targets.

To ignite such a thermonuclear microexplosion requires a source of energy highly localized in space and time. The needed combination of well-controlled energy, power, and density of energy deposition lies far beyond all previous experience. A stepwise approach toward their ultimate attainment by massive arrays of high power pulsed laser systems has been pursued for several years. In addition, efforts have been made over a comparable period to gradually extend the capability of high power pulsed-diode electron beam technology originally developed for other applications, and more recently (by changing the polarity) of proton beams, toward the relevant power and energy ranges. It is probable that some aspects of the physics of pellet targets will be studied experimentally on a single-shot basis by these methods within a few years, but the capability to ignite a single high-gain pellet in these ways lies farther in the future.

Attainment of the repetition rate capability to run a significant power plant is even more uncertain and depends on future research and development programs followed by the elaboration of technologies based on them.

However, there exists a mature well-developed technology, that of high-energy accelerators, which, when applied to heavy ions in low charge states, could meet all requirements for a power plant. It appears possible to do this largely within the bounds of known systems and techniques and their straightforward engineering extrapolations, and without need for a long sequence of construction projects escalating through several orders of magnitude toward the final goal. The organized national program to develop heavy-ion ignition systems is new and therefore small. Following conceptual studies by a few individuals, a two-week summer study was sponsored by ERDA in California in July 1976. Some sixty experts, familiar with a wide range of accelerator and other relevant science and technology, focused attention entirely on full-scale power plant requirements rather than neutron production or "scientific break-even" experiments. The central result was that the approach merited serious attention. No fundamental flaws were found, but system design studies, some physics experiments and calculations, and certain hardware development and construction were found needed to establish technical feasibility. Formal ERDA funding began about eight months ago for programs at Argonne, Brookhaven, Lawrence Berkeley, and Lawrence Livermore Laboratories and smaller special efforts elsewhere at a start-up rate of order $2 million per year.

It is perhaps surprising, and is certainly encouraging, that three widely differing kinds of accelerator systems were found to show promise, based on a synchrotron, an rf linac, and an induction linac as the main supplier of ion kinetic energy. In addition, the target designers can accept a spectrum of capabilities with varying energies, powers, pulse durations, and numbers and sizes of beam spots on the target. Further, there are a multiplicity of choices of ion species and charge state. As might be expected, the optimization over all these ranges among many workable accelerator systems was not initially transparent; efforts to resolve this complicated problem will continue for some time.

In the next section the pellet target ignition requirements and some reactor vessel properties are indicated. Reasons for the suitability of heavy ions in low charge states, and the relevance of existing accelerator technology, are summarized in the following sections. Next some features of igniter systems based on the three main accelerator types named above are described. Finally a few of the activities now under way are mentioned.

2. REQUIREMENTS OF AN IGNITER SYSTEM

The 1976 summer study was based on a nominal plant producing 1000 megawatts of electric power, corresponding to detonations at the rate of one ton of high explosive equivalent (4×10^9 Joule) per second. Detonation rates of order one to ten per second were considered. The requirements for igniting such targets were estimated by workers experienced in laser-fusion target design, who more recently have considered heavy-ion ignition. An energy of 1 to 10 megajoule must be supplied per target at a peak power in the

range 100 to 600 terawatt ($1 \text{ TW} = 10^{12}$ watt). Some pulse-shaping is required, with about 60 percent of the energy delivered in a time of 6 to 10 nanosecond, the balance arriving earlier at an increasing rate over about four times this period. The specific energy deposition in a heavy material within the target must be in the range 20 to 30 megajoules per gram. A number of differing target designs were considered, with the confidence level of the designers ranging from high for the higher figures above to moderate for the lower ones. One of the results of more recent target design work has been an increase of confidence in some of the less demanding designs.

Geometrical factors are of great importance in designing igniter systems. From two to a large number of beam spots on the target might be used, each having a radius of one to a few millimeters. The radius of the inner wall of the reactor vessel lies in the range 7 to 15 meters; a nominal value of 10 m has been used in most estimates. The total area of beam and vacuum ports should not exceed ten percent of the inner wall surface.

Economic and operational considerations indicate that the igniter system should have an overall energy conversion efficiency from mains to beam of ten percent or more, and require that it have high availability and a useful life of order twenty years.

3. USE OF HEAVY IONS IN A LOW CHARGE STATE

From the energy, specific energy deposition, and spot size requirements one sees that the required particle range lies within roughly an order of magnitude of one gm/cm^2 for a small number of beam spots on the target. From the range-energy relation this is found to correspond to kinetic energies of a few tens of GeV for heavy ions (mass number $A \sim 200$) . For this reason a high energy accelerator is required. The corresponding peak electric currents lie in the range of a few thousand amperes for such ions in a singly charged state ($q = 1$). Kinetic energies are a little lower and currents a little higher for ions with A as low as ~ 100 , so that the potential condidates include a wide range of ions. Methods for the multiplication of conventional accelerator currents, contained and controlled by well-understood methods, into the few thousand ampere range will be described below.

These parameters are in strong contrast to those for light ions. Protons of the same range have an energy of order 10 MeV, corresponding to a required current of order ten million amperes. Current multiplication and space charge containment into the million ampere range are impractical in conventional accelerators.

For heavy ions the electric current is proportional to the charge state q , and space charge problems increase with various powers of q . For higher charge states ($q > 5$?) designs that cope with these problems become increasingly unattractive.

4. CAPABILITIES OF ACCELERATOR TECHNOLOGY

The design, construction, and utilization of large high-energy particle accelerators is based on a mature and versatile technology. Since the end of World War II it has developed at an increasing rate in the United States, western Europe, and the Soviet Union. This activity, motivated almost entirely by an intense desire to understand the fundamental nature of matter, represents the largest commitment of men, money, and material ever made to the pursuit of basic knowledge in pure science. Included among these machines are both linear and circular systems of several kinds for accelerating electrons, protons,

and both light and heavy ions; systems for maintaining circulating beams for times ranging from seconds to hours; and devices for performing a wide variety of operations on particle beams. Although the properties of machines actually constructed have been dictated for the most part by the goals of high energy physics, many insights have been gained into possible extensions for which motivations were lacking in the past.

The performance record is excellent. It is hard to find a single example of an accelerator construction project in which the machine failed to operate well or to produce valuable results in research. All the larger ones have worked well and most of them are still working.

As a result of this experience it is possible reliably to estimate construction cost and time and operating cost of a large accelerator system when its design has been specified. Thus far each of them has been designed and built as one of a kind on a custom basis, but even the largest have cost less than a modern power plant.

The following specific capabilities are directly relevant to the suitability of a heavy-ion accelerator system as the igniter for a commercial-scale power plant.

(a) Stored Energy

Circulating beams of relativistic protons containing stored energies of several magajoules are routinely produced at the CERN Laboratory in Geneva and at the Fermi National Accelerator Laboratory in Illinois. It was in part the realization that such stored energies existed which led to some early conceptual studies of heavy-ion igniters.

(b) Experience with Long Complex Systems

A heavy-ion igniter system will have technical components with a total length measured in kilometers. (This will also be true of possible future laser and relativistic electron beam igniters at the power plant scale.) There exists much experience at this scale; the Stanford Linear Accelerator is three kilometers long, and the length of the synchrotron and associated transport lines at the Fermi Laboratory exceeds ten kilometers. Each has been in routine operation for several years.

(c) Spot Size and Distance

Ion beams are often focused on spots of order one millimeter at distances of order ten meters in high energy physics laboratories. Space charge does not prevent doing this at currents in the thousand ampere range, but would be a serious problem for protons or electrons in the million ampere range. (However, such focusing is usually accomplished in a good vacuum; the influence of a higher pressure likely to be present in the reactor vessel is now being studied. A preliminary opinion is that the resulting charge and current neutralization effects are not necessarily unfavorable.)

(d) Repetition Rates

Many types of accelerators operate at rates of one cycle per second or even much higher. Substantial experience exists with rapid-cycling synchrotrons. The marginal cost of increasing the repetition rate of either an rf linac or an induction linac beyond that needed to supply a single

reactor vessel is relatively small, and it appears that these types of main drivers would most efficiently serve two or more vessels.

(e) Power Conversion Efficiency

This property has not been of primary concern in high-energy research accelerators, but ten percent has been achieved and for appropriate types of accelerators thirty percent or greater can be designed for with confidence. The contrast here is particularly strong with other possible future full-scale igniter systems, whose efficiencies are unknown and will depend on technologies that do not exist at present.

(f) Availability

After initial periods of run-in and debugging high energy machines can be very reliable when well maintained. Unscheduled outages can run at five to ten percent over extended periods. Even with inclusion of scheduled preventative maintenance the experience compares favorably with that of conventional commercial generating units.

(g) Useful Life

The useful life of a large research accelerator has been determined in the past by changing research interests rather than by physical deterioration. A useful life of more than twenty years can be confidently expected. For example, the Bevatron at Berkeley continues in normal operation after startup in 1954.

(h) Experience with Heavy Ions

Although most large machines accelerate protons or electrons, there is substantial experience with a wide variety of ions much heavier than protons at modest currents and energies both in linear accelerators and in cyclotrons. In addition, heavy ions are routinely accelerated to very high energies (hundreds of GeV) at Berkeley in the combined Superhilac-Bevatron system known as the Bevalac.

The requirement farthest beyond present accelerator experience is the large final beam power and corresponding high final current. Several methods are available to achieve "current multiplication", and they can be combined in many ways.

(a) Acceleration at Constant Bunch Length

Here the current is proportional to velocity, which increases by a factor of order 100 in going from 1 MeV to 10 GeV; the multiplication factor $F_a = v_f/v_i$.

(b) Multi-turn Injection and Single-turn Extraction

This method can be used with a synchrotron or a storage-accumulator dc ring magnet. The multiplication factor F_m is the number of turns injected. There is experience with ~ ten turns, and fifty turns are thought to be possible.

(c) Longitudinal Compression of a Beam Bunch

Here the current increases inversely with bunch length. The factor $F_\ell = L_i/L_f$. The process is familiar in synchrotrons, in which the factor may be substantially increased over conventional values of order 10 by a special rf system; the same technique may be applied to bunches stored in an accumulator ring. Gradual bunch compression will take place normally in a properly designed induction linac for heavy ions and can be greatly increased in a supplementary compression

line following acceleration; overall compressions by a factor of order 100 are possible.

(d) Longitudinal Chopping

If a beam traversing either a circular or straight-line orbit is chopped lengthwise into n pieces which then follow paths adjusted to bring them to the target together, the current on target is increased by the factor $F_n = n$. Values of n in the range 2 to 100 have been considered.

It is confidently expected that ion sources can be developed by adaptation of known designs to produce 50 to 100 milliamperes of the desired ion species. These may be operated in parallel and their beams combined, with further paralleling of low-velocity accelerating elements, if required, providing a factor F_p . The final current is then the product of all factors times the source current. The total multiplication required is in the range 10^4 to 10^5 and it is apparent that there are many ways by which to achieve it.

Although it might be thought that there is no experience with heavy-ion sources, it is of historical interest that the greatest array of ion sources ever constructed produced singly charged uranium ions for the electromagnetic separation plant at Oak Ridge, Tennesee during World War II.

Heavy ions in a low charge state emerge from the usual 1 MV high-voltage column following the ion source with a very much smaller velocity than protons or other light ions. Special systems for their low-velocity acceleration must be designed, constructed, and tested, but several known types of structures appear capable of meeting this need. It is a general property of high-current accelerators that most of the developmental problems arising in their design relate to their very low energy components. As another historical note, deuteron currents of about half an ampere were accelerated to several MeV in the early 1950's at Livermore, California in an rf linac conceived as the front section of a much longer one extending the energy to several hundred MeV. It was evident at that time that the difficult part of the task had been accomplished and that the structure could have been extended in a straightforward way.

A few problems are less familiar; one of these is the question of current-limited beam transport. The form of the expression for the limiting current in a quadrupole or solenoid magnet transport line is known, but the numerical coefficient (representing the fraction of the theoretical maximum which can be contained in practice) depends on possible instabilities and on detailed properties of the beam structure. In recent months much progress has been made on theoretical and computational studies of the instabilities. Experimental verifications will be required but these can be obtained with low-energy beams.

A new problem arises from the possible occurrence of charge-exchange collisions between ions due to their relative motions within a bunch. Beams of hydrogen ions contain no electrons to exchange, and previous beams of ions that are not fully stripped have been too weak for this process, which results in eventual loss of both ions, to be of concern. Cross sections for electron exchange in low-velocity collisions of heavy ions in low charge states are not well known. Estimates indicate they may be large enough to limit the allowable time of residence of ions in the system to values incompatible with synchrotron acceleration (which is slower), but longer than required by the linac systems. Therefore this effect influences the determination

of an optimum igniter system. Theoretical work and detailed computations to improve the estimates are under way, and crossed-beam experiments to measure selected cross sections may be needed.

5. COMPARISON OF IGNITER SYSTEMS

As mentioned in the introduction, heavy-ion igniter systems using a synchrotron, an rf linac, and an induction linac to supply most of the beam energy have shown promise of meeting the requirements. A brief comparison of some of their features will illustrate the complexitites of selecting the optimum design.

The synchrotron and the rf linac are both widely and thoroughly understood; experience with each has accumulated over a thirty year period. The world's largest and highest-energy machines are synchrotrons. The proton rf linac at Los Alamos, New Mexico has a length of about one kilometer; it and the many others constructed as injectors for very large machines are representative of this highly developed type. Both kinds have been used to accelerate heavy ions for nuclear physics research. Neither can produce the needed beams directly; in each case the accelerated particles will be loaded by multi-turn injection into a number of dc storage or accumulator ring magnets in which they are bunched and then extracted for simultaneous delivery to the target. They also share the property of being space-charge limited only at injection, with lower limiting currents at lower injection energies, so that selection of the injection energy and provision of an appropriate injection current are central problems of system design and optimization. However, for the present application they display some striking differences; among these are cost, ion residence time, and features of the pre-injection components and injection regime.

Synchrotron Systems

The synchrotron is much less costly, with large total energy gain per meter of structure. Its focusing and accelerating components are re-used repetitively over a very large number of turns, while ions traverse a linac structure only once. Associated with this feature is the large difference in acceleration times mentioned earlier in connection with beam loss by charge-exchange collisions. To avoid this loss a synchrotron will have to cycle rapidly and handle the largest possible beam per cycle. These requirements favor choosing a relatively high injection energy, which increases the length and cost of the needed rf linac injector and thereby somewhat diminishes the high cost-effectiveness of the synchrotron. Multi-turn injection with a number of turns beyond present experience may also be advantageous. Because the synchrotron aperture is fixed by the size needed at injection, the whole space must be filled with the highest magnetic field at full energy when the usefully occupied fraction of it is smallest. The cost of power supplies to provide this field can be significant for fast-cycling synchrotrons.

It is possible to produce some bunch compression in a synchrotron; if this is done the space charge limit may also be encountered at full energy.

Rf Linac Systems

In contrast, the rf linac structure has a high cost due to a smaller energy gain per meter of structure, and a very short time of acceleration. It can be pulsed at a high enough repetition rate

to fill the accumulator rings so quickly that the charge-exchange loss is negligible. In return for its high cost, such an accelerator could provide the ignition power for two or even several separate reactor vessels by filling additional sets of rings during the time it would be idle in a single-vessel system.

Because of the low space charge limit at low velocity it appears necessary to divide the very lowest velocity part of the system into a series-parallel "tree" with the output of many separate ion sources combined, e. g. in pairs feeding half as many short pre-accelerators with outputs paired again, etc., for a few stages until all have been combined into a single beam while still at a relatively low energy, for injection into the main linac.

Acceleration is at constant current in an rf linac so that the required current multiplication must be accomplished in the source "tree" and (by the other methods described earlier) within and following the accumulator rings.

The Induction Linac

Induction linear accelerators are not widely known among those with experience in high energy machines for physics research because thus far they have been built only for the acceleration of electrons up to 30 MeV . However, they are well suited to the direct acceleration of currents of several thousand amperes or more in very short pulses from a few microseconds down to a few nanoseconds, matching the igniter requirements. An induction linac consists of a linear array of singly-pulsed nonresonant structures containing annular gaps through which the beam passes and across which the accelerating fields appear. The pulsing sequence is synchronized so that a field is present at a gap only when the beam bunch is passing through it. The technology needed to accomplish this is relatively simple and well understood. The energy for each module is stored in capacitors and switched by triggered spark gaps. The modules are designed so that the desired pulse duration corresponds to the time required to saturate the magnetic material with which they are loaded. Iron is suitable for pulses of about 0.2 to 2 microseconds and ferrite for 10 to 200 nanoseconds; no loading is needed for shorter pulses, for which a radial line geometry is suitable. An important property of the induction linac is that the efficiency of energy transfer to the beam may be very high. Practical experience with several machines covers currents up to 5000 amperes, repetition rates to 360 Hertz, gap voltages to 500 kilovolts, and path-averaged accelerating fields of 0.1 to 1 million volts per meter. Reliability is indicated by regular operation of a machine containing 550 modules at 360 Hertz for several years with high-quality pulse reproducibility.

The ion bunch length can be controlled by use of pulse shapes with slightly sloping tops; these ramped pulses may be arranged to produce increasing current amplification by pulse shortening during acceleration. After attaining full energy, the use of steeply ramped sawtooth pulses with average value zero can produce a powerful longitudinal compressive force. Such an accelerator has the unique potential of providing a single-pass straight-through system from injector to target, avoiding the need for storage in accumulator rings. The simplicity of this system is very attractive. The complexities and possible losses of multi-turn injection and other beam manipulations are avoided; gas scattering and charge-exchange losses are negligible.

Like the rf linac, the induction linac is more costly than a synchrotron and is capable of supplying several reactor vessels, but in contrast an optimum system will remain close to the transverse space charge limit over most of its length. An even greater difference is the much higher current at every energy. Because the accelerating modules become undesirably large for pulse durations greater than about a microsecond, the injected current must be of the order of a hundred amperes. Therefore an unusual injector is required. A multi-aperture source with nonresonant drift tubes, and a low-energy (~ 1 GeV) accumulator ring charged by an rf linac, both appear capable of providing such currents; a number of other concepts are being considered. Here again the developmental problems are seen to be concentrated in the low-energy components.

It is probable that the energy conversion efficiency from the mains to the beam could exceed 30% for some of the accelerator systems. This feature is no doubt unique to heavy-ion igniters; the target experts indicate that it may be exploited by using targets that have smaller gain but generate more tritium by the D-D reaction during the burn than they contain initially. The tritium can be recovered from the debris pumped out on each cycle, avoiding the need for a large, complicated and costly lithium blanket around the reactor for tritium regeneration and greatly reducing the tritium inventory.

6. WORK IN PROGRESS

Target and reactor vessel design studies are proceeding at Livermore and some special problems, such as charge-exchange cross sections and plasma effects on ion beams inside the reactor, are being worked on at other places, but the efforts on accelerator systems are concentrated at the Argonne and Brookhaven National Laboratories and the Lawrence Berkeley Laboratory. Only a few activities representative of this work will be mentioned here. As emphasized above, many of the developmental tasks involve hardware at the very low velocity end. At Brookhaven systems for very low velocity acceleration of xenon ions are being worked on. At Argonne an existing type of heavy ion source is being upgraded, with a goal of 100 mA, and will be coupled to an existing dynamitron being modified to produce 1.5 MV. At Berkeley a large-aperture high-current cesium source and high-voltage column and a flexible "test stand" for further acceleration and study of current-limited transport in solenoid and quadrupole focusing are being constructed.

Experiments have been conducted at Brookhaven, using the large proton synchrotron there, which show that the conventional space charge limit in a ring can be exceeded by a substantial factor during transient longitudinal "implosion" of a bunch just before extracting it. In addition, some methods of providing space charge neutralization within an ion beam are being investigated. If successful, such techniques could be of great significance by easing the design of final compression and transport, accumulation in a ring, and low-velocity acceleration.

At Argonne low-velocity linac designs are under study and a general computer analysis of different accelerator parameters and configurations is in progress.

The Berkeley program includes theoretical and computational studies of transport limits, a comprehensive examination of complete induction linac systems, and analyses of final bunch compression and of synchrotron parameters.

During recent months there has been much discussion of an appropriate intermediate-size accelerator construction project to demonstrate significant technical capability and achievement, particularly of certain features lying beyond those already reduced to practice. A one-week workshop attended by about 70 accelerator experts was held at Brookhaven in October 1977 to study this question and review progress since the 1976 summer study. As mentioned earlier, some study of pellet target physics with target gains less than unity will have been conducted using other igniter systems by the time an accelerator could be brought on line; therefore a possible objective of a heavy-ion demonstration project might be to explode a target with a gain of order unity. This requires an energy of only about a hundred kilojoules to be delivered, and produces a rather small bang, like an ounce of dynamite. However, it requires an igniter power in the 50 terawatt range, only about half that for a moderate-confidence pellet having a gain of order 100. Because the scale and cost of a heavy-ion igniter system are determined primarily by the power required, rather than the energy, it is not possible to construct an inexpensive small-scale pilot model plant.

Therefore it appears that the goals of the first construction project should be selected to prove out techniques likely to be required by all or several of the presently plausible accelerator scenarios, and that the usefulness of the resulting ion beams for bombarding targets should be given little weight. Such a project might, for example, include an ion source, low-velocity section, and rf linac to an energy of order 1 GeV, feeding a dc accumulator ring by about 50 turn injection. The ring would contain an rf system to shorten the bunch, which after extraction would pass through a pulsed-gap induction linac designed not to accelerate it but to compress it further, producing the highest possible peak current. Such a system would demonstrate many features of a full-scale igniter, and the beams produced would be useful for experiments on focused-bunch propagation in a variety of simulated reactor vessel environments. Discussion of different systems of this kind will continue during the next few months.

7. CONCLUSION

The reactor vessel of an inertial-confinement fusion power plant would be much simpler than that for magnetic confinement and the requirements for target ignition may be calculated from the well-known base of thermonuclear weapon technology. A high-energy heavy-ion igniter may prove to be the fastest one on the route to commercial levels of power, and the most assured in that it relies primarily on well-established technology, particularly at the high-energy end of the system. Work to date indicates that a widely differing variety of system components and design parameters are available, encouraging the hope that an optimum system will be economically attractive. Should this be the case, the field of high energy physics can return a major contribution to benefit the public which has supported it so generously.

REFERENCES

1. ERDA Summer Study of Heavy Ions for Inertial Fusion, July 19-30, 1976, Report LBL-5543 (110 pp.), December 1976, Lawrence Berkeley Laboratory.
2. Science 194, 307, October 15, 1976.
3. Proceedings of the National Particle Accelerator Conference, Chicago, March 1977; round-table discussion (pp. 1382-1384) and papers in the session on applications. IEEE Trans. Nucl. Sci. NS-24, No. 3.
4. Proceedings of the Brookhaven Workshop on Heavy Ion Fusion, October 17-21, 1977. Brookhaven National Laboratory Report (available December 1977).